<u>**CODE 26**</u>

VALIDATION OF ULTRASONIC PULSE TO QUALITY CONTROL OF RECYCLED AGGREGATE SELF-COMPACTING CONCRETE

Revilla-Cuesta, Víctor[1]*; Santamaría, Amaia[2]; Espinosa, Ana B.[3]; Chica, José A.[4]; Manso, Juan M.[1]; Ortega-López, Vanesa[1]

1: Department of Civil Engineering, University of Burgos
e-mails: {vrevilla; jmmanso; vortega}@ubu.es
2: Department of Mechanical Engineering, University of the Basque Country
e-mail: amaia.santamaria@ehu.es
3: Department of Construction, University of Burgos
e-mail: aespinosa@ubu.es
4: Fundación Tecnalia, Research and Innovation
e-mail: joseantonio.chica@tecnalia.com

ABSTRACT

One of the main operations in any civil work is to verify that the concrete supplied and placed on site reaches the required minimum compressive strength. This verification is usually performed statistically through the preparation and testing of a large number of specimens. However, its indirect control is also useful due to its simplicity, ease of execution, and low cost. One of the most common methods to perform this operation is the measurement of the Ultrasonic Pulse Velocity (UPV) of the cast concrete, checking that its value corresponds to the necessary concrete's strength class. This study aims to analyze whether this indirect measurement, widely used in vibrated concrete produced with natural aggregate, is also valid when large quantities of Recycled Concrete Aggregate (RCA) are added to Self-Compacting Concrete (SCC). For this purpose, six SCC mixes were produced with 100% coarse RCA and variable fine RCA contents (0%, 50%, and 100%). In addition, two different types of powder were used: limestone filler <0.063 mm and limestone fines 0/0.5 mm. The determination of the compressive strength and the UPV at 7 and 28 days in all mixes allowed demonstrating the existence of a close relationship between these two magnitudes in this type of concrete. It was even possible to develop highly accurate simple-regression models to interrelate both variables. These findings show that the use of SCC with RCA in engineering works would still allow the control of compressive strength using one of the most common traditional techniques, the ultrasonic pulse.

KEYWORDS: Recycled concrete aggregate; self-compacting concrete; on-site quality control; ultrasonic pulse velocity; compressive strength.

1. INTRODUCTION

Concrete quality control is one of the most common operations in any civil work. The preparation of specimens that are subsequently tested for compressive strength (EN 12390-3 [1]) enables to determine whether the concrete reaches the compressive strength established in the construction project. However, this procedure only allows controlling the concrete of one-off mixes, and may therefore be insufficient in the case of a large quantity of concrete being placed on site, such as, for example, in a bridge or in a medium-sized building [2]. In these cases, it is necessary to perform this quality control at multiple points, for which direct quality control is logistically complicated, as well as excessively expensive. In this kind of civil works, indirect quality control of concrete, determining its compressive strength, is a technique that is highly valued for its versatility, simplicity and low cost [3].

The usefulness of indirect quality control of concrete is not limited only to newly constructed structures. In the case of rehabilitation of existing structures and buildings, it is often necessary to determine the compressive strength of the concrete with which it is constructed due to the absence of precise drawings indicating it. Core drilling is, perhaps, the technique of choice because it allows the compressive strength to be measured with high accuracy. However, its use entails considerable cost in addition to the damage caused to the structure [4]. Again, indirect determination of compressive strength is a technique, possibly not as accurate, but cheap and with minimal difficulty of execution [5].

Traditionally, two indirect measures have been used to determine the compressive strength of concrete. On the one hand, the hammer rebound index, which relates the surface hardness of concrete to its compressive strength [2]. On the other hand, the Ultrasonic Pulse Velocity (UPV), which relates the compressive strength and modulus of elasticity to the propagation velocity of an ultrasonic wave in the concrete mass through the density of the material [6]. Figure 1 shows an UPV device used to determine this magnitude in concrete, the most common procedure being the direct method, in which the transducers are placed opposite each other [7]. The validity of these indirect measurements, including UPV, for estimating the compressive strength of conventionally vibrated concrete is widely accepted. In fact, a UPV between 2.5 and 3.2 km/s has traditionally been considered to correspond to low-strength concrete; between 3.2 and 3.7 km/s, medium-strength concrete; between 3.7 and 4.2 km/s, high-strength concrete; and greater than 4.2 km/s, very-high-strength concrete [6].

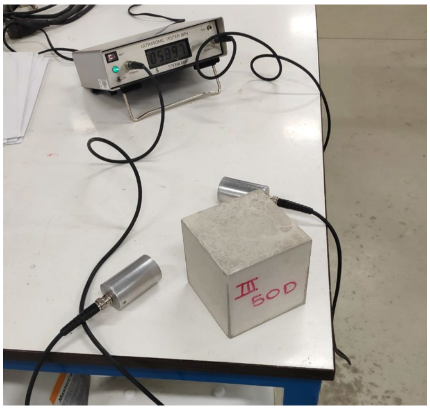

Figure 1: UPV device.

The trend to increase the sustainability of the construction sector has led to the promotion of the use of non-conventional concretes. First, the use of Self-Compacting Concrete (SCC) is being promoted, since its high filling capacity and passing ability allows it to be placed on site without the need of vibration. The suppression of vibration means a significant reduction in energy consumption during its placement, in addition to enabling concreting to be performed in any location [8]. On the other hand, the use of concrete produced with alternative materials, waste or industrial by-products, to reduce the environmental impact caused by the production of conventional materials, Portland cement and Natural Aggregate (NA), is spreading [9]. One of the most common alternative materials is Recycled Concrete Aggregate (RCA), which is obtained by crushing rejected concrete elements. The presence of adhered mortar in the coarse fraction and of altered mortar particles in the finer fraction usually results in a worsening of the mechanical behavior of the concrete, although the use of this waste in concrete reduces the environmental damage of quarries and gravel pits caused by the production of NA [10].

In line with the above, it seems evident that it is necessary to verify that the techniques commonly used in conventional concrete, such as UPV, are also valid for alternative concrete. In this way, the use of alternative concretes can be promoted, thus reducing the environmental damage of the construction sector. Up to date, the usefulness of UPV has only been analyzed in vibrated concrete manufactured with both coarse and fine RCA [10]. This study aims to deep in this research field, showing the validity of UPV to indirectly estimate the compressive strength of SCC made with RCA. For that, six SCC mixtures were prepared with 100% coarse RCA; 0%, 50%, or 100% fine RCA; and two different aggregate powders, limestone filler <0.063 mm and limestone fines 0/0.5 mm. In all the mixtures, slump flow (EN 13350-8 [1]), compressive strength (EN 12390-3 [1]) at 7 and 28 days, and Ultrasonic Pulse Velocity (EN 12504-4 [1]) at the same ages were determined. Furthermore, the statistical relationship between these last two magnitudes was accurately evaluated.

2. MATERIALS AND METHODS

2.1. Materials

Standardized CEM I 52.5 R (EN 197-1 [1], density around 3.1 Mg/m^3 and clinker content around 98%) was used in the preparation of all the mixes. The added water was obtained from the supply network of Burgos, the city where the study was carried out. Finally, two admixtures were also used to achieve high self-compactability: a plasticizer and a viscosity regulator.

As indicated above, two different aggregate powders were used: limestone filler <0.063 mm and limestone fines 0/0.5 mm. Both were used for two reasons. On the one hand, to have a larger number of mixes available for statistical analysis. Secondly, to evaluate the performance of a SCC made with limestone fines 0/0.5 mm, which is more sustainable than limestone filler due to its lower energy consumption during its manufacture because of its larger particle size [11]. Its physical properties and particle gradation are shown in Table 1 and Figure 2, respectively. Both the density and water absorption and the granulometry were suitable for SCC production.

All mixes were made with 100% coarse RCA 4/12.5 mm. The fine aggregate fraction consisted of siliceous sand 0/4 mm and/or fine RCA 0/4 mm (replacement percentages of the NA with RCA: 0%, 50% and 100%). Both RCA fractions were obtained by crushing precast concrete elements. The compressive strength of the parent concrete was 45 MPa. The physical properties of the aggregates are shown in Table 1. As expected, the RCA was lighter and had a higher water absorption than the NA [8]. Its particle size was continuous (Figure 2), thus suitable for the manufacture of concrete.

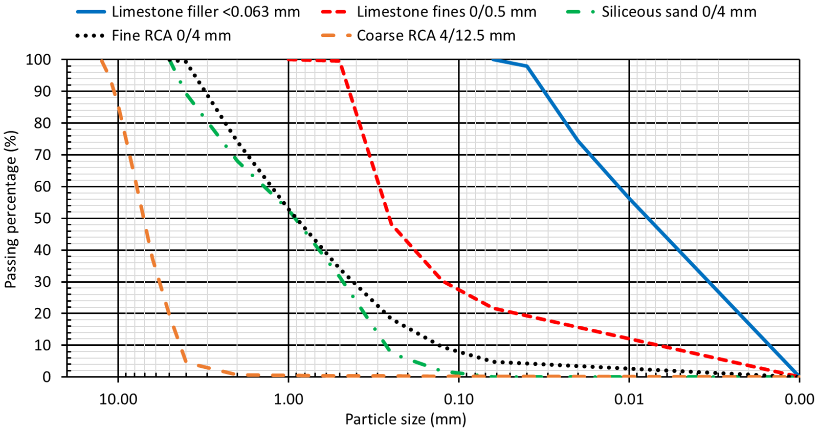

Figure 2: Particle gradation of the aggregates.

Table 1: Physical properties of aggregates.

Aggregate	Density (Mg/m^3)	24-h water absorption (% wt.)	Fineness modulus
Limestone filler <0.063 mm	2.77	0.54	-
Limestone fines 0/0.5 mm	2.60	2.57	1.22
Siliceous sand 0/4 mm	2.58	0.25	3.49
Fine RCA 0/4 mm	2.37	7.36	3.11
Coarse RCA 4/12.5 mm	2.42	6.25	6.30

2.2. Mix design

First of all, the composition of the mix made with 0% fine RCA (100% siliceous sand) and limestone filler <0.063 mm was defined. The design objective was to obtain a SCC of slump-flow class SF3 (slump flow between 750 and 850 mm [12]). For this purpose, the recommendations of Eurocode 2 [13] and EFNARC [12] were followed, with subsequent empirical modifications to achieve the desired slump flow. Next, the mixes with 50% and 100% fine RCA and the same aggregate powder were prepared, performing the substitution by volume correction. The water content was adjusted to compensate for the high water absorption of the RCA, thus keeping the effective water-to-cement ratio constant (equal to 0.50) and thus also the slump-flow class. The next step was to replace the limestone filler <0.063 mm with limestone fines 0/0.5 mm. In this substitution, it was necessary to adjust the content of both aggregate powder and fine aggregate because the limestone fines had a lower proportion of fines than the limestone filler. Since all the mixtures were of slump-flow class SF3, all the results obtained were comparable to each other.

Table 2 shows the composition of the mixtures. The mixtures were labelled with the code "*N/A*":

- *N* referred to the percentage of fine RCA added: *0*%, *50*% or *100*%.
- *A* indicated the aggregate powder used: *F* (limestone filler <0.063 mm) and *L* (limestone fines 0/0.5 mm).

Table 2: Mix design.

Component	**0/F**	**50/F**	**100/F**	**0/L**	**50/L**	**100/L**
Cement	300	300	300	300	300	300
Water	185	210	235	185	210	235
Plasticizer	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
Limestone filler <0.063 mm	165	165	165	0	0	0
Limestone fines 0/0.5 mm	0	0	0	335	335	335
Siliceous sand 0/4 mm	1100	550	0	940	475	0
Fine RCA 0/4 mm	0	505	1010	0	435	865
Coarse RCA 4/12.5 mm	530	530	530	530	530	530

2.3. Experimental tests

The SCC was manufactured using a staged mixing process to maximize flowability [5]. Thus, in the first stage, all the aggregates and half the water were added. Subsequently (second stage), the cement and the remaining water were added. In the third stage, the admixtures were poured. After each stage, the SCC was mixed for three minutes and rested for 2 minutes.

After the manufacture of each mix, the slump-flow test (EN 12350-8 [1]) was performed to check that the mix had a slump flow between 750 and 850 mm. Subsequently, six 10x10x10-cm cubic specimens were prepared to determine the compressive strength (EN 12390-3 [1]) and the UPV (EN 12504-2 [1]) by applying the direct method. Both properties were measured at 7 and 28 days, using 3 specimens at each age. After manufacturing, the specimens remained for one day in the laboratory (20±2 ºC and relative humidity of 60±5%), at which time they were demolded and stored in a humid chamber (20±2 ºC and relative humidity of 95±5%) until the testing time.

3. RESULTS AND DISCUSSION

3.1. Slump flow

All the mixes presented a slump-flow class SF3, as shown in Figure 3. Therefore, it can be observed that the use of large amounts of RCA (100% coarse RCA and up to 100% fine RCA) did not prevent the production of a concrete with high self-compactability if a proper design of the SCC was conducted. Each modification in the raw materials used to produce the SCC affected its filling capacity:

- The addition of fine RCA increased the slump flow. Although this residue presented a more irregular shape than siliceous sand and a higher water absorption [10], its higher fines content compensated for these negative aspects and improved the fresh performance.
- On the other hand, the use of limestone filler <0.063 mm resulted in a higher slump flow of SCC. The larger particle size of the limestone fines 0/0.5 mm and their more irregular shape hindered their flow and slightly reduced the flowability of the SCC [8].

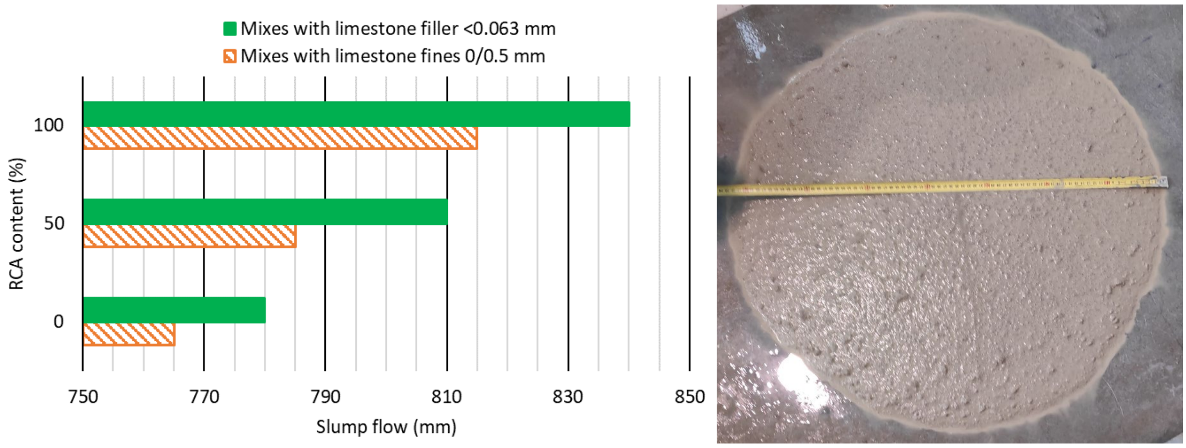

Figure 3: Slump flow of the mixes (left); slump-flow test of mix 0/L (right).

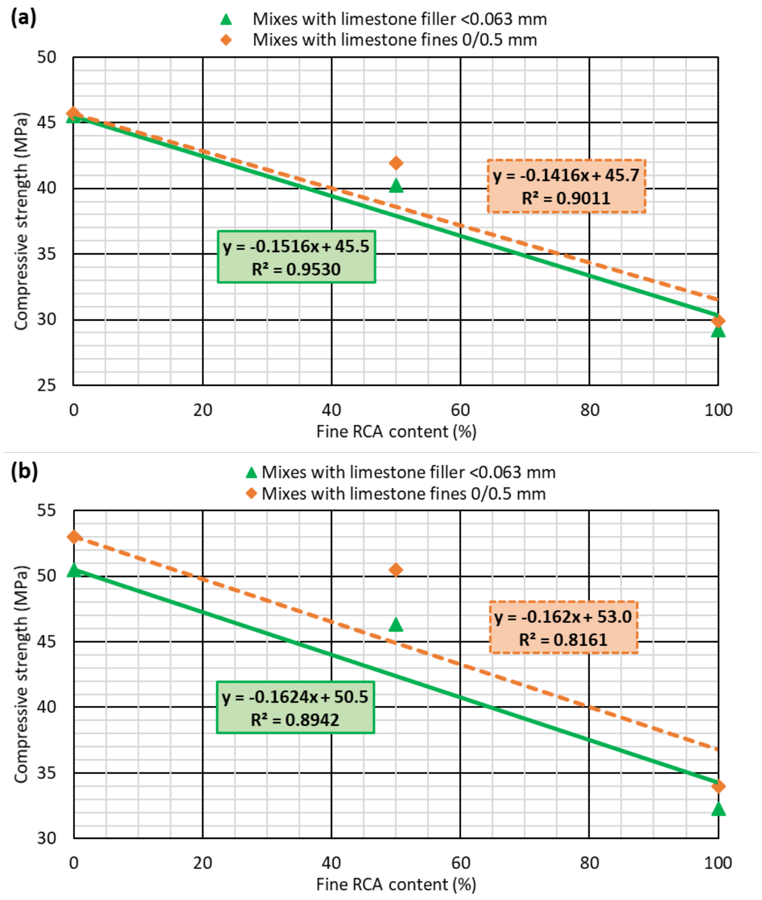

Figure 4: Compressive strength of the mixes: (a) 7 days; (b) 28 days.

3.2. Compressive strength

The 7- and 28-day compressive strength of the mixes is shown in Figure 4. All the mixtures exhibited a suitable compressive strength for structural use [13], although the use of fine RCA caused an approximately linear decrease in strength due to the presence of adhered mortar in the coarser particles, the existence of altered mortar particles in the finer fraction, and the increase of porosity of the cementitious matrix that its use caused [14]. In accordance with this linear trend, the decrease in strength caused by the addition of 50% fine RCA was lower than expected, with the addition of 100% fine RCA being much more harmful.

Regarding the aggregate powder, the mixtures with limestone fines 0/0.5 mm had a higher compressive strength. This is explained by the fact that limestone fines 0/0.5 mm allowed the creation of a higher quality cementitious matrix [15]. In addition, their higher water absorption (Table 1) allowed for greater internal curing [15], which caused a more noticeable increase in strength from 7 to 28 days.

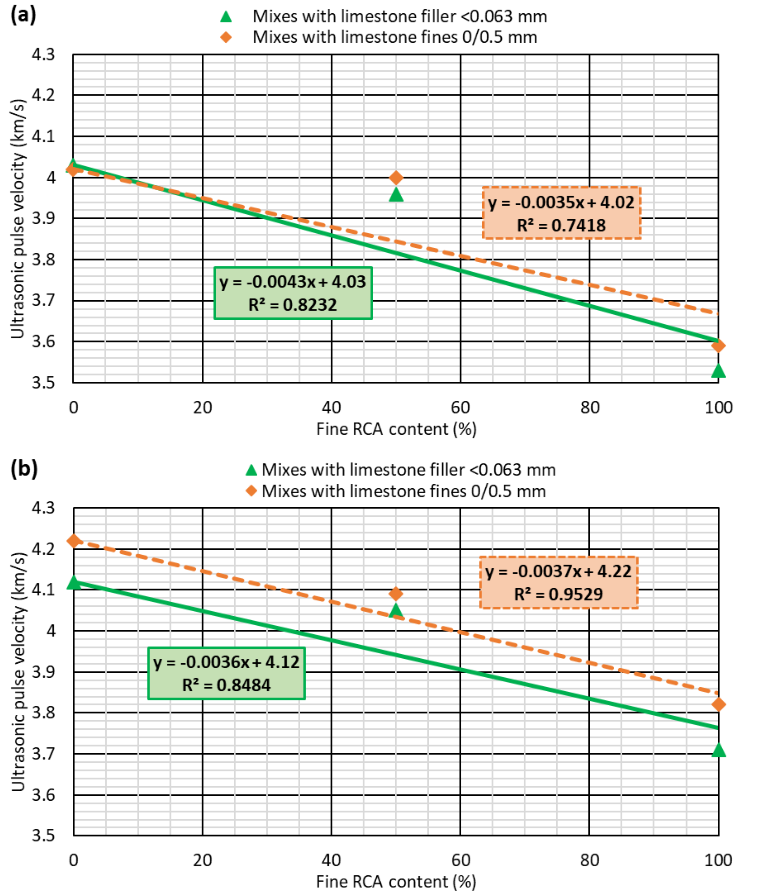

Figure 5: Ultrasonic pulse velocity of the mixes: (a) 7 days; (b) 28 days.

3.3. Ultrasonic pulse velocity (UPV)

The UPV of the mixes at both 7 and 28 days is shown in Figure 5. The values obtained corresponded to a concrete of adequate quality for structural use, although, according to the equivalence between compressive strength and UPV exposed in the introduction, slightly higher than expected [6]. A number of aspects also shown in the compressive strength can be observed in the results obtained:

- First, the UPV increased with age, being higher at 28 days than at 7 days. The development of strength over time by the cementitious matrix explains this behavior [5].

- Second, increasing the fine RCA content of SCC led to a decrease in UPV. This decrease was due to the increased porosity of the cementitious matrix when adding fine RCA and to the lower density of this waste compared to NA [14]. This decrease exhibited a linear trend, especially at 28 days.
- Finally, the use of limestone fines 0/0.5 mm increased the UPV because it created a higher quality cementitious matrix [15]. As with compressive strength, this increase was especially notable at 28 days.

3.4. Statistical relationship between the compressive strength and the ultrasonic pulse velocity

Table 3 shows the relationship between the compressive strength of the SCC and the UPV. It can be noted that in all cases a high coefficient R^2, higher than 95%, was obtained. This shows the validity of this indirect measure to accurately predict the compressive strength of SCC produced with large amounts of RCA. Another aspect to highlight is that the regression model obtained had the same expression (same formula with different adjustment coefficients) regardless of age or whether both ages were considered simultaneously. This demonstrates that it is possible to standardize this relationship to evaluate the quality of this type of concrete by statistically adjusting a large number of experimental results [5].

Table 3: Relationship between compressive strength (*CS*) and *UPV*.

Aggregate	Simple-regression model	Coefficient R^2 (%)
7 days	$CS_7 = \frac{1}{0.0747 - 0.0032 \times (UPV_7)^2}$	98.82
28 days	$CS_{28} = \frac{1}{0.0780 - 0.0034 \times (UPV_{28})^2}$	96.16
7 and 28 days jointly	$CS = \frac{1}{0.0753 - 0.0032 \times (UPV)^2}$	97.57

4. CONCLUSIONS

The following conclusions can be drawn from the aspects discussed:

- The evolution of the compressive strength and the UPV over time, as well as when modifying the fine RCA content or the type of aggregate powder was similar, which proves the existence of a close relationship between both properties.
- The estimation of the compressive strength could be performed accurately regardless of the age considered.
- The regression model between both magnitudes was always the same (same expression with different coefficients) regardless of age. This shows that the relationship between both magnitudes can be standardized.

This paper is only a preliminary evaluation of the prediction of the compressive strength of SCC with RCA through the UPV. The limited number of experimental values used means that the models developed are not reliable for their practical application, since it would be necessary to statistically adjust a larger number of data. However, it shows some useful guidelines for the development of those models.

5. ACKNOWLEDGEMENTS

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6. BIBLIOGRAPHY

[1] EN-Euronorm. Rue de stassart, 36. Belgium-1050 Brussels, European Committee for Standardization. 2020.

[2] Kazemi M, Madandoust R, de Brito J. Compressive strength assessment of recycled aggregate concrete using Schmidt rebound hammer and core testing. *Constr Build Mater*. 2019; 224: 630-638. https://doi.org/10.1016/j.conbuildmat.2019.07.110.

[3] Jones R. The non-destructive testing of concrete. *Mag Concr Res*. 1949; 1(2): 67-78. https://doi.org/10.1680/macr.1949.1.2.67.

[4] Qasrawi H. Effect of the position of core on the strength of concrete of columns in existing structures. *J Build Eng*. 2019; 25: 100812. https://doi.org/10.1016/j.jobe.2019.100812.

[5] Revilla-Cuesta V, Skaf M, Serrano-López R, Ortega-López V. Models for compressive strength estimation through non-destructive testing of highly self-compacting concrete containing recycled concrete aggregate and slag-based binder. *Constr Build Mater*. 2021; 280: 122454. https://doi.org/10.1016/j.conbuildmat.2021.122454.

[6] Jones R. The ultrasonic testing of concrete. *Ultrasonics*. 1963; 1(2): 78-82. https://doi.org/10.1016/0041-624X(63)90058-1.

[7] Barluenga G, Puentes J, Palomar I, Guardia C. Methodology for monitoring Cement Based Materials at Early Age combining NDT techniques. *Constr Build Mater*. 2018; 193: 373-383. https://doi.org/10.1016/j.conbuildmat.2018.10.205.

[8] Santos S, da Silva P R, de Brito J. Self-compacting concrete with recycled aggregates – A literature review. *J Build Eng*. 2019; 22: 349-371. https://doi.org/10.1016/j.jobe.2019.01.001.

[9] Shi C, Li Y, Zhang J, Li W, Chong L, Xie Z. Performance enhancement of recycled concrete aggregate - A review. *J Clean Prod*. 2016; 112: 466-472. https://doi.org/10.1016/j.jclepro.2015.08.057.

[10] Revilla-Cuesta V, Skaf M, Faleschini F, Manso JM, Ortega-López V. Self-compacting concrete manufactured with recycled concrete aggregate: An overview. *J Clean Prod*. 2020; 262: 121362. https://doi.org/10.1016/j.jclepro.2020.121362.

[11] Rebello TA, Zulcão R, Calmon JL, Gonçalves RF. Comparative life cycle assessment of ornamental stone processing waste recycling, sand, clay and limestone filler. *Waste Manage Res*. 2019; 37(2): 186-195. https://doi.org/10.1177/0734242X18819976.

[12] EFNARC. Specification Guidelines for Self-compacting Concrete, European Federation of National Associations Representing producers and applicators of specialist building products for Concrete. 2002.

[13] EC-2. Eurocode 2: Design of concrete structures. Part 1-1: General rules and rules for buildings. CEN (European Committee for Standardization). 2010.

[14] Evangelista L, De Brito J. Concrete with fine recycled aggregates: A review. *Eur J Environ Civ Eng*. 2014; 18(2): 129-172. https://doi.org/10.1080/19648189.2013.851038.

[15] Santamaría A, Ortega-López V, Skaf M, Chica JA, Manso JM. The study of properties and behavior of self compacting concrete containing Electric Arc Furnace Slag (EAFS) as aggregate. *Ain Shams Eng J*. 2020; 11(1): 231-243. https://doi.org/10.1016/j.asej.2019.10.001.