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# The effect of recycled aggregates on the accuracy of the maturity method on vibrated and self-compacting concretes

## Abstract

Fine and coarse recycled aggregate used jointly as partial replacement of natural aggregate is not allowed for structural concrete in many international standards. More studies about it are needed towards more ecofriendly standards. This research studies one important aspect for structural concrete: the influence of recycled aggregate on the accuracy of the maturity method. A total of 7 different mixes were studied with two types of reference concretes: vibrated (VC) and self-compacting concrete (SSC). For vibrated concrete, we studied 4 mixes with different partial replacements of fine and coarse recycled aggregates (of the total amount of aggregates): 0%, 8%, 20% and 31%. For self-compacting concrete, the partial replacements were 0%, 20% and 50% of the total amount of aggregates. We found that, for percentages equal or higher than 20%, the higher is the percentage of recycled aggregate, the higher the activation energy. It was observed that a unique curve “Maturity – Relative strength ($S/S_\infty$)” can be used for each type of concrete (SSC or VC) independent of the percentage of recycled aggregate. In addition, we found higher accuracy of the estimations using the hyperbolic equation for the curve “Maturity – $S/S_\infty$” than using the exponential equation; applying the hyperbolic approach, less than 3% of the estimations had an error higher than 10%.

## 1. Introduction

In the last 25 years a greater awareness has been developed toward to the need to protect the environment. The international community has developed different initiatives to promote a sustainable development. Proof of this are, for example, the “Roadmap to a Resource Efficient Europe”, the European Union new strategy about the circular economy [1] or the Paris Climate Change Conference, in December 2015 [2]. Some of the guidelines are the reduction of $CO_2$ emissions, the efficient management of resources and the reduction of the use of natural resources. For this reason, it is very important to conduct studies on waste possible uses, in such a way that they may be transformed into by-products, from both an environmental and future circular economy point of view.

A branch of this type of studies covers the utilization of waste as components for building materials production. For example, studies on the effect of recycled aggregates in concrete [3,4] and in asphalt [5], marble powder [6] or glass powder [7], filler or copper slag [8,9] and biomass ash in concrete [10] or in asphalt mixtures [11,12].

The waste concrete, crushed, becomes a new material: fine and coarse recycled aggregates. The joint utilization of the fine and coarse fraction has a double benefit from the environmental point of view: the $CO_2$ emissions are reduced because sieving is not necessary to separate the fine and coarse fractions, and 100% of the recycled aggregate produced is used, so a new waste is not generated [13].

While it is true that both of them have important advantages, in addition to economic savings, it should be noted that there are several disadvantages. In order to obtain a concrete similar to a reference one, a good adjustment of the particle size distribution must be done when the aggregate is replaced, and it must be checked that the resulting grading curves are similar to the curves of the original concrete. Moreover, fine recycled aggregate is banned by most of the regulations for the manufacturing of structural concrete [14]. For this reason, it is necessary to gain more knowledge about the influence of this recycled material with the aim of contributing to the development of more permissive and sustainable regulations, without compromising security. There are many studies on recycled concrete aggregates. Some of them cover the production, management of recycled plants and their optimal location [15,16], others cover the influence of coarse recycled aggregates on the workability, compressive, flexural and tensile strength [17], modulus of elasticity, creep and shrinkage and durability [18,19] or about the effect of fine recycled aggregates on the mechanical properties of concrete [20]. There are also studies about the effect of recycled aggregate on the mechanical behavior of concrete beams under shear and/or flexural test [21,22]. There are studies about the influence of the curing temperature on the recycled aggregate effect on compressive strength of concrete [23]. There are studies about the influence of mineral additions (fly ash and silica fume) on the properties of concrete with 100% of recycled aggregates [24]. There are also studies about the correlation of the elastic modulus and the mixture proportioning and characteristics of aggregates [25,26]. But no studies about the effect of the recycled aggregate on the maturity estimations were found. The application of the maturity method is very important to ensure the structural security, specially, during the construction phase, at early ages [27,28]. For these reasons, this research studies the influence of the partial replacement of natural aggregate by recycled aggregate in order to analyze possible singularities due to the incorporation of fine and coarse recycled aggregates; as well as to gain knowledge about the influence of fine and coarse recycled aggregate on the maturity evolution of vibrated and self-compacting concretes.

There are numerous formulas for the estimate of compressive strength according to the maturity. One of the formulas most commonly used (Eq. 1) is the formula proposed by Nykanen, in 1956 [27,29] according to a maturity index M (also called time-temperature factor, TTF) and a constant factor k. The term maturity index was introduced by Saul [30] who, in 1951, proposes the formula, better known as Nurse-Saul (Eq. 2). In 1954, Rastrup [31] defines equivalent age according to equation 3 and in 1977, Hansen and Pedersen [32] propose an improved formula for the calculation of the equivalent age (Eq. 4), based on the Arrhenius equation.

$$S = S_{\infty}.(1 - e^{k.M}) \qquad \text{(Eq. 1)}$$

$$M = \sum_{0}^{t} (T - T_0) \cdot \Delta t \tag{Eq. 2}$$

$$t_e = \frac{M}{(T_r - T_0)} \tag{Eq. 3}$$

$$t_e = \sum_{0}^{t} e^{\frac{-E}{R} \cdot [\frac{1}{273+T} - \frac{1}{273+Tr}]} . \Delta t \tag{Eq. 4}$$

where S is the strength estimated with the formula, $S_\infty$ is the infinite strength (strength stabilized in time), M is the maturity index (°C·hours or °C·days), k is the constant that depends on the w/c ratio and the cement type, T is average concrete temperature during time interval $\Delta t$ (°C), $T_0$ is the datum temperature or minimum temperature for which concrete gains strength (°C), $\Delta t$ is the time interval (days or hours), $t_e$ is the equivalent age (days or hours), $T_r$ is the reference temperature (°C), E is the activation energy (J/mol) and R is the Gas constant (J/mol).

From equation 1, it can be concluded that for the same maturity, the relative strength $S/S_\infty$ is equal, provided that the concretes compared are produced with the same cement and have the same w/c ratio. Therefore, according to equation 1, concretes with the same reference mix composition, and modifying solely the replacement ratio of the recycled aggregate, should have the same curve maturity index – $S/S_\infty$ ratio (there should not be variations due to different w/c ratios and/ or different the type of cement). It can be said that concretes with the same water/cement ratio and type of cement should have the same curves M- $S/S_\infty$ and $t_e$ - $S/S_\infty$.

Assuming that k does not depend on the replacement level of the recycled aggregate, and considering equations 1, 3 and 4, it can be concluded that:

$$M = \frac{1}{k} \ln\left(1 - \frac{S}{S_\infty}\right) \tag{Eq. 5}$$

$$M(t) = T_r . \sum_{0}^{t} e^{\frac{-E}{R} \cdot [\frac{1}{273+T} - \frac{1}{273+Tr}]} . \Delta t \tag{Eq. 6}$$

Besides the strength adjustment formula of Nykanen (Eq. 1), there are other strength adjustment formulas, such as the logarithmic function (Eq.7) and hyperbolic function (Eq. 8) proposed by Kee in 1971 [33]. The parameters a, b and A are constants to determine, related with the water/cement ratio and the cement type.

$$S = a + b \cdot \log(M) \tag{Eq. 7}$$

$$S = \frac{M}{\frac{1}{A} + \frac{M}{S_\infty}} \tag{Eq. 8}$$

There are several papers about the use of the maturity method to estimate the concrete compressive strength, including recent papers about maturity method for mass concrete [34,35], steel fiber reinforcement concrete [36] or sprayed concrete [37].There are few studies on the maturity of eco-concretes, for example concretes with supplementary cementitious materials [9,38,39], or with the addition of other wastes as rice husk ash [39]. However, no studies have been found on the influence of fine and coarse recycled aggregates on the accuracy of the estimation of concrete compressive strength applying the maturity method.

## 2. Significance of research

For all these reasons, in this paper, the influence of the joint replacement of fine and coarse recycled aggregate on the activation energy has been studied on vibrated and self-compacting concretes. In addition, the influence of recycled aggregates on the accuracy of the maturity method was also studied on both types of concrete. ASTM C1074 and previous studies assumed that the activation energy depends mainly on the cementitious materials and water/cement ratio. It is valid for concretes with natural aggregate but, taking into account that the recycled aggregates have special properties (potential presence of unhydrated cement or other cementitious materials, hydrated cement paste and higher water absorption than natural aggregates), we expected that coarse and fine recycled aggregate may have an effect on the activation energy of concrete. This effect would imply that the activation energy, using the method of the equivalent mortar, should not be used in the case that we have recycled aggregates since we can miss part of the effect of recycled aggregates on the real activation energy of concrete. In addition to that, several estimates of compressive strength evolution were made through exponential and hyperbolic equation models, using the time-temperature factor or using the activation energy and the Arrhenius equation, in order to quantify the effects of the recycled aggregate on the accuracy of each method and model.

## 3. Materials and methods

### 3.1. Materials

Two plain concretes were studied as reference concretes: a self-compacting concrete (SCC0) and a vibrated concrete (VC0). Each of them was used in a different pre-cast factory; SCC0 was used to make reinforced beams and the VC0 to make pre-stressed beams. Using recycled aggregate from wastes of the same factories, this research studies the influence of the percentage of the fine and coarse recycled aggregate on the activation energy. In both cases the size of the recycled aggregate is 0/12 (fine and coarse jointly). The recycled aggregate used for SCC has a 47% of fine aggregate and a 53% of coarse aggregate. The recycled aggregate used for VC has a 40% of fine aggregate and a 60% of coarse aggregate. The substitutions had been done according to this distribution of the recycled aggregates. The fine fraction of recycled aggregate partially replaces the fine natural aggregate with a maximum size of 5 mm. The coarse fraction of recycled aggregate partially replaces the coarse natural aggregate with a maximum size 12 mm (same maximum size than total recycled aggregate).

For vibrated concrete, four mixes were studied: VC0, VCR8, VCR20 and VCR31 (with 8%, 20% and 31% of replacement of the total amount of aggregate by recycled aggregate). For this particular reference concrete (VC0), the 31% substitution resulted in the complete substitution of one of the coarse natural aggregate of the mixture by recycled aggregate.

For self-compacting concrete three mixes were studied: SCC0 (Plain SSC), SSCR20 (20% of replacement of the total amount of aggregate by recycled aggregate) and SSCR50 (50% of replacement of the total amount of aggregate by recycled aggregate).

Table 1.a presents the mix design used in vibrated concrete. Table 1.b shows the mix design of the self-compacting concretes. The same mixtures were used in a previous study about the influence of the curing temperature on the correlation between ultrasonic pulse velocity and compressive strength [23].

*Table 1.a. Mix designs used in vibrated concretes*

| Material | VC0 | VCR8 | VCR20 | VCR31 |
|---|---|---|---|---|
| CEM I 52.2 R-SR 3 (Kg) | 400 | 400 | 400 | 400 |
| Quartz Fine Natural aggregate 0/2 (Kg) [FA 0/2] | 308 | 308 | 308 | 308 |
| **Quartz Fine Natural aggregate 0/5** (Kg) [FA 0/5] | **608** | **539** | **437** | **343** |
| **Quartz Coarse Natural aggregate 4/12** (Kg) [CA 4/12] | **300** | **223** | **108** | **2** |
| Quartz Coarse Natural aggregate 10/20 (Kg) [CA 10/20] | 600 | 600 | 600 | 600 |
| Recycled aggregate 0/12 (Kg) [RA 0/12] | --- | 145 | 363 | 563 |
| Effective water/cement ratio | 0.45 | 0.45 | 0.45 | 0.45 |

*Table 1.b. Mix designs used in self-compacting concretes*

| Material | SCC0 | SCCR30 | SCCR50 |
|---|---|---|---|
| Cement I 52.5 N-SR (Kg) | 335 | 335 | 335 |
| Quartzite Filler (Kg) | 320 | 320 | 320 |
| Quartz Fine Natural aggregate 0/2.5 (Kg) [FA0/2.5] | 370 | 370 | 370 |
| **Quartz Fine Natural aggregate 0/5** (Kg) [FA 0/5B] | **510** | **375** | **172** |
| **Granite Coarse Natural aggregate 6/12** (Kg) [CA 6/12] | **810** | **607** | **303** |
| Recycled Natural aggregate 0/12 (Kg) [RA 0/12B] | --- | 338 | 845 |
| Additive (Kg) | 5.4 | 5.4 | 5.4 |
| Effective Water / Cement | 0.5 | 0.5 | 0.5 |

Figure 1 shows the particle size distribution of all aggregates used in this research. The designation of each aggregate is summarized in Table 1.a and Table 1.b. The flakiness index is 5 for the recycled aggregate used on SCC (RA0/12B) and 9 for the recycled aggregate used in vibrated concrete (RA0/12).

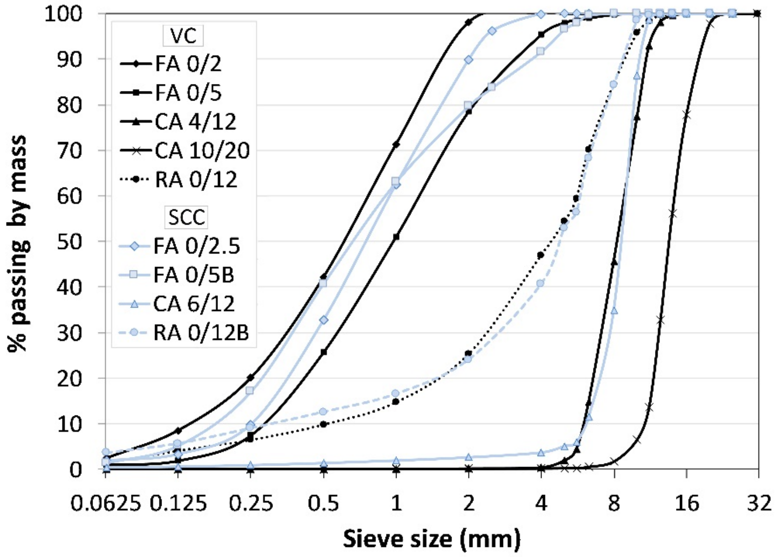


*Figure 1. Particle size distribution of aggregates*

### 3.2. Methods

70 liters mixtures are prepared for each of the concretes studied and 60 cubic specimens 10x10x10 cm$^3$ are obtained from each of them. These 60 specimens are divided into three groups. Each 20 specimens group is cured

at a different temperature: 5 °C, 20 °C and 45 °C. Two specimens of each group have an internal temperature sensor with the aim of monitoring the evolution of the internal concrete temperature.

Three specimens of each temperature group are tested at the ages of 1, 2, 3, 4 or 6, 7 and 28 days. The remaining two specimens of each group (the specimens monitored with the internal temperature sensor), are tested at 90 days or more, with the purpose of getting a value closer to the strength at infinite time.

With the compressive strength data at three different temperatures, the activation energy is calculated in accordance with the procedure indicated in the ASTM C1074-11 standard [40]. In addition, the activation energy will be calculated for temperatures lower and higher than the reference temperature (20 °C).

Afterwards, an analysis of the influence of fine and coarse recycled aggregates on the estimations according to the maturity method is done. According to equation 1, concretes VC0, VCR8, VCR20 and VCR31 should have the same curve maturity index - $S/S_\infty$ ratio, since they have the same type of cement and the same water/cement ratio. This reasoning is applicable to the curves SCC0, SCCR20 and SCCR50, that should be identical, according to equation 1. Moreover, as the maturity could be calculated using the Arrhenius (Eq. 6) formulation and it is defined as the equivalent age multiplied by a constant. It can be concluded that, following the previous reasoning, concretes VC0, VCR8, VCR20 and VCR31 should have the same curve equivalent age index - $S/S_\infty$ ratio, and this is applicable to the curves SCC0, SCCR20 and SCCR50. It will be checked if this is acceptable or, on the contrary, it is necessary to do some modification for concretes with fine and coarse recycled aggregate.

In addition, a comparison will be done between the data obtained from the exponential formulation (Eq. 1) and the obtained from the hyperbolic formulation (Eq. 8). Moreover, a comparison of both results will be done considering if the time-temperature factor is used for the calculation of the maturity (Eq. 2 ) or the maturity based in the equivalent age by using Arrhenius equation (Eq. 6).

## 4. Results and discussion

### 4.1. Activation energy

The compressive strength values of each concrete at the different ages and curing temperatures are shown in Figure 2.a and Figure 2.b. The activation energy of each concrete was calculated using these data, according to ASTM C1074-11 [40] using the concrete samples, since the calculation with equivalent mortar would not capture the potential influence of recycled coarse aggregate on the activation energy.

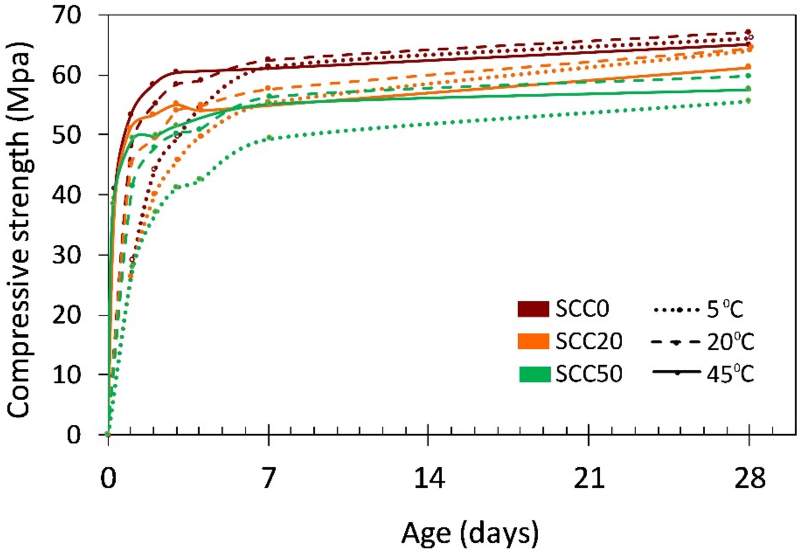


*Figure 2.a. Compressive strength of self-compacting concretes*

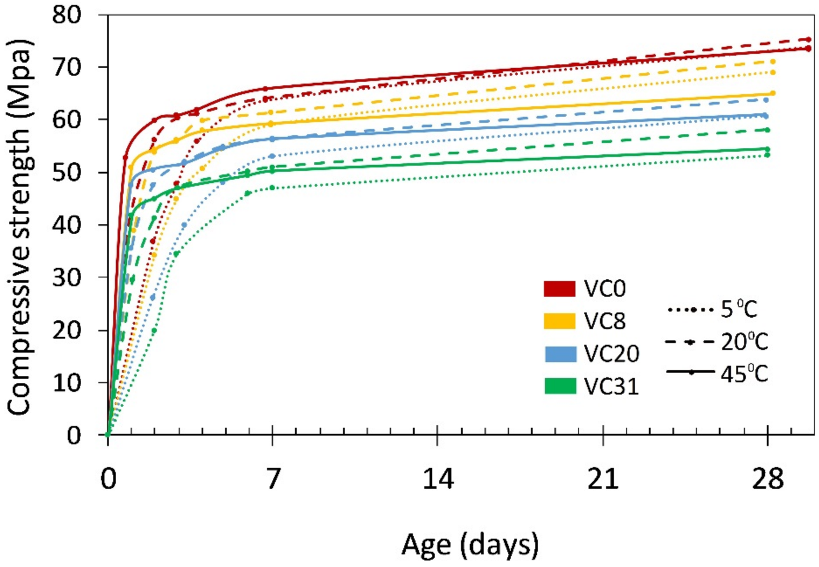


*Figure 2.b. Compressive strength of vibrated concretes*

In figure 3, the influence of the recycled aggregates on the activation energy of the reference concretes and the concretes with recycled aggregate is shown. It is observed that for low replacement ratios (8%), the activation energy is barely affected and even is slightly lower than the obtained for the corresponding reference concrete. While for higher replacement levels (from 20%), in both, vibrated and self-compacting concrete, it is observed an increase in the activation energy when increasing the substitution percentage.

The activation energy calculated according to the ASTM C1074-11 [40] with three temperatures (in this case 5°C, 20°C y 45°C) is applicable in the whole range of temperatures studied. In the case that a concrete temperature history will be foreseeably under 20°C or, above, this fact can be considered and a correction of the activation energy can be done.

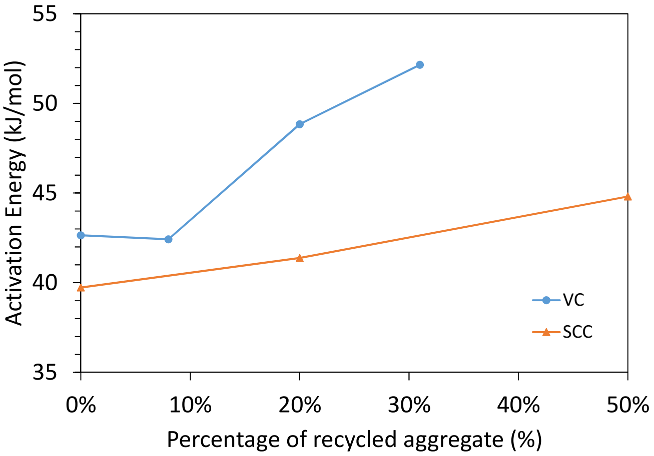


*Figure 3. Activation energy according to the recycled aggregate percentage*

If the values of 1/temperature (1/kelvin) are represented on the abscissa axis, and the logarithm of the values K obtained for each temperature are represented on the ordinate axis (being K the ratio between the ordinate on the coordinate origin and the slope of the line 1/age against 1/strength) and they approach a straight line, the slope of that line is equal to "-Ea/R" (being R the universal gas constant).

Figure 4 shows the plot of the inverse of the temperature vs. Ln(K) for each of the studied self-compacting concretes. In Figure 5 the inverse of the temperature vs. Ln(K) was represented for each of the vibrated concretes studied.

As shown in figures 4 and 5, and in table 2, for all the concretes studied, vibrated and self-compacting (with the exception of SCCR50, because the three values of $E_a$ are very similar), if the low temperatures range is taken (lower than 20 °C), the activation energy is higher than the calculated with the three temperatures according to the ASTM. On the contrary, for higher temperatures, the activation energy is lower than the calculated according to the ASTM criteria.

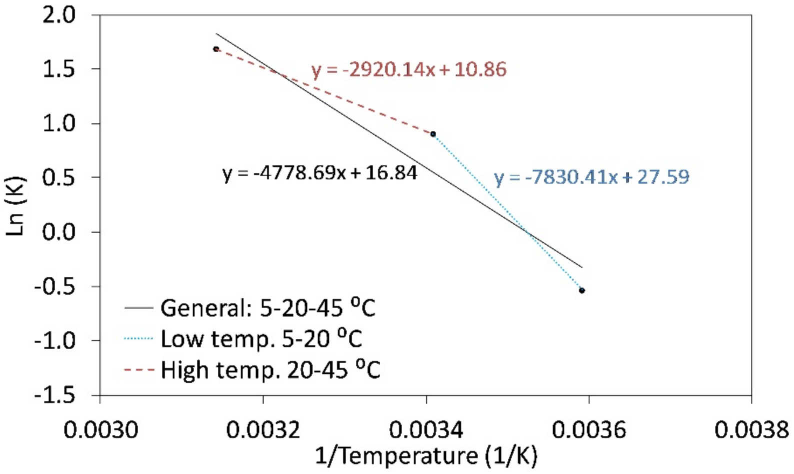


*Figure 4.a. Inverse of the temperature against Ln (K) for concrete SCC0*

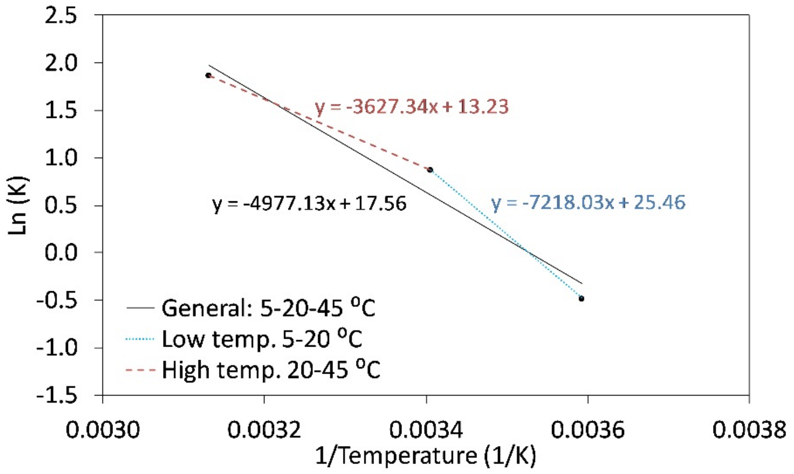


*Figure 4.b. Inverse of the temperature against Ln (K) for concrete SCC20*

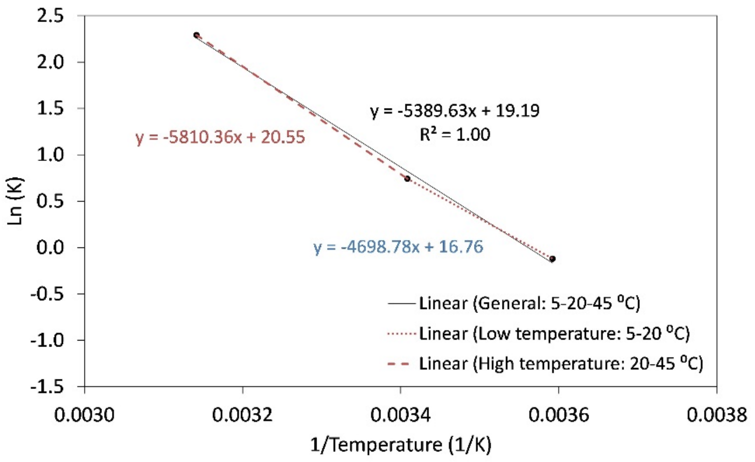


*Figure 4.c. Inverse of the temperature against Ln (K) for concrete SCC50*

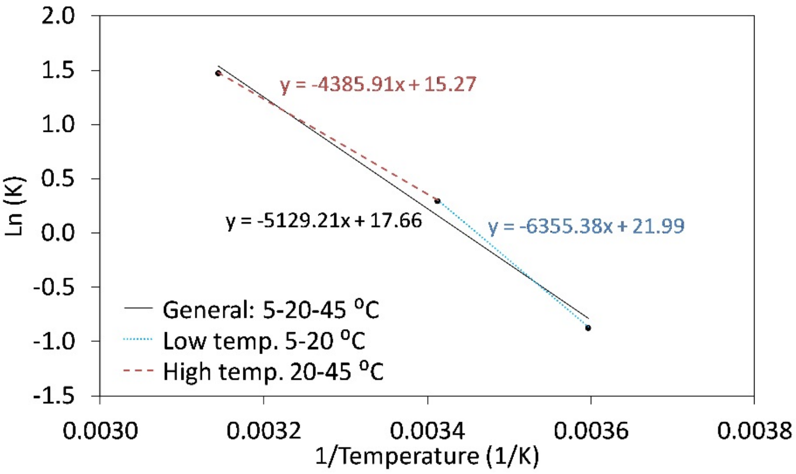


*Figure 5.a. Inverse of the temperature against Ln (K) for concrete VC0*

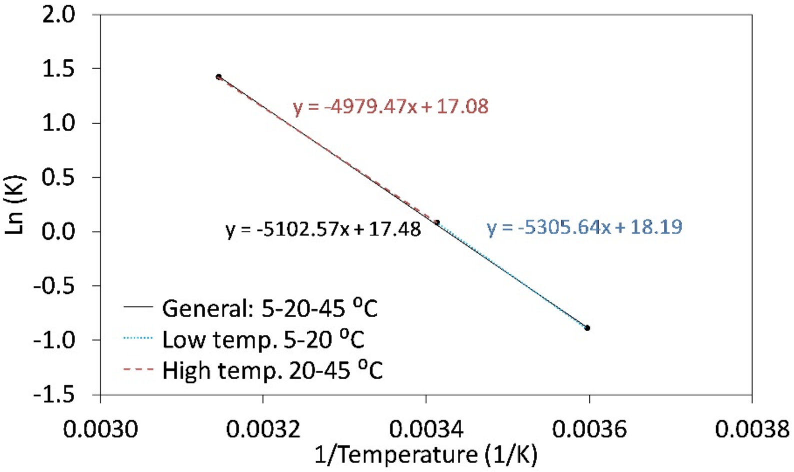


*Figure 5.b. Inverse of the temperature against Ln (K) for concrete VCR8*

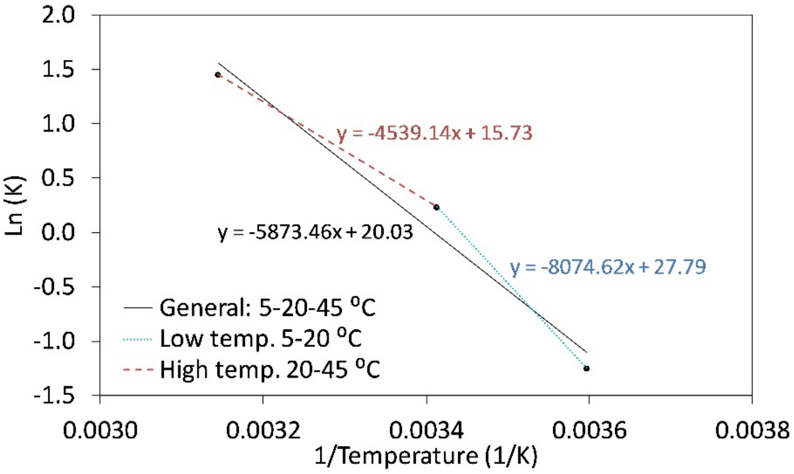


*Figure 5.c. Inverse of the temperature against Ln (K) for concrete VCR20*

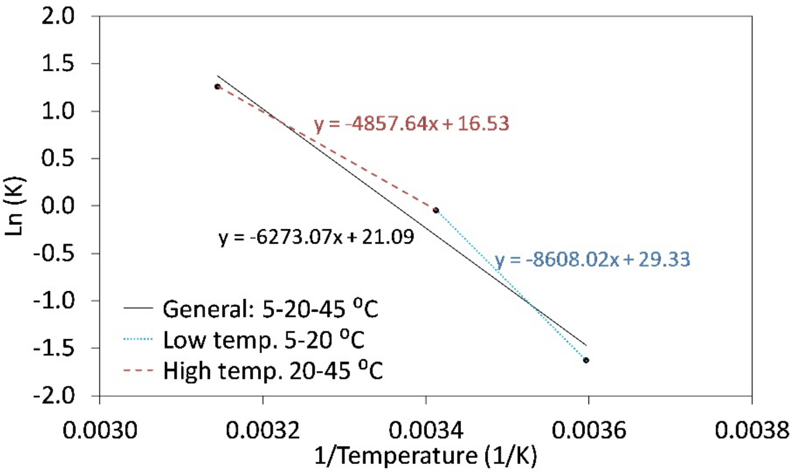


*Figure 5.d. Inverse of the temperature against Ln (K) for concrete VCR31*

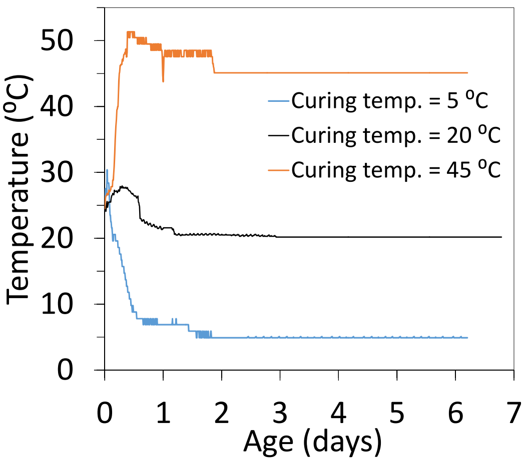
In table 2, a summary of the energy activation results is shown. As mentioned earlier, recycled aggregate causes an increase in the activation energy calculated according to the ASTM, for both self-compacting and vibrated concretes (with the exception of VCR8, with a low content of recycled aggregate). This fact can also be observed for the activation energies calculated only for low temperatures or high temperatures, with the exception of self-compacting concretes in the range of low temperatures (5 – 20°C). For vibrated concretes, it is observed that the higher the temperature is, the lower the influence of the recycled aggregate on the activation energy.

Table 2. Stabilized strength and activation energies (SCC0, SCCR, VC0 and VCR)

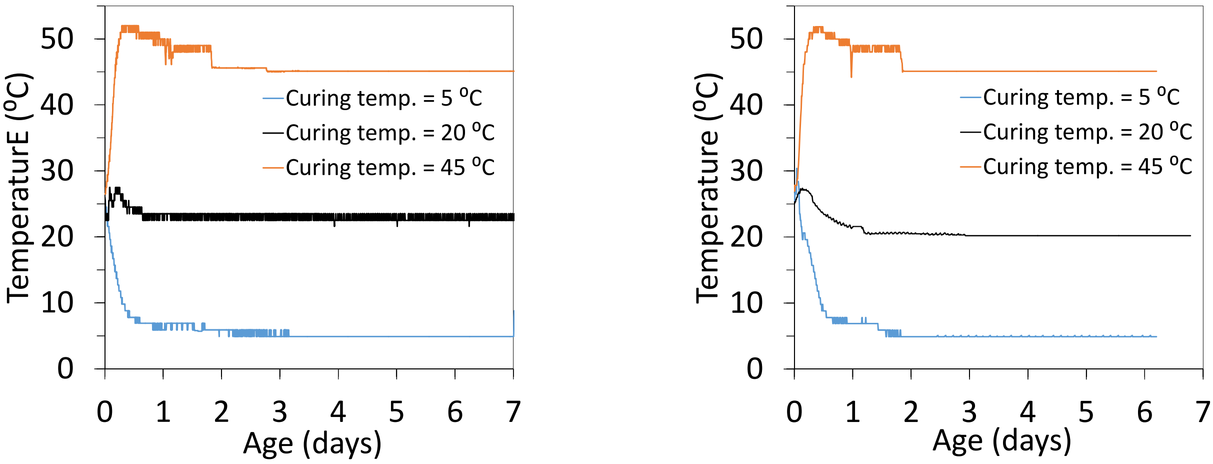
| Parameter | $T^a$ (°C) | SCC0 | SCCR20 | SCCR50 | VC0 | VCR8 | VCR20 | VCHR31 |
|---|---|---|---|---|---|---|---|---|
| $S_\infty$ (MPa) | 5 | 70.9 | 69.7 | 64.3 | 80.9 | 76.6 | 68.3 | 63.6 |
| | 20 | 70.0 | 69.3 | 63.6 | 80.0 | 76.0 | 68.0 | 63.2 |
| | 45 | 66.7 | 62.4 | 58.8 | 73.5 | 65.0 | 60.9 | 55.0 |
| $K_T$ (1/días) | 5 | 0.587 | 0.621 | 0.886 | 0.418 | 0.410 | 0.286 | 0.195 |
| | 20 | 2.473 | 2.399 | 2.010 | 1.348 | 1.089 | 1.264 | 0.954 |
| | 45 | 5.388 | 6.484 | 2.886 | 4.374 | 4.143 | 4.273 | 3.513 |
| Total Ea (kJ/mol) | - | 39.73 | 41.38 | 44.81 | 42.65 | 42.43 | 48.84 | 52.16 |
| Ea $t^a$ low (kJ/mol) | 5-20 | 65.11 | 60.01 | 39.07 | 52.84 | 44.11 | 67.14 | 71.57 |
| Ea $t^a$ high (kJ/mol) | 20-45 | 24.28 | 30.16 | 48.31 | 36.47 | 41.40 | 37.74 | 40.39 |

### 4.2. Influence of recycled aggregate on the results of maturity method and comparative of estimations.

Figures 6 and 7 show the evolution of the internal curing temperature for the different concretes at each external curing temperature. This data is used to calculate the time-temperature factor, also named maturity index (Eq. 2), and the equivalent age through the Arrhenius equation (Eq. 4).



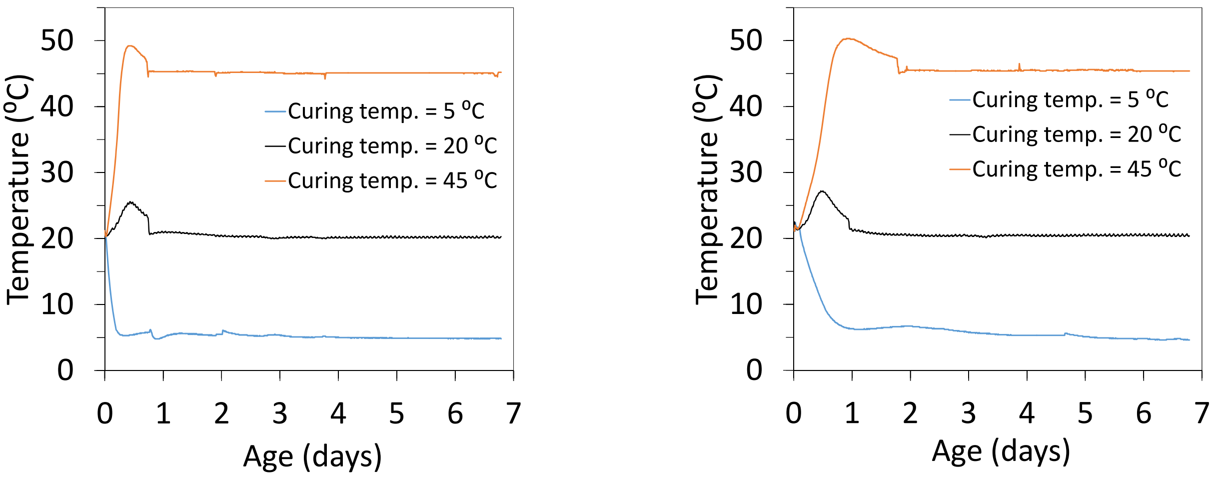
6.(a) Concrete SCC0



6.(b) Concrete SCCR20

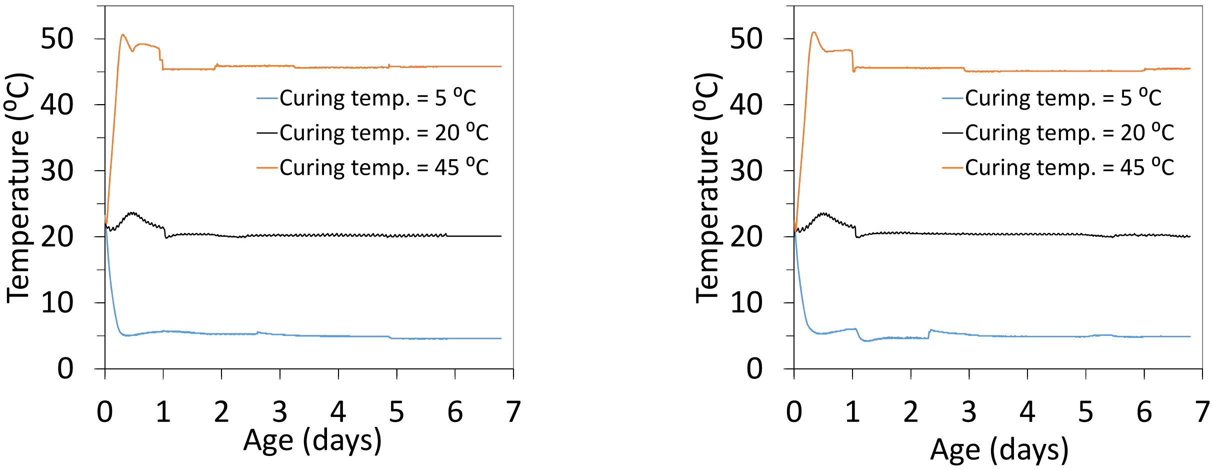
6.(c) Concrete SCCR50

Figure 6. Evolution of internal curing temperature of self-compacting concretes.



7.(a) Concrete VC0

7.(b) Concrete VCR8



7.(c) Concrete VCR20

7.(d) Concrete VCR31

Figure 7. Evolution of internal curing temperature of vibrated concretes.

As explained in the introduction, according to the maturity method, since concretes VC0, VCR8, VCR20 and VCR31 have the same w/c ratio and type of cement, they should have an unique curve “Maturity - $S/S_\infty$ ratio”. In the same way, the maturity curves of concretes SCC0, SCCR20 and SCCR50 must converge in a single curve.

Figure 8 shows the Maturity index vs. compressive strength divided by the compressive strength at infinite time (stabilized compressive strength) for self-compacting concretes (Figure 8.a) and for the studied vibrated concretes (Figure 8.b). In the same way, figure 9 shows the results obtained of the equivalent age vs. compressive strength divided by the compressive strength at infinite time. It is not observed a clear influence of the recycled aggregate on the curves “$S/S_\infty$ - Maturity index”, and “$S/S_\infty$ - equivalent age”.

These results suggest that it could be possible to find an unique curve regardless of the percentage of recycled aggregate. Therefore, it seems feasible to do the assumption that the value of “k” (from the exponential equation for estimation of compressive strength) and the value of “A” (from the hyperbolic equation for estimation of compressive strength) are independent of the percentage of recycled aggregate, without having considerable errors.

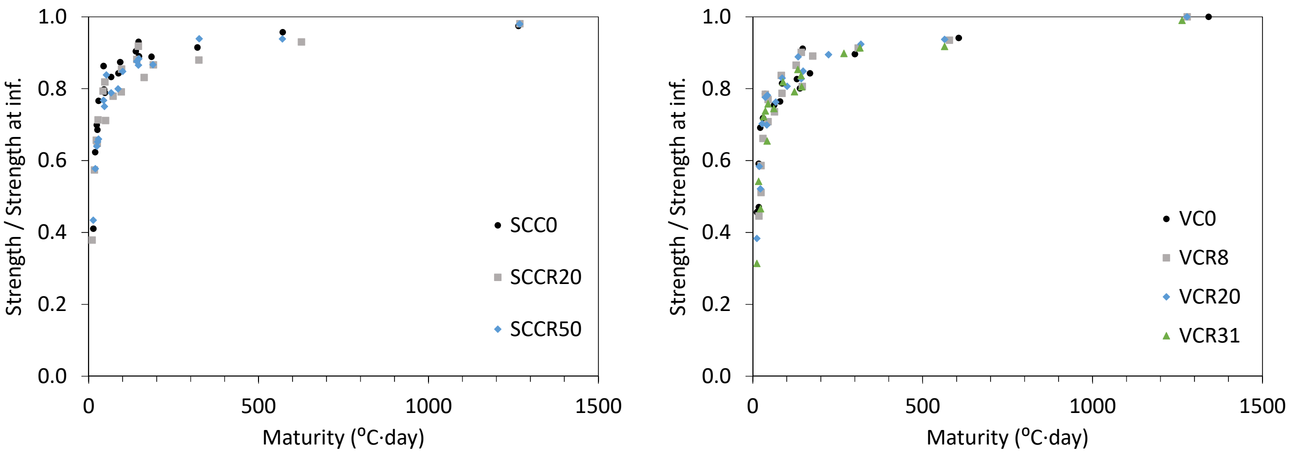


Figure 8. Maturity index - S/S∞ ratio. (a) Self-compacting concretes (b) Vibrated concretes

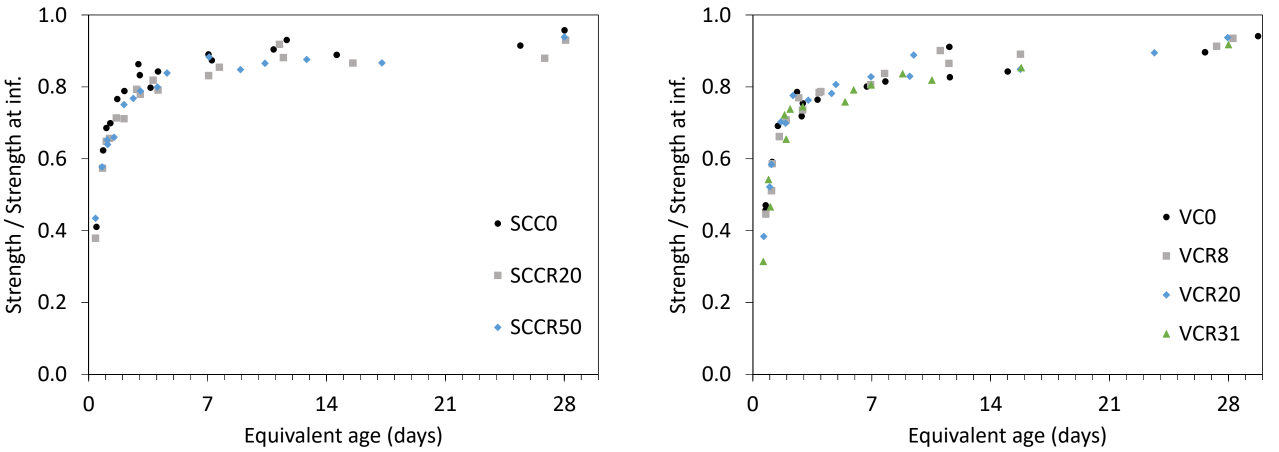


Figure 9. Equivalent age - S/S∞ ratio. (a) Self-compacting concretes (b) Vibrated concretes

To check this, a comparative of the compressive strength estimation against the real strength is made using two of the more widely accepted formulations: the exponential (Eq. 1) and the hyperbolic (Eq.8). In both formulations, the maturity index (M) is used to calculate the estimated strength. Due to the existence of several formulas to calculate this index, it was calculated by two different ways: “maturity index” as a time-temperature factor (Eq. 2) and “maturity index” as the product of equivalent age (Arrhenius equation) by the reference temperature (Eq. 6). We will check the difference of accuracy between each method of calculating “M” for estimations using exponential and hyperbolic formulation. The optimum values of k” and “A”, which minimize the root mean quadratic error of the compressive strength estimation (Eq. 9), will be calculated with the exponential (Eq. 1) and hyperbolic (Eq. 8) equations, respectively.

$$ECM = \frac{1}{n}\sum_{i=1}^{n}\left(\widehat{S_i} - S_i\right)^2 \qquad \text{(Eq. 9)}$$

In order to observe the error made when assuming the values of “k” and “A” independent of the type of aggregate, the real compressive strength vs. estimated compressive strength is represented for each type of concrete studied (SCC0 and SCCR on the one hand, and VC0 and VCR on the other hand), using the value of “k” from the exponential equation and “A” from the hyperbolic equation, calculated in accordance with the following assumption:

“The value of the parameter (“k” or “A”) is the same for all the mixtures of the same type of concrete (SSC0 and all the SCCR, or, VC0 and all VCR), and equal to the value calculated from the reference concrete SCC0 or VC0”.

Figures 10 and 11 show a comparison between the real data against the estimated results using both equations (Exponential and Hyperbolic), calculated according to our assumption. In addition, for each of the equations, the results using time-temperature factor and the results using the equivalent age are shown.

In each of the graphs within Figures 10 and 11, the bisector and the two types of boundary lines were remarked. The dashed lines define the ±10% error, and the dotted lines define the area of maximum error ±20%. The bisector indicates the line of exact values (no error).

As shown in Figures 10 and, in all of the cases studied, the hyperbolic equation gives us more accurate results than the exponential equation. In fact, applying the hyperbolic equation, the vast majority of the estimations have an error equal or lower than 10%.

The estimations using equivalent age are slightly more accurate than the estimations using TTF. The results are really close and calculating the TTF requires less data. In fact, the value the activation energy is not required to get the TTF.

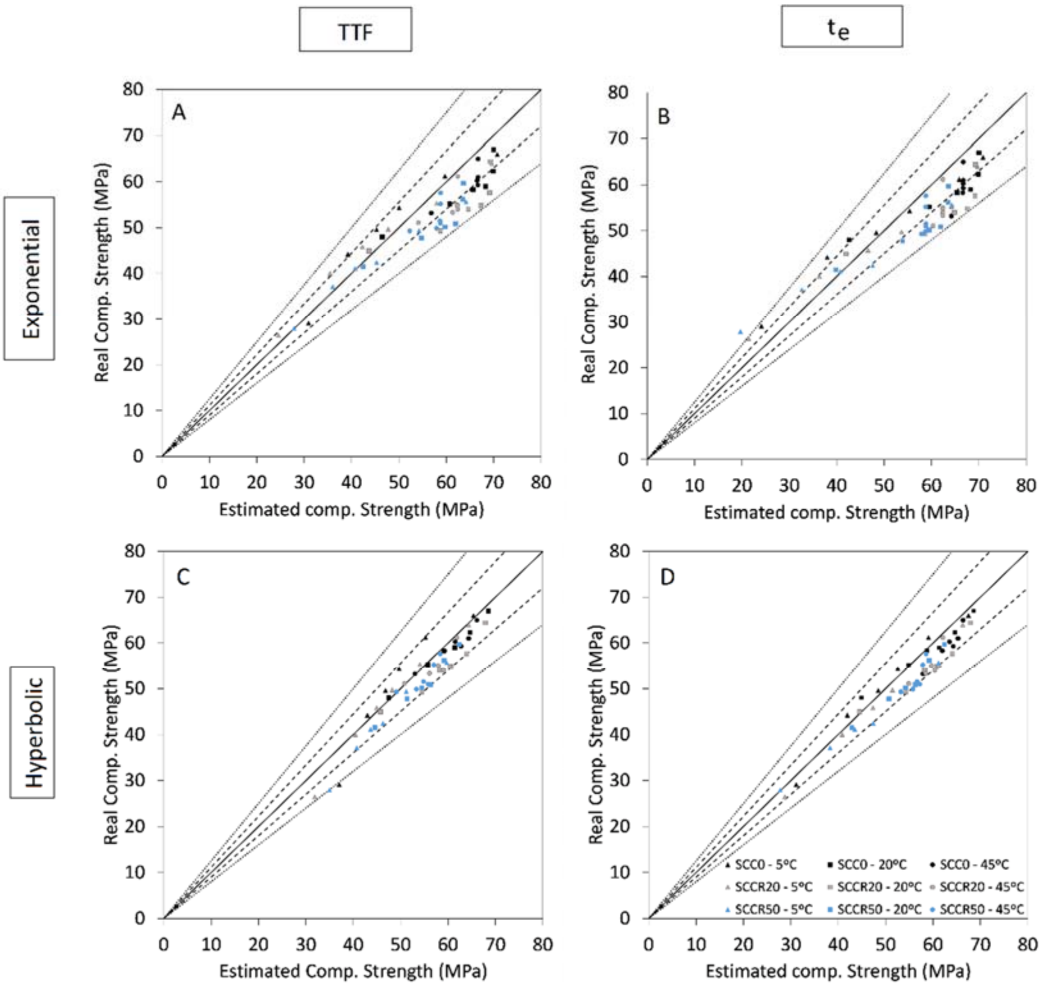


Figure 10. Real compressive strength vs. compressive strength estimation in self-compacting concretes. (a) Estimation using Exponential equation and time-temperature factor. (b) Estimation using Exponential equation and equivalent age. (c) Estimation using hyperbolic equation and time-temperature factor. (d) Estimation using hyperbolic equation and equivalent age.

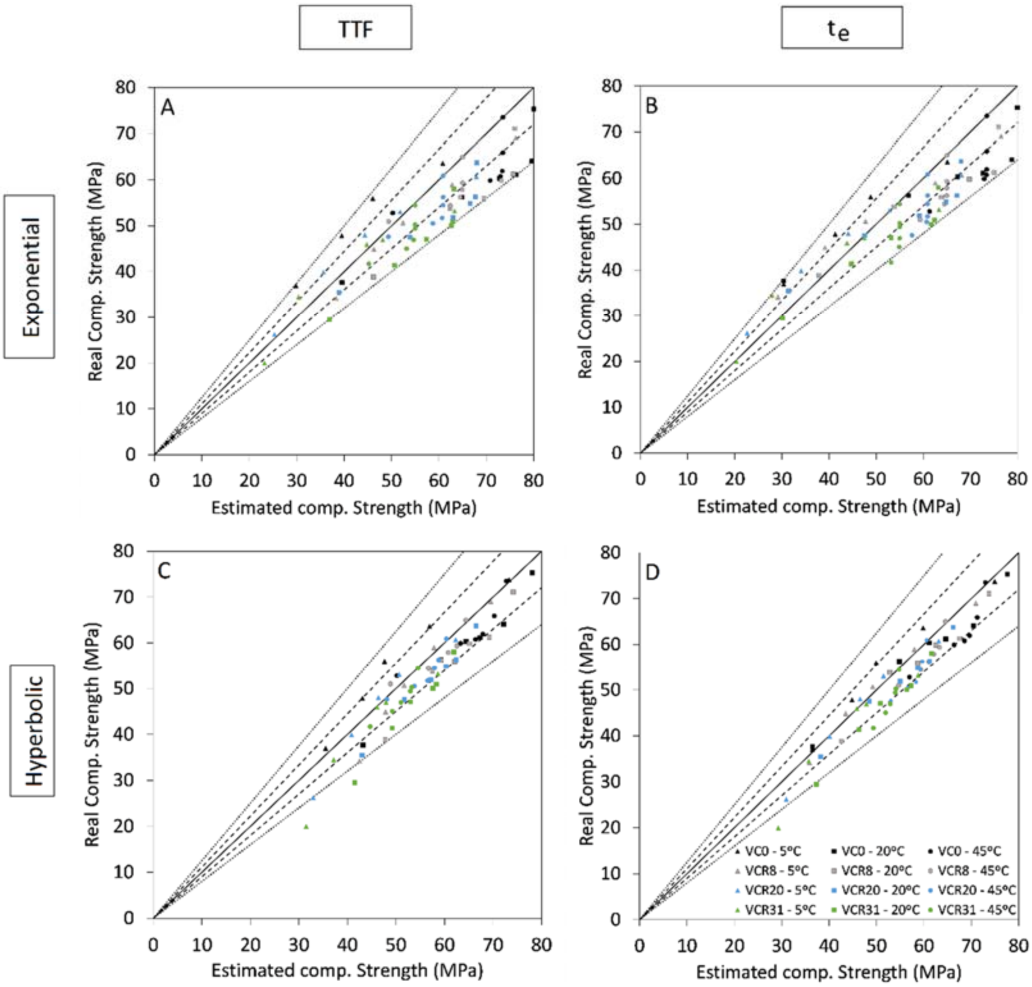


Figure 11. Real compressive strength vs. compressive strength estimation in vibrated concretes. (a) Estimation using Exponential equation and time-temperature factor. (b) Estimation using Exponential equation and equivalent age. (c) Estimation using hyperbolic equation and time-temperature factor. (d) Estimation using hyperbolic equation and equivalent age.

## 5. Conclusions

For percentages equal or higher than 20%, it was observed that increasing the replacement level of natural aggregate by recycled aggregate (fine and coarse), the activation energy increased. With low percentages (8%) non-significant variations were observed on the activation energy.

For all the concretes, vibrated and self-compacting (with exception of SCCR50), if only the low range of temperatures is considered, the activation energy is higher than the calculated with three temperatures according to the ASTM Standard. On the contrary, for higher temperatures, the activation energy is lower than the calculated according to the ASTM criteria.

Therefore, it seems reasonable to recommend that a correction on the activation energy should be considered in the case of concrete subjected to very high temperatures (or very low) steadily. Ideally, the activation energy should be calculated with three temperatures, being the middle temperature similar to the mean temperature at which the concrete will be subjected.

There is only a relationship between $S/S_\infty$ and maturity (or equivalent age) regardless of the amount of recycled aggregate replaced, so it can be admitted the assumption that the coefficient “k” in the exponential equation (Eq.

1) is not dependent on the type of aggregate, even if used in eco-concretes with different percentages of fine and coarse recycled aggregate.

Better results are obtained with the hyperbolic equation (Eq. 8) than with the exponential (Eq. 1) in both cases: if the maturity index taken is equal to the time-temperature factor, and also if it is calculated with the equation that uses the Arrhenius formula to calculate the equivalent age: less than 3% of the estimations slightly exceed the 10% error in self-compacting concretes. In the case of vibrated concretes, less than 14% of the estimations have an error higher than 10% (less than 5% of the estimations have an error slightly higher than 20% and only 9% of the estimations have an error between 10% and 20%).

The estimations using the equivalent age are slightly more accurate than the estimations using the time-temperature factor. But the difference between both of them is very small. In some cases, this small difference of accuracy does not compensate the larger quantity of data that the application of the Arrhenius equation requires, which also needs the activation energy value.

Previous studies claimed that type of aggregate is not one of the main factors that can affect the activation energy, but they were based on studies of concretes with natural aggregates. Natural aggregates have usually low water absorption and they do not have unhydrated cement particles that can react with water. The special characteristics of recycled aggregates, including higher water absorption and presence of unhydrated and hydrated cement particles, affect the activation energy and the maturity of concrete, as observed in this research.

## Ethical statement

Authors state that the research was conducted according to ethical standards.

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