Concrete with fine and coarse recycled aggregates: E-modulus evolution, compressive strength and non-destructive testing at early ages

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ABSTRACT

The combined use of fine and coarse recycled aggregates in the manufacture of concrete has multiple advantages from the economic and environmental points of view. There is a lack of knowledge about the behavior of concretes containing recycled aggregates, manifested by strong limitations (even prohibitions) in international standards for structural purposes. This paper aims to study the influence of fine and coarse recycled aggregate of concrete (jointly), with particular emphasis on the evolution of the kinetics of E-Modulus and its relationship with compressive strength and non-destructive testing.

Concretes with different degrees of replacement of natural aggregates by recycled aggregates were studied: 0% (reference concrete), 8%, 20% and 31% of the total amount of aggregates. E-Modulus Measurement through Ambient Response Method (EMM-ARM) was used to monitoring the E-Modulus evolution. We also studied the influence of these recycled aggregates on the correlation between E-Modulus and compressive strength, as well as with two non-destructive testing techniques: Ultrasonic Pulse Velocity, and electrical conductivity. The activation energy of the studied concretes, based on data computed from compressive strength measurements at different curing temperatures was calculated.

We observed a negative influence of recycled aggregate on the evolution of E-Modulus from the first 12 hours, compared to the reference mixture. The crossover effect on E-Modulus evolution produced by high curing temperatures affects more to the concretes with recycled aggregate. Our data evidenced that the maturity correction for E-Modulus evolution, based on the activation energy of compressive strength, produced accurate superposition of E-modulus in the equivalent age domain.

Keywords: Recycled aggregate, E-modulus, Non-destructive test, electrical conductivity, green concrete, Maturity

1. Introduction

The European Union has established a new strategy on circular economy, in which a more clever use and management of wastes is intended. Indeed, EU-issued documentation [1,2] claims that improvements in eco-design, prevention and reuse of wastes could produce a net saving of up to 600.000 million euros per year for the European Companies. Similar pathways are being paved throughout the world in view of the recent Paris climate agreement [3]. In fact, developing ways to transform wastes in by-products, has a significant importance from the environmental and economical points of view. A relevant branch of this type of approach is the valorization of construction and wastes, using them as materials for manufacturing concrete and other construction materials [4–13]. In such context, the use of concrete wastes as recycled aggregates is an interesting option [3,6,14]. There is a significant number of studies on the influence of coarse recycled aggregate on the mechanical and physical properties of concrete [9,15–18] and it is known that its use produces a decrease of density, compressive strength and E-modulus in concrete, as compared to identical mixtures based on natural aggregates. Nevertheless, some standards like EHE-08 [19],consider that the use of coarse aggregate substitution percentages under 20% does not induce any significant effect on concrete properties. Therefore, it allows the use of recycled aggregates to produce structural concrete within such limits, without requiring any additional studies (as compared to those required for conventional concrete with natural aggregates).

There are studies on the influence of coarse recycled concrete aggregate on the relationship between compressive strength and E-modulus, which is a very important matter in view of the prescriptive aspects of nowadays regulations, being centered on defining concrete classification of mechanical performance with basis on compressive strength only. For example, in the work of Kakizaki et al. [20] and Katz [21] a correction was proposed. The correction uses one variable: density. Other authors proposed to take into account two factors: density and percentage of substitution of coarse recycled concrete aggregate [22]. Genetic programing, model tree and/or artificial neural networks have been used in order to predict certain properties of concrete in the last few years [15,17,23,24]. Some researchers have proposed formulas to estimate the compressive strength and/or E-Modulus in concretes with coarse recycled aggregates [15,23–26]. A recent study [17] proposed new formulations (analytical and based on genetic programing) for estimating the compressive strength using a combination of non-destructive tests and other factors related to the curing conditions and composition of the eco-concrete. In that study several types of eco-concrete were investigated, including concretes with different replacement percentages of fine and coarse recycled aggregate. The proposed formulas are very accurate but they estimate compressive strength only; the E-Modulus has not yet been studied with such framework.

The studies about the influence of the fine recycled aggregate on the physical and mechanical properties of concrete are scarce, but there is some literature on the subject [14,27–29]. These studies conclude that for low percentages of substitution of fine recycled aggregate (equal or less than 25%) the decrease in compressive strength is not significant and, in some cases, even a slight increase is observed. However, another particular study by Khatib [27] observed an important decrease of the compressive strength (24%) with 25% of replacement. Also, in that particular study [27], for percentages higher than 25%, there is agreement that an important decrease of compressive strength is to be expected. For E-Modulus, with a replacement of 30%, the variation is small. With a 100% of replacement of fine aggregate, the decrease is important, close to 20% [27]. Note that, nowadays, the use of fine recycled aggregate of concrete is not allowed for structural concrete in several standards [19,30–32].

In comparison with the use of coarse or fine recycled aggregate alone, the combined use of fine and coarse aggregate produces a higher economic and energetic saving in the concrete production process because the sieving for separating fractions is not necessary and all of the produced recycled material is used, which means that there is no generation of a new by-waste.

There are some studies on concretes with the combined use of fine and coarse recycled aggregates [6,14,17,33–39]. Some of these studies [14,17,34,40] suggest that the use of coarse recycled aggregate has a higher impact on the compressive strength and on E-modulus than the use of fine recycled aggregate. A recent paper studied the influence of replacement of fine and coarse recycled aggregate on the evolution of compressive strength and its relation with ultrasonic pulse velocity depending on the curing temperature [14]. **None of the contributions found in the literature has yet focused on the influence of the replacement on the evolution of the E-Modulus at early ages of concrete beams, neither on its relationship with several UPV tests and compressive strength.** In addition, there are several studies relating the electrical conductivity with the mechanical properties of concrete [41–43]. It was found only one recent paper [42] about the influence of the coarse recycled aggregate on the electrical conductivity (at 56 days). **No studies about the influence of the recycled aggregate on the electrical conductivity at early ages were found. No studies about the influence of the partial replacement of the recycled aggregates on the relationship between E-Modulus and electrical conductivity at early ages were found.**

The aim of the research reported herein is precisely to close such **research gaps** and contribute to a better understanding of the influence of fine and coarse recycled aggregate on the mechanical properties of concrete at early ages and in order **to advance towards more permissive and more sustainable standards**, without incurring structural risk.

2. Materials and methods

2.1. Materials

The recycled aggregate used in this research originates from decommissioned precast concrete sleepers with compressive strength higher than 30 MPa. After an adequate treatment (crushed and removed impurities with magnetic separation) a recycled aggregate with 0/12 mm fraction (RA-0/12) was obtained. This is the same recycled aggregate used in a recent study [14] dedicated to the study of the influence of the partial replacement of this recycled aggregates on the relationship between compressive strength and UPV in function of the curing temperature Its water absorption is 5.51% and its density of particles after oven drying is 2 280 kg/m^3.

The composition analysis of the recycled aggregate was performed following the standard EN-933-11:2009 [44]. The 83.86% of the total recycled aggregate is under the category “Unbound aggregate, natural stone, Ru (%)”. The sum of “Unbound aggregate, natural stone (Ru (%))” and “Concrete, concrete products, mortar Rc (%)” is higher than 97%. The absorption of this recycled aggregate is according to the EN-1097-6 [45], is 5.5%. In order to have the same effective water/cement ratio for all mixtures, the corresponding water of the absorption will be added to the aggregates as extra water, as it was done in previous studies [46,47].

For the studied concretes, in addition to the recycled aggregate (RA-0/12), several natural aggregates were used: two fractions of fine quarzitic aggregate 0/2 (NA-0/2) and 0/5 (NA-0/5), and two fractions of coarse quarzitic aggregate 4/12 (NA-4/12) and 10/20 (NA-10/20). The cement used was CEM I 52.5 S/SR-3.

Figure 1 shows the particle size distribution of all of aggregates used in this work, following the standard EN 933-1:2012 [48], and table 1 summarizes the main properties of all of aggregates used.

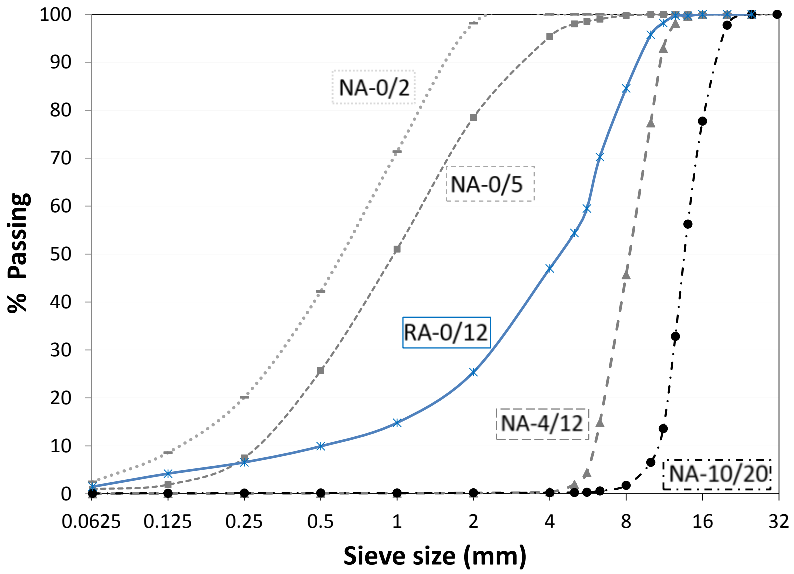


Figure 1. Particle size distribution of aggregates

Table 1. Aggregate properties

Property	Standard	NA-0/2	NA-0/5	NA-4/12	NA-10/20	RA-0/12
Apparent particle density (Mg/m³)	EN 1097-6	2.61	2.52	2.82	2.56	2.61
Oven-dried particle density (Mg/m³)	EN 1097-6	2.56	2.46	2.76	2.53	2.28
Saturated surface-dried particle density (Mg/m³)	EN 1097-6	2.58	2.48	2.78	2.54	2.41
Water absorption (%)	EN 1097-6	0.89	0.95	0.75	0.44	5.51
Particles smaller than 0.063 mm (%)	EN 933-1	2.50	1.00	0.00	0.10	1.50
Particles smaller than 4 mm (%)	EN 933-1	---	---	0.40	0.20	47
Flakiness index	EN 933-3	---	---	≤ 15	≤ 15	9.26

A standard vibrated concrete of a precast plant was used as a reference concrete (C0) with the mix composition presented in table 1. This concrete was used to fabricate pre-stressed beams.

A total of four mixtures of concrete were studied. The percentages of replacement of recycled aggregate were calculated taking as a reference the total amount of aggregate. Apart from the reference mixture without recycles aggregates (plain concrete, named C0), the percentages of partial replacement were 8%, 20% and 31% corresponding to the mixtures of concrete named in Table 1 as RC8, RC20 and, RC31, respectively. With 31% of replacement, the natural aggregate 4/12 (NA-4/12) was completely replaced, as it can observed in Table 1. Therefore higher replacement percentages were not tested.

Taking into account the particle size distribution of all of aggregates, the replacement of fine and coarse natural aggregate by recycled aggregate 0/12 was done in such a way that the total particle size distribution of all concretes was as close as possible to the particle size distribution selected for the reference concrete (C0).

To do that, we have considered that 47% of the added recycled aggregate (which is fine recycled aggregate according to the particle size distribution of RA-0/12) is replacing natural sand NA-0/5 and the 53% left (which is coarse recycled aggregate according to the particle size distribution of RA-0/12) is replacing the coarse natural aggregate NA-4/12.The moisture of the aggregates were measured and the compensation of water was made doing a correction on the amount of the water added.

The difference in the produced volume is 3% in the worst case (comparison between C0 and RC31). This small change in global value of volume has very little impact on the actual percentage of paste (in mass) per unit volume between distinct mixes (1.1% in the worst case, C0 vs. RC31). The ratio cement/aggregates by mass did not change.

Table 2. Mixtures of concrete

Material	C0	RC8	RC20	RC31
CEM I 52.2 R-SR 3 [Kg]	400	400	400	400
Recycled aggregate 0/12 (RA-0/12) [Kg]	---	145	363	563
Natural sand 0/2 (NA-0/2) [Kg]	308	308	308	308
Natural sand 0/5 (NA-0/5) [Kg]	608	539	437	343
Coarse Natural aggregate 4/12 (NA-4/12) [Kg]	300	223	108	2
Coarse Natural aggregate 10/20 (NA-10/20) [Kg]	600	600	600	600
Effective water/cement ratio	0.45	0.45	0.45	0.45
Total volume (liters)	1020	1028	1040	1052

Mixing procedure was established following the next steps:

1. Moisten the mixer with a wet cloth.
2. Add natural sand and mix for 30 seconds.
3. Add cement and mix for 60 seconds.
4. Add coarse natural aggregate and recycled aggregate, and mix for 60 seconds.
5. Without stopping the mixer, add water slowly for 30 seconds and mix for 60 seconds.
6. Without stopping the mixer, add the superplasticizer slowly for 30 seconds and mix the necessary time until the power consumed by the mixer will be stabilized.

The slump test was performed according to the UNE-EN 12350-2:2009 Standard to assess the consistency of the concrete mix.
The slump in all cases was very similar, 19 cm +/- 1cm. No trend of changes of slump related to the percentage of recycled aggregate was found. The reason is that we used wet aggregate with a moisture close to its absorption value (aggregates close to SSD condition) and we did the calculations to adjust the mixing water to make sure that, in total, we had the absorption water plus the effective water we wanted.

2.2. Methods

The following experimental techniques have been adopted: E-Modulus Measurement through Ambient Response Method (EMM-ARM) [49], internal electrical conductivity and internal temperature through a combined sensor (ConSensor) [43,50,51] and Ultrasonic Pulse Velocity test (UPV) [52]. The activation energy was also calculated, following the method described in ASTM C1074-11 [53]. In the following paragraphs, a brief description of these methods is provided in an individual and sequential manner.

- *EMM-ARM:*

The EMM-ARM is a method of automatic and continuous monitoring of the evolution of E-Modulus in hardening materials, such as concrete. The monitoring starts right after the concrete casting of the test specimen is finished. This method is based on the continuous modal identification of the resonant frequency of the test specimen, which consists in a hollow tube filled with the material to be tested (concrete in this case). The resonance frequency of the composite beam allows direct estimation of the E-modulus of concrete based on the equations of motion of the system. The accuracy, repeatability and other methodological aspects of EMM-ARM have been tested and successfully demonstrated in a number of studies [4,54–61]. To check the set-up and validate the method again, the standard test of E-modulus of C-0 was tested at 28 days, according to UNE-EN 12390-13: 2013.

To perform the EMM-ARM test two beams were made for each concrete. The beams have a circular transversal section with 98 mm diameter and the simply supported span is 1 meter [59]. The beam was cast and placed in the measurement position (in a climatic chamber at 20°C) within less than 30 minutes from the beginning of mixing. Measurements were made with a high sensitivity accelerometer (PCB 393B12 with mass of 210 g; sensitivity 10 V/g; measurement range of ±0.5 g; frequency range: 0.15 to 1000 Hz) per beam (at mid-span) and a 24-bit NI 4431 dynamic signal analyzer. In order to have better results, in this experimental program the EMM-ARM tests were carried out with imposed excitation induced by a custom-made non-contact electromagnetic actuator. A sine sweep signal (with linear frequency variation between 10 and 200 Hz) with 40 s duration was used as excitation signal. The frequency of acquisition was 1250 Hz. One value of E-Modulus was estimated every 12 minutes based on time series of measurement of 5 minutes and waiting periods of 7 minutes.

In addition, a complementary study about influence of a change of the curing temperature on the evolution of E-Modulus was done for two of the studied concretes (C0 and RC8). For these concretes, two additional beams were fabricated and tested with EMM-ARM at a curing temperature of 40 °C. The aim was to observe if it is acceptable to apply the correction of maturity using the activation energy calculated, for the E-Modulus evolution curves.

- *Electrical conductivity:*

For each concrete, one specimen with size 300 x 200 x 110 mm^3 was casted with an embedded sensor placed in the center of gravity of the sample. The sensor is an analogue sensor. This sensor can measure the electrical conductivity with a wide dynamic range and approximately 100 kHz, using a 2-point method [4,50,62]. The sensor's setup also included a NTC temperature sensor. This sensor has the ability to record data from the end of the concrete casting.

The mold was made of a non-conductive material (PVC with 1 mm of thickness) so as not to influence the results. One value of electrical conductivity and internal temperature were registered each 10 minutes, using an automatic machine called ConSensor 2.0. After cast, the samples were kept in inside the molds, covered with plastic film and placed in a climatic chamber during all the time test. The curing temperature was 20 ^{o}C and the samples were in the mold during all the test.

- *Ultrasonic Pulse Velocity (UPV) and compressive strength:*

20 cubic samples with 100 mm side were casted and cured at 20 °C. During the first day into the mold, they were covered with plastic film and kept in a climatic chamber with 95% of humidity and temperature 20 °C. After the first day, the samples were demolded and placed into a water bath, inside of a climatic chamber. The UPV test was performed according to EN-12504-4 standard [52] and compressive strength test was performed according to EN 12390-3 standard [63]. They were performed at 1, 2, 3, 4 (or 6), 7 and 28 days. Three samples

were tested at each age. The average values were calculated. The 2 remaining samples were instrumented with internal temperature sensors.

- *Activation energy and maturity method:*

The previous methods are performed using samples with different size. Changes in the size of the sample can impact the internal temperature development (due to hydration heat) and consequently changes in the equivalent age. In order to get the correlations between the results of the methods in a meaningful way, we need to compare values with the same equivalent age. For that purpose, the activation energy was calculated according to ASTM C1074-11 [53], using 100 mm cubic samples. To that end, it was necessary to do the compressive strength test with samples cured at 3 temperatures (5, 20 and 45 °C). For each temperature, samples were tested at 6 different ages between 1 and 31 days [14]. With the activation energies, the equivalent age was calculated using the Arrhenius equation [53,64] in order to do the correlations between results of different tests.

The data regarding the evolution of compressive strength of samples cured at standard temperature will be also used, along with the data regarding the evolution of E-Modulus, to study the influence of the recycled aggregates on the relationship of E-Modulus and Compressive strength at early ages.

3. Results and analysis

3.1. Influence of the recycled aggregates in the evolution of E-Modulus at early ages.

Figure 2 shows the evolution of E-Modulus at early ages for concretes with different replacement percentages of natural aggregate by recycled aggregate. Two beams were tested for each concrete. The differences between the results of the two beams of each concrete are negligible (less than 1%), for that reason, the averaged curve of each is presented. The evolution of E-Modulus of the four concretes is similar during the first hours and no influence of recycled aggregate is observed. However, from the 10 – 12 first hours, the influence of recycled aggregate is clear: the higher replacement, the lower E-Modulus. Note that the replacement level influences the E-Modulus, even with low percentages (RC8). With low percentages, the compressive strength is not so affected [14].

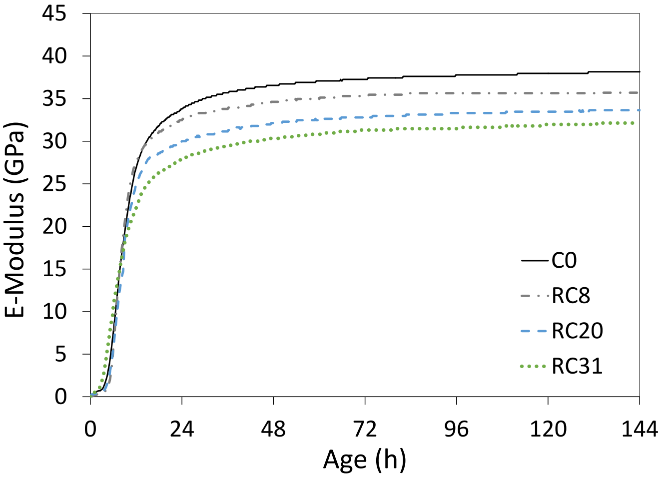


Figure 2. Evolution of E-Modulus

To check the set-up of the test, the E-Modulus test according to UNE-EN 12390-13: 2013 was performed at 7 days for concrete C0. The result of the standard test was 39.4 GPa, while the result under the same conditions with EMM-ARM was 38.3 GPa. The error is lower than 3%.

Figure 3 shows the loss of E-Modulus for each concrete compared to the reference concretes (C0) at the same ages. From the first 72 hours, the loss percentages of E-Modulus are stabilized and they are around 6% for RC8, 12% for RC20 and 16% for RC31. It means that the loss of E-Modulus seems quite proportional to amount of recycled aggregate. The influence of the recycled aggregate on the E-Modulus at 24 hours is lower than at 144 hours for concretes with 8% recycled aggregate. The concrete with 20% of recycle aggregates, its influence is similar at 24 hour and at 6 days, in comparison with the reference concrete. In contrast, the concrete with 31% of recycled aggregate is higher at very early ages (24 hours) than at 144 hours (6 days).

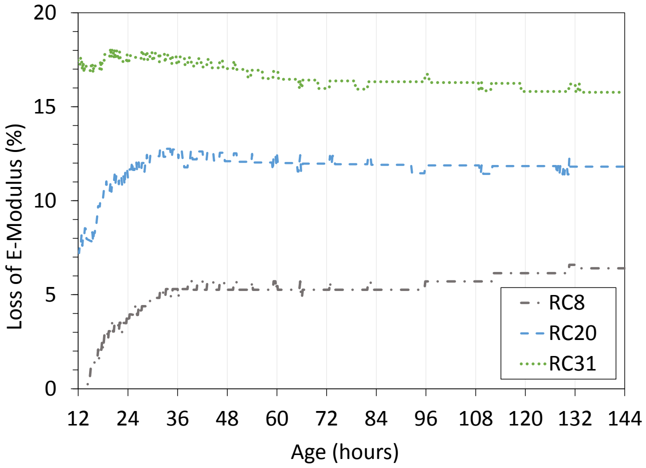


Figure 3. Evolution of the loss of E-Modulus compared to C0

3.2. Influence of the recycled aggregates in the evolution of ultrasonic pulse velocity and conductivity

- *Evolution of the ultrasonic pulse velocity (UPV).*

Figure 4 shows the evolution of the UPV in the concretes studied. The influence of the recycled aggregates in its evolution does not have a clear trend. At early ages, the reference concrete and the concrete with 8% of recycled aggregate show similar values of UPV. In concretes with higher percentages of recycled aggregate, from 4 days, the values of UPV of concretes with recycled aggregate are clearly lower than the values for the reference concrete at the same ages.

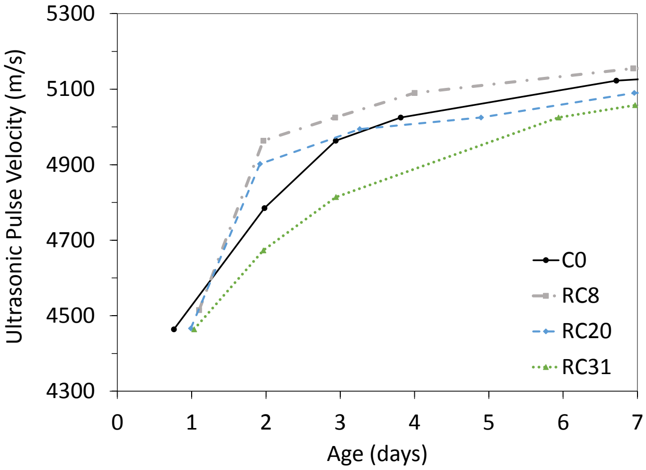


Figure 4. Evolution of ultrasonic pulse velocity

- *Evolution of the electrical conductivity*

As it can be observed in Figure 5, the percentage of recycled aggregate has influence on the electrical conductivity: from the first 48 hours, the higher the percentage of recycled aggregate is, the higher the electrical conductivity is.

During the first 12 hours, when the concrete is not hard, the change in electrical conductivity is not clearly related to percentage of recycled aggregate: the values of RC31 at early ages (less than 12 hours) are not consistent with the hypothesis that the recycled aggregate increases the electrical conductivity.

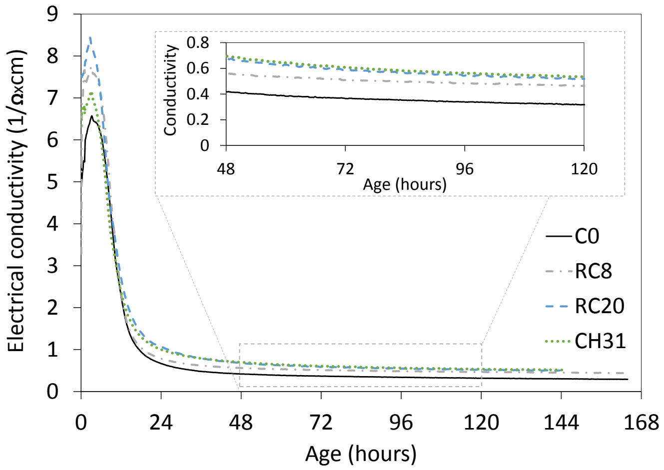


Figure 5. Development of electrical conductivity

Figure 6 shows that, in the selected ages (2, 3 and 6 days) the electrical conductivity increases with the percentage of recycled aggregate. This fact can be explained by the relationship between the amount of recycled aggregates and the porosity. The higher the amount of recycled aggregates is, the higher the porosity. A higher porosity implies a higher diffusion coefficient [65,66]. And, a higher diffusion coefficient implies a higher electrical resistivity [65,66]. It means, the higher percentage of recycled aggregate, the higher electrical resistivity is expected. Also, it shows that, as the age increases, when the concrete is increasing its maturity, the electrical conductivity decreases.

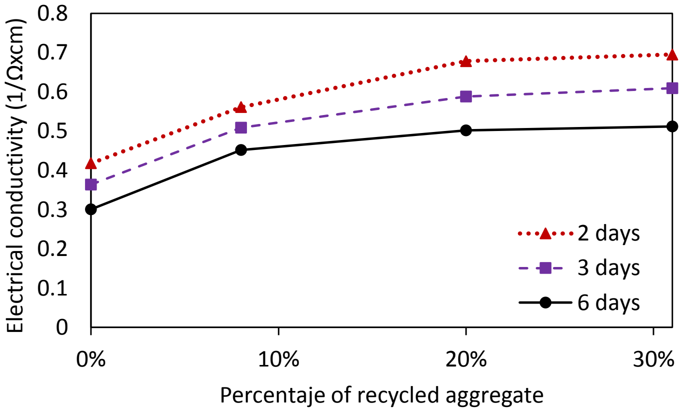


Figure 6. Electrical conductivity in function of percentage of recycled aggregate

3.3. Influence of the recycled aggregates in the relationship between E-Modulus and non-destructive testing.

- *Maturity corrections.*

Due to the difference in the volume of the samples used for each method, the history of internal temperature for each type of sample is different (figure 7). Therefore, the measurements of the different methods could not be correlated directly because it would be a correlation between values of samples with a different equivalent age. A maturity correction should be necessarily performed.

The record of internal temperature for the samples of 100 mm (used for UPV and compressive strength) is practically indistinguishable from the record of internal temperature for the samples used for EMM-ARM method (for the same concrete). This record of internal temperatures is very different from the record of internal temperatures of the samples used for the measurement of electrical conductivity.

Thus, in the case of the correlations between electrical conductivity and any other test performed, it will be necessary to calculate the equivalent ages using the Arrhenius equation [53,64,67,68], taking into account the record of internal temperatures showed in Figure 7. In this way, the distortion produced by the use of samples with different size will be eliminated and the correlations will be done correctly comparing data with the same equivalent age.

The activation energy was calculated using the data of the evolution of the compressive strength at different temperatures of each concrete, studied in one of our previous research [14], according with ASTM C1074-11 [53]. In the case of the samples cured at 5 °C, the value at 1 day is rejected because of experimental/handling difficulties associated to insufficient hardening of the specimen at such age. The activation energy for C0 is 42.65 kJ/mol, for RC8 is 42.43 kJ/mol, for RC20 is 48.83 kJ/mol and for concrete RC31 is 52.16 kJ/mol.

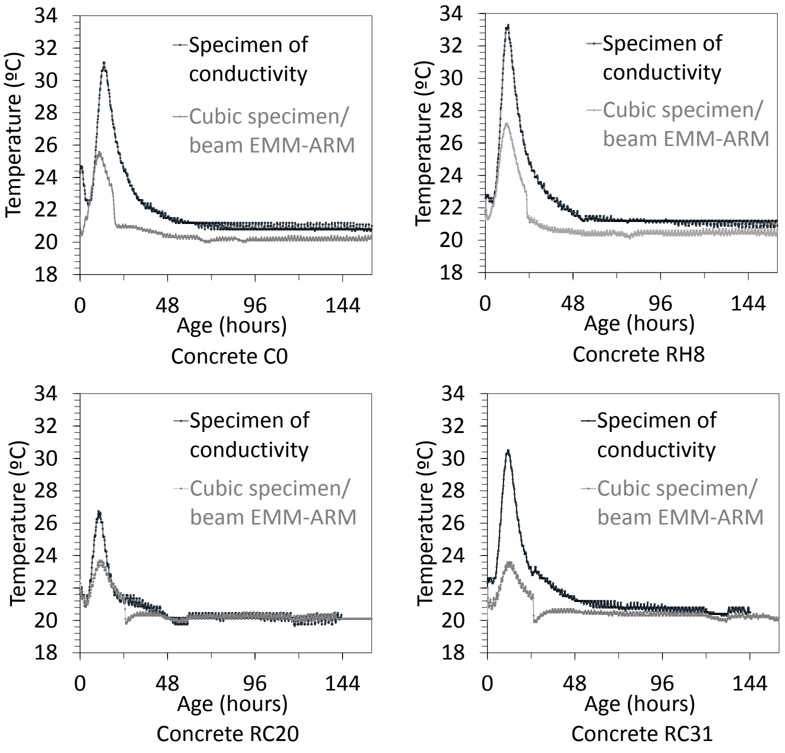


Figure 7. Comparative of internal temperature in different specimens

- *Correlations between E-Modulus and UPV*

According to the literature [64], it is known that the theoretical relationship between square of the UPV and E-modulus for a homogeneous material is affected by two main additional parameters: density and Poisson's ratio. In Figure 8, the correlation between E-Modulus and UPV from the first 12 hours is represented. It can be observed that the amount of recycled aggregate influences greatly this correlation. For the same value of UPV, the corresponding E-Modulus for C0 and RC31 have a difference over 20%. The higher the amount of recycled aggregate is, the lower the E-Modulus corresponding to the same value of UPV is.

The Poisson's ratio does not present significant changes due to the replacement of recycled aggregate; in a recent study [69] researchers found that the Poisson's ratio is the same for a plain concrete and for a concrete with 100% of replacement of coarse aggregate (in both cases Poisson's ratio was equal to 0.21). So, the differences of the relationship between E-Modulus and UPV could be based on the difference of density due to the partial replacement of recycled aggregate. The higher the amount of recycled aggregate is, the lower density is. This fact can explain that, for a given E-Modulus, the corresponding UPV is higher the higher the amount of recycled aggregate is (lower density) [46,47,70], according with Eq. 1. It is needed to remark that, in reality, the concrete is not an isotropic material, so Eq. 1 can be only used to capture a trend, but not to do an exact calculation of the E-Modulus.

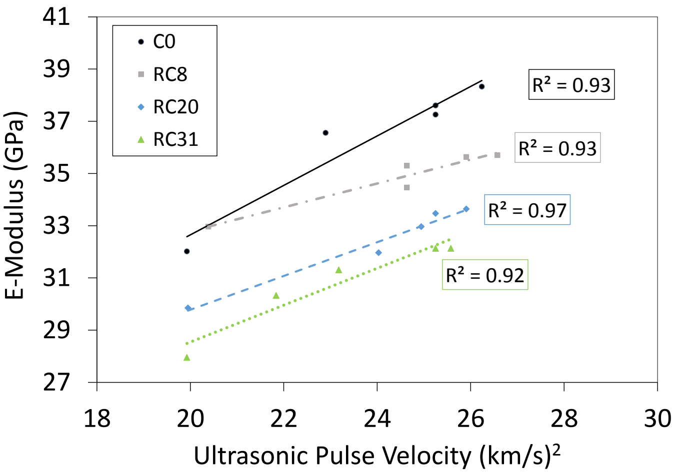


Figure 8. Correlation between (UPV)^2 and E-Modulus

- Correlation between E-Modulus and electrical conductivity

In figure 9, it can be observed the correlation between E-Modulus and internal electrical conductivity for values of E-Modulus higher than 20 GPa. The higher the amount of recycled aggregate is, the lower value of E-Modulus corresponds to the same value of electrical conductivity, except for the concrete with a low percentage of recycled aggregate (RC8) with values of E-Modulus lower than 30 GPa. Thus, it can be concluded that the recycled aggregate influence the correlation between E-Modulus and internal electrical conductivity.

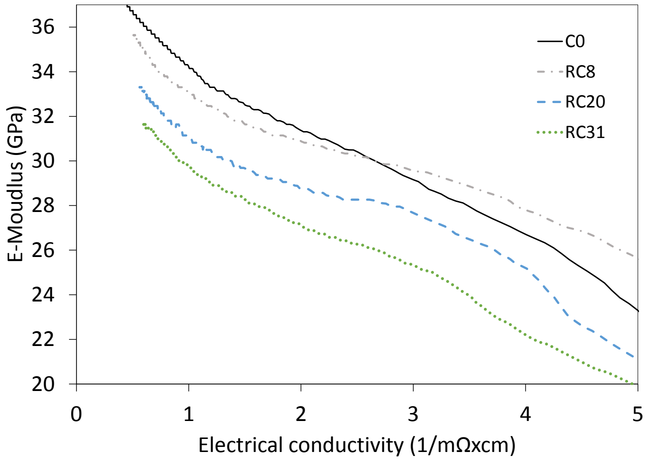


Figure 9. Correlation between electrical conductivity and E-Modulus

3.4. Influence of the recycled aggregates in the relationship between E-Modulus and compressive strength

Figure 10.a shows the evolution of the compressive strength of each concrete and Figure 10.b shows the relationship between E-Modulus and compressive strength at early ages. For the same value of compressive strength, the higher the amount of recycled aggregate is, the lower the corresponding E-Modulus. This fact could be important; if the standard equations are used for estimating the E-Modulus, using the data of compressive strength in concretes with recycled aggregates, this could result in an overestimation of the E-Modulus. Nevertheless, note that with a replacement of 31% of the total aggregate by recycled aggregate, the overestimation is lower than 10%. However, for higher percentages of recycled aggregate, the overestimation could be higher than 10% and, it could be necessary to do some changes in the standard equations for estimating the E-Modulus because the results could be out of the security side.

Table 3 compares the value of modulus according to the experiments vs. the estimated modulus using the equation from the Eurocode 2 [71] to estimate the modulus based on the compressive strength for concrete made with quarzitic aggregates. For reference concrete, C0, applying the equation from EC-2 we obtain an underestimation of the modulus lower than -4%.

Table 3. E-modulus from test vs estimation of E-Modulus from EC-2 based on compressive strength for C0

Age (Days)	E-Modulus (GPa)	Estimated Modulus EC-2 (GPa)	Difference (%)
1.98	36.56	35.44	-3.1
2.94	37.26	36.18	-2.9
3.81	37.61	36.32	-3.4
6.72	38.33	36.82	-3.9

The difference between the real modulus and the estimated modulus based on EC-2 equation is higher, the higher is the amount of recycled aggregate. Whereas for the reference concrete C0, applying the EC-2 equation causes an underestimation of the E-Modulus of -3.9% (at 7 days), the difference is +7.1% (overestimation) for concrete RC31 at the same age.

The Eurocode 2 [71], the Model Code [72] and the EHE-08 [19] suggest that the type of aggregate could affect the relationship between E-Modulus and compressive strength. For example, in the standard EHE-08 [19] there are some correction factors for some types of aggregates. In this standard, there is not any correction coefficient for recycled aggregate. However, it may be different according to the quality of the recycled aggregate. No previous studies have been found about the influence of fine and coarse recycled aggregate used jointly on the correlations between E-Modulus and compressive strength at early ages.

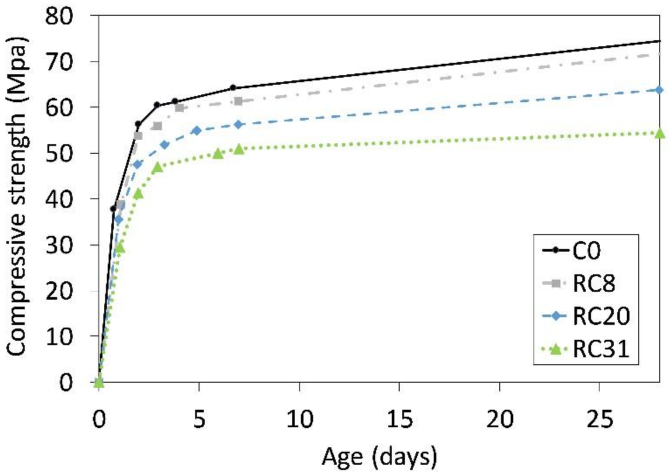


Figure 10.a. Compressive strength at early ages and at 28 days

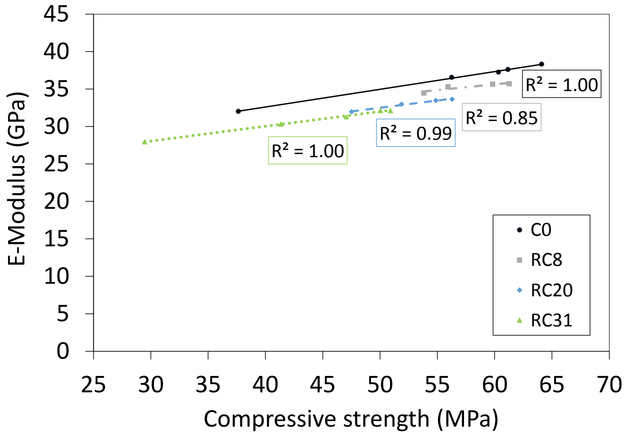
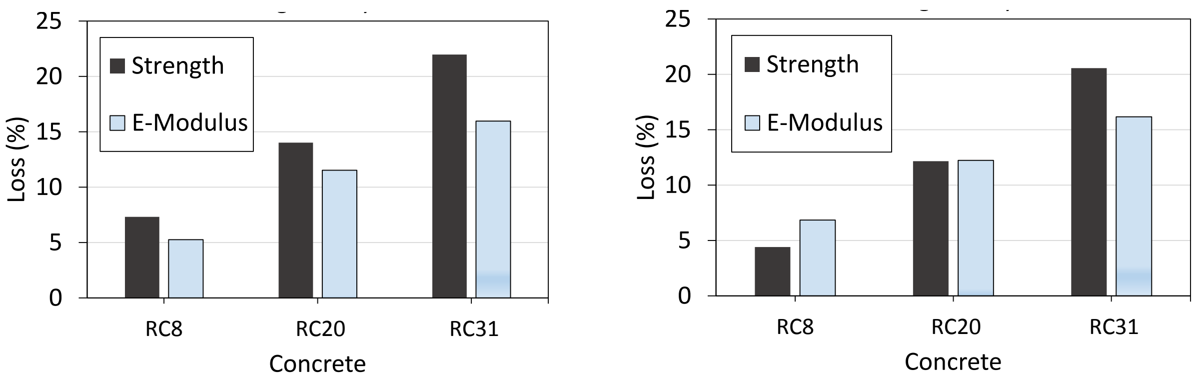


Figure 10.b Correlation between compressive strength and E-Modulus

As it can be observed in Figure 11.a, at 3 days, the percentage loss of compressive strength due to the use of recycled aggregate is substantially greater than the percentage loss of E-Modulus. However, as can be observed at 7 days in Figure 11.b, the same effect is only present in the case of the concrete with the highest amount of recycled aggregate (31% of the total aggregate). In the case of RC8, at 7 days, the influence in the E-Modulus is clearly higher than in the compressive strength. In in-situ works, the control value is usually the compressive strength, but the results suggest that in the case that low percentage of recycled aggregate (RC8), the E-Modulus should be the control factor.



11.a) At 3 days 11.b) At 7 days

Figure 11. Comparison between % loss of compressive strength and % loss of E-Modulus, due to using recycled aggregate.

3.5. Influence of curing temperature in the evolution of E-Modulus and applicability of maturity correction using the activation energy calculated with compressive strength data.

The influence of the curing temperature in the evolution of the E-Modulus was studied for the concretes C0 and RC8. For that purpose, in addition to the EMM-ARM test with beams cured at 20 °C, a test group with beams cured at 40 °C was performed. As it can be observed in Figure 12, high temperatures (40 °C) accelerate the evolution of E-modulus buildup at very early ages (first hours), but the final value of E-Modulus at 7 days is lower than the value observed at the same age for the beams cured at 20 °C. A negative effect can be observed at 48 hours (and even before). The effect of high temperatures, in the case of compressive strength, was reported in studies for many years [73], but the crossover effect in compressive strength is usually observed later than in the case of E-Modulus observed in Figure 12. This suggests something really important: the negative effect of high temperatures at early ages is higher in E-Modulus than in compressive strength.

At a curing temperature of 40 °C, the influence of the recycled aggregate is observed from earlier ages than in the beams cured at 20 °C. The influence of recycled aggregate is slightly affected by the curing temperature: the difference between the effect of recycled aggregates at a curing temperature of 20 °C and 40°C is around 12%.

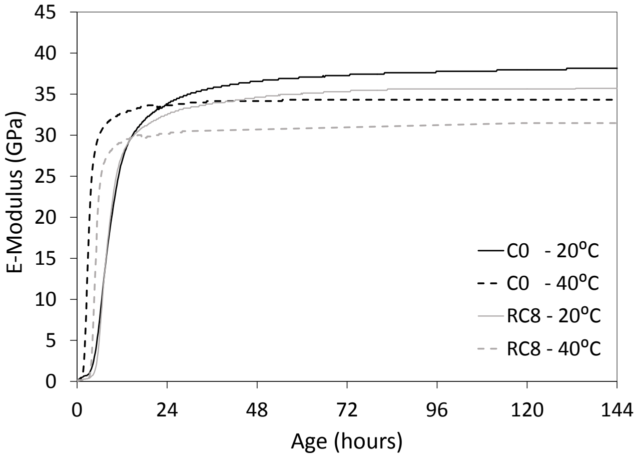


Figure 12. Evolution of E-Modulus in function of curing temperature (C0 y RC8)

Figure 13 shows the equivalent age vs ratio of E-Modulus at each age divided by the stabilized E-Modulus at 7 days for each concrete and each temperature.

The activation energy used in each case corresponds to the activation energy for each concrete calculated with the data of compressive strength. There is an study that suggest that the activation energy is different for different properties [74]. But, in the cases of the present study, it seems that the activation energy calculated with the data of compressive strength is applicable for correcting the values of E-modulus. The curves calculated are really close.

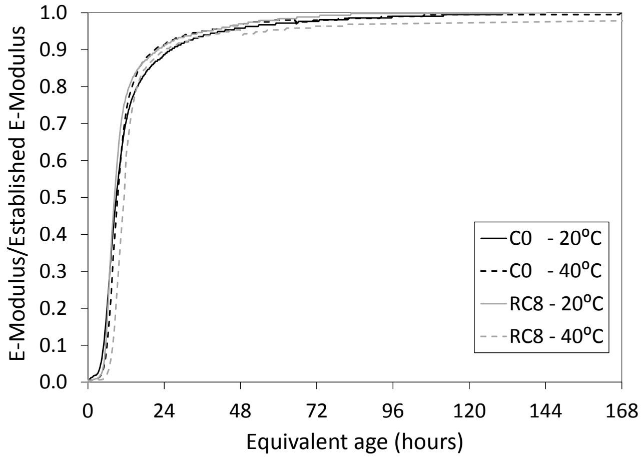


Figure 13. Evolution of the relative E-Modulus vs equivalent age

4. Conclusions

From the first 12 hours, the influence of the fine and coarse recycled aggregate starts to be noted; the higher the amount of recycled aggregate is, the lower the E-Modulus. From the first 24 hours, the loss of E-Modulus due to the use of recycled aggregate has certain proportionality with the amount of recycled aggregate replacement.

The replacement of natural aggregate by recycled aggregate has a clear influence on the relationship between E-Modulus and the NDT used: UPV and internal electrical conductivity. In both of them, it is observed that for the same value of NDT, the higher the amount of recycled aggregate is, the lower the corresponding E-Modulus (except in the case of low replacement, RC8, which has the opposite trend for low values of E-Modulus in its correlation with internal electrical conductivity).

At early ages, the correlation between E-Modulus and compressive strength is affected by the amount of recycled aggregate. Not considering this fact could result in an overestimation of the E-Modulus. However, note that even with the highest replacement tested in the present study, the overestimations are not over 10%. For higher percentages of recycled aggregate, the overestimation could be higher than 10% and, it could be necessary to do some changes in the standard equations for estimating the E-Modulus, because the results could be out of the security side.

It is observed that, at 7 days, the negative effect of the recycled aggregates is higher in the E-Modulus than the in the compressive strength in concretes RC8 (8% of recycled aggregate) and RC20 (20% of recycled aggregate). In practice, this fact should be considered because the control parameter is usually the compressive strength.

An important conclusion is that, analyzing the data, it can be observed that the crossover effect due to increase of the internal curing temperature is higher for the E-Modulus than for the compressive strength, at early ages. This fact should be considered in locations with warm weather or in constructions with a huge volume of concrete, where temperatures could achieve high values.

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