# Self-compacting recycled aggregate concrete using out of service railway superstructures wastes

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**Keywords:** Self-compacting concrete, recycled aggregate concrete, slab track, ballast, sleepers, mechanical properties, durability.

**Highlights:**

- Ballast and sleepers recycled aggregates meet structural concrete requirements.
- Self-compacting recycled concrete fulfilling all mechanical requirements.
- The three concretes characterised fulfil the durability requirements.
- The possibility of manufacturing concretes with low $CO_2$ emissions is demonstrated.
- The importance of the relation W/C has been verified.

**Abstract**

When ballast and/or sleepers, exceed its useful life, they must be replaced with new components. As consequence, a large volume of construction and demolition waste is generated. In addition, some of the main economic items in this type of actions are those that correspond to the cost and transportation of new materials, landfill disposal or waste management plants. These wastes are susceptible to being valorised as recycled aggregates for the manufacture of new slab track. Technically, economically y environmentally the out of use sleepers and ballast wastes shows excellent qualities in order to produce recycled aggregates for the manufacture of new railway components.

## 1. Introduction

For approximately 130 years, rail traffic has been carried out, mostly on ballasted track. The most demanding requirements, due to the appearance of high-speed networks, are higher axle loads, higher train frequencies and greater environmental awareness, all of which has led to a demand for track systems without ballast, also called slab track systems. The slab track involves an important economic saving in maintenance and a better mechanical behaviour, although it requires a higher initial investment with lower constructive performances [1].

There are comparative studies between the traditional track, formed by sleepers and ballast, and the slab track, analysing economic aspects such as the reduction in maintenance costs or the life cycle cost and technical aspects like weight reduction or higher lateral track resistance [2,3]. In the present work, it is proposed that, when the superstructure is obsolete, a second life should be given to any element of the superstructure that can be recycled. In addition, this solution is a better solution from the mechanical point of view and therefore involves lower maintenance costs. In this way, an economic benefit is generated, on the one hand, from the saving in the purchase of the new materials and, on the other hand, from the savings in the transport to the landfill of the removed material. The environmental benefits are derived also, from the same points: both the reduction in the use of natural resources and the reduction of the volume of waste generated after the withdrawal of the obsolete ballasted track are avoided.

The use of RA for the manufacture of concrete is relatively widespread nowadays, since it is used in different concrete construction projects [4,5]. Although the properties of the recycled aggregates (RA) must be analysed before dosing a concrete because these have some important differences with respect to natural aggregates, such as the contaminants or higher absorption coefficient [6,7], been these differences more important in the fine particles. Consequently, the recycled concretes (RC) made with RA have some disadvantages such as a higher porosity, worse frozen-thaw behaviour [8] or less compressive strength than the traditional concrete [9]. The use of fine particles has also been studied and shows that the concretes with RA have a worse behaviour to durability and worse mechanical properties [10,11]. For these reasons, the standards impose some limitations on the use of coarse aggregates and ban the use of fine recycled aggregates, for example, the EHE-08 or EN 13242 [12,13] or provide catalogues such as the Construction and demolition waste catalogue [14], which classifies each waste, specifying its possible uses, although these regulations are rather conservative.

With the aim of optimizing the construction process, the use of a self-compacting concrete is proposed, which avoids the process of vibrating the concrete, improving the construction performances [15,16]. The design criteria for the concrete that composes the slab track covers, on the one hand, a minimum compressive strength at 28 days of 37 MPa [17]. In addition, it is established that it is a self-compacting concrete complying with the requirements demanded in the European standard EN 206+A1 [18]. In addition, the durability behaviour was analysed in order to guarantee the long-term life of the structure. Firstly, as a mean reference of the durability behaviour of the concretes, the permeability of the concrete was analysed. In a second test round, the recycled aggregate concretes were tested with different durability tests such as the frozen-thaw and drying-wetting cycles test.

## 2. Materials and methods

### 2.1. Cement

A cement type CEM IV (V) 32.5 N [19], with a density of 2.85 g/cm$^3$ according to UNE 80103 [20] and a Blaine specific surface area of 3885 cm$^2$/g according EN 196-6 [21] to supplied by Cementos Alfa (Spain), was used. This type of cement contains approximately 40% less clinker than a type CEM I cement and allows sufficient mechanical properties for a slab track [22]. Furthermore, the use of this cement type reduces the environmental footprint of the concrete reducing the $CO_2$ emissions.

### 2.2. Superplasticizer additive

An additive in order to obtain the desired fluidity of the self-compacting concrete, a superplasticizing additive MasterGlenium® ACE 450 BASF [23] was used. To define the optimal quantity of additive, Marsh cone test was carried out, according to ASTM C939-97 [24], with the modification that a part from the 200 ml which must be tested, also, 500, 750 and 1000 ml were analysed in order to obtain a more robust and measurable results.

### 2.3. Recycled aggregates

To produce the recycled aggregate (RA), on one hand, out-of-use sleepers and, in the other hand, out-of-use ballast aggregates were crushed and sieved. From these materials, six different types of aggregates were obtained, Table 1. With these six aggregate fractions, three different types of concretes were mixed. The first of them is made only with RA from crushed ballast (RC-B), the second with RA from crushed sleepers (RC-S) and the third with a mix between aggregates from crushed ballast and aggregates from crushed sleepers in the track proportion (RC-M).

The crushing process of the ballast and sleepers out-of-use for use as RA for the manufacture of slab track, are presented in Figure 1 and Figure 2.

Figure 1: Ballast waste generation in the renewal of ballast track (left) and out-of-use concrete sleepers (right).

Figure 2. Process of crushing ballast and sleeper waste.

To obtain RA from the ballast and from the out-of-use sleepers, the first step followed was to find the out-of-service ballast and the sleepers. This material was given by the ADIF (Spanish state-owned railway infrastructure manager under the responsibility of the Ministry of Public Works and Transport) [25]. This procedure was done in the waste treatment plant VALORIA RESIDUOS S.L. (Spain) using a portable jaw crusher which was able to separate the steel from the concrete. Once the material was crushed, 3 sieves were used to separate each aggregate in three different sizes: 0-2 mm, 2-5 mm and 5-15 mm, in order to ease the mix proportion of these concretes. A sample of each aggregate size is shown in Figure 3.

Table 1: Aggregate identification.

| Code | Waste | Size [mm] |
|---|---|---|
| RA-FBS | Ballast | [0-2] |
| RA-BS | Ballast | [2-5] |
| RA-BCA | Ballast | [5-15] |
| RA-FSS | Sleepers | [0-2] |
| RA-SS | Sleepers | [2-5] |
| RA-SCA | Sleepers | [5-15] |

(a) RA-FBS (b) RA-FSS (c) RA-BS (d) RA-SS (e) RA-BCA (f) RA-SCA

Figure 3: RA produced using ballast and sleepers.

These RA were subjected to mechanical and geometrical tests in order to be able to mix a self-compacting concrete. These tests were divided into two main groups, aggregate properties and impurity characterization.

The measured aggregate properties were the densities according to EN 1097-3 [26], the absorption according to EN 1097-6 [27], the grading curve according to EN 933-1 [28], the flakiness index according to EN 933-3 [29] and the Los Ángeles abrasion test according to EN 1097-2 [30].

The main issue when RA are used is the presence of the impurities. In order to quantify these impurities, a visual characterization was carried out. 1 kg of RA-BCA and RA-SCA were separated according to the origin of each particle. At the end of the process, all the groups were weighted, and the percentage of each material were calculated.

The main properties of the RA are shown in Table 2, and the grading curves are represented in Figure 4.

Table 2: General aggregate properties.

| **Material** | **Real density** [g/cm³] | **Apparent specific gravity** [g/cm³] | **Bulk specific gravity** [g/cm³] | **Absorption** [% wt.] | **Los Angeles coefficient** [%] | **Flakiness index** [%] |
|---|---|---|---|---|---|---|
| RA-FBS | 2.89 | - | - | - | - | - |
| RA-BS | 2.73 | - | - | - | - | - |
| RA-BCA | | 2.48 | 2.37 | 1.9 | 20 | 14 |
| RA-FSS | 2.62 | - | - | - | - | - |
| RA-SS | 2.51 | - | - | - | - | - |
| RA-SCA | - | 2.34 | 2.09 | 5.1 | 36 | 5 |

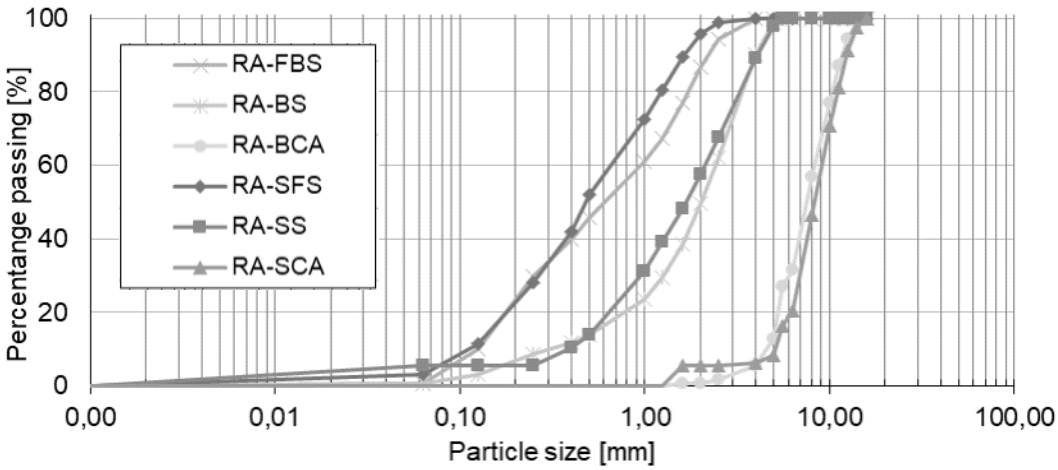



Figure 4: Aggregates grading curves.

From the visual characterization it ca be concluded that in the crushed ballast aggregates, there is less than 1% wt. of impurities, Figure 5, and in the crushed sleepers, there are no impurities. This is because the ballast aggregates had materials coming from the ground. Meanwhile, the sleepers were taken one by one and, for this reason, they have no impurities. A ballast sample was analysed and no hydrocarbons were detected.

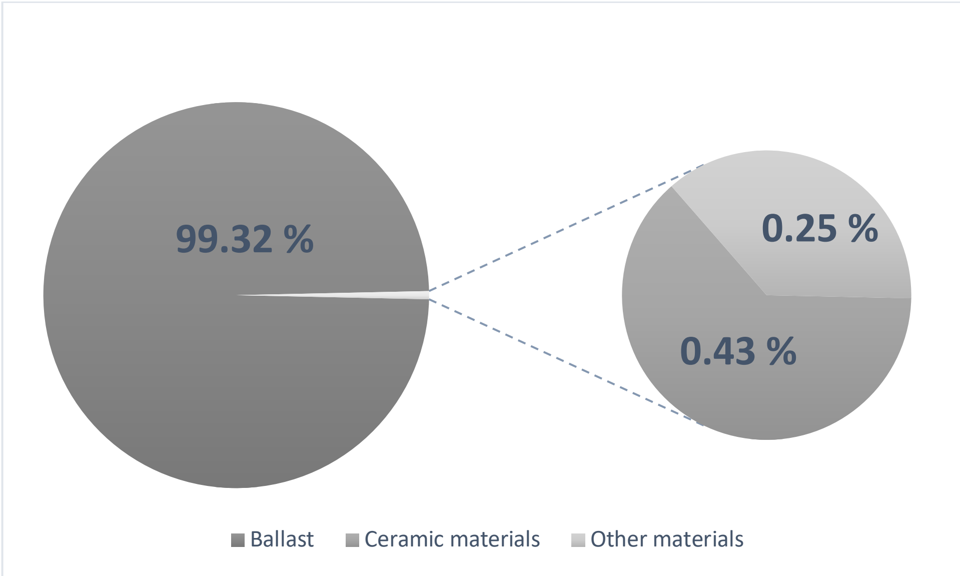



Figure 5: Ballast composition.

### 2.4. Mix proportions

The mix proportions were defined in several sub steps. Firstly, the quantity of superplasticizer additive, this process has been defined in 2.2. Secondly, the relation between the different sands and the cement quantity were fixed, through 40 mortar tests per material, in which the mini-slump test and the compressive strength were determined. The final mix proportions are shown in Table 3.

RC-B and RC-S were designed using 100% of incorporation of RA and the RC-M using a proportion of 1/7 RA from sleeper and 6/7 RA form ballast). The mix proportions are shown in Table 3.

Table 3: Mix proportions.

| Material | RC-B | RC-S | RC-M |
|---|---|---|---|
| Water | 225 | 200 | 221 |
| Cement | 500 | 500 | 500 |
| Superplasticizer additive | 10 | 10 | 10 |
| RA-FBS | 790 | - | 677 |
| RA-BS | 320 | - | 274 |
| RA-BCA | 522 | - | 447 |
| RA-FSS | - | 690 | 98 |
| RA-SS | - | 283 | 40 |
| RA-SCA | - | 587 | 83 |
| Water/cement ratio | 0.45 | 0.40 | 0.44 |
| % sand [0-2 mm] from the total sand | 70 | 70 | 70 |
| % coarse aggregate from the total aggregates | 35 | 40 | 36 |
| % superplasticizer additive/cement | 2.00 | 2.00 | 2.00 |

It can be observed that the mix which uses RA from crushed sleepers is lower than the one which uses crushed ballast, which might be expected [9], but due to the geometry of the RA-B, it is necessary to increase the quantity of water required for obtaining a self-compacting concrete.

### 2.5. Workability

The workability tests on the self-compacting concrete have been carried out according to its corresponding standard. On the one hand, the results of the tests have been compared with the EN 206 [18] and, on the other hand, with The European Guidelines for Self-Compacting Concrete from [31]. The tests which were carried out to measure the workability of the concretes were: the slump flow test, according to the EN 12350-8 [32] which takes as a reference the EN 12350-2 [33]; the L-box test according to EN 12350-10 [34] standard, using the bars model B for the L-Box test; the V-funnel test was carried out according to EN 12350-9 [35] and the GTM screen stability test according to EN 12350-11 [36]. Also, the fresh concrete density was measured.

### 2.6. Tests on hardened concrete

Once the mix proportions were established for a self-compacting concrete, different size specimens were manufactured in order to characterize the main properties of the hardened concrete, such as the uniaxial compressive strength, the Young's modulus or durability.

#### 2.6.1. Physical properties

The bulk densities were obtained according to EN 12390-7 [37]. Additionally, the accessible porosity and the absorption coefficient were measured according to UNE 83980 [38].

#### 2.6.2. Mechanical properties

To obtain the mechanical properties of the 3 types of concrete, the uniaxial compressive strength test and Young´s modulus tests were performed at different ages in order to analyse the evolution of these properties. The uniaxial compressive strength tests were performed according to the standards EN 12390-3 and EN 13290-3/AC [39,40], using cubes of 100 mm side. These tests were performed at the ages of 1, 2, 3, 5, 7, 28, 90 and 180 days. The Young´s modulus test were performed according to the EN 12390-13[41] at the ages of 7, 28, 90 and 180 days using cylindrical specimens of 200 mm of height and 100 mm of diameter.

#### 2.6.3. Wear resistance

The wear resistance was measured following EN 1338 [42]. These tests were performed at the age of 90 days. The test samples for the wear tests were cut to perform these wear tests on an interior surface of the sample.

#### 2.6.4. Durability

As is well known, the presence of fly ash means that the concretes continue to undergo important changes until the age of 90 days [43], so all the durability tests were carried out at the age of 90 days instead of 28 due to the important quantity of fly ash present in the cement.

To analyse the long-term life of the concrete, the first step was to measure the permeability of the concrete; this parameter was obtained in two ways: the oxygen permeability test, according to the standards UNE 83966 [44], UNE 83981 and UNE 83981-ERRATUM [45,46] and the water permeability test according to EN 12390-8 and EN 12390-8/M [47,48] standards. 3 cylindrical standardized samples of 150 mm diameter and 300 mm high were cut in 3 cylinders of 100 mm of height. The top and the bottom of all the samples were removed by cutting. These 9 subsamples were used for the oxygen and water permeability testing.

To analyse the shrinkage, specimens of 300x50x50 mm were prepared and measured the variation of length with time according to UNE 83318 [49].

Frozen-thaw cycles tests were performed according to the standard UNE-CEM/TS 12390-9EX [50], using the alternative method of the cubes, with the modification that the samples were tested at the age of 90 instead of 28 days. In addition, the frozen time was increased to 42 h in order to raise to -15°C [51].

Drying-wetting cycles test were performed taking as a reference EN 14066 [52]. During these tests, 100 cycles of 8 h sink in water and 16 h in the oven at 70°C were performed. The evolution of the weight and the ultrasound crossing time were measured to analyse the damage suffered by the samples. In addition, after these 100 cycles, the samples were subjected to the uniaxial compression test to measure the residual compressive strength.

# 3. Results and discussion

## 3.1. Workability

Table 4 shows the workability results. Figure 6 shows details of the workability of the concrete.

(a) RC-B slump flow. (b) RC-S slump flow. (c) RC-M slump flow.

Figure 6: Slump flow test.

Table 4: Workability tests value results.

| Test | | | | EN 206-9 | | | EFNARC | | |
|---|---|---|---|---|---|---|---|---|---|
| | RC-B | RC-S | RC-M | RC-B | RC-S | RC-M | RC-B | RC-S | RC-M |
| Slump flow SF [mm] | 700 | 730 | 800 | SF2 | SF2 | SF3 | OK | OK | OK |
| $T_{50cm}$ test [s] | 2 | 2.5 | 2 | VS2 | VS2 | VS2 | OK | OK | OK |
| L box test method | 0.90 | 0.90 | 0.95 | PL1 | PL1 | VPL1 | OK | OK | OK |
| V funnel test [s] | 7.5 | 13.5 | 6.0 | VF1 | VF2 | VF1 | OK | No OK | OK |
| GTM screen stability test method [%] | 1.0 | 8.8 | 8.8 | SR2 | SR2 | SR2 | OK | OK | OK |
| Fresh concrete density [g/cm$^3$] | 2.4 | 2.3 | 2.4 | --- | --- | --- | --- | --- | --- |

In the Figure 6, it can be seen that there are no segregation. On the one hand, in all the photos, you can see that there are aggregates even in the border of the flow spread, and on the other hand, no one presents a water/paste/mortar ring beyond the coarse aggregate. The RC-S has a higher quantity of aggregates on the border of the flow spread, which is cause of the higher quantity of aggregates and the higher viscosity of the mortar cause by the lower w/c ratio. Also, it can be appreciated that the perimeter of the flow spread is much regular in the RC-B, its mean a higher thixotropic behaviour reflected in a lower value in the V funnel test.

As has been demonstrated by other authors, it is possible to mix a self-compacting concrete using RA [53]. While the increase in RA from crushed concrete normally reduces the workability of the concretes [54], in this case, due to the geometry of the particles, observed in the flakiness index, the RC-S is the concrete which obtains the best results in the slump flow and the L-box test.

### 3.2. Tests on hardened concrete

Once it was proved that the workability of the concretes was adequate, several tests specimens were manufactured in order to analyse its hardened properties. The physical properties, mechanical properties and durability behaviours were analysed.

#### 3.2.1. Physical properties

The physical properties are shown in Table 5.

Table 5: Density and porosity of the different concrete.

| Mix | Bulk specific gravity [g/cm$^3$] | Apparent specific gravity [g/cm$^3$] | Bulk saturated surface dry [g/cm$^3$] | Absorption coefficient (%wt.) | Accessible porosity (%vol.) |
|---|---|---|---|---|---|
| RC-B | 2.27 | 2.51 | 2.37 | 4.1 | 9.2 |
| RC-S | 2.12 | 2.35 | 2.22 | 4.8 | 10.1 |
| RC-M | 2.26 | 2.50 | 2.36 | 4.2 | 9.5 |

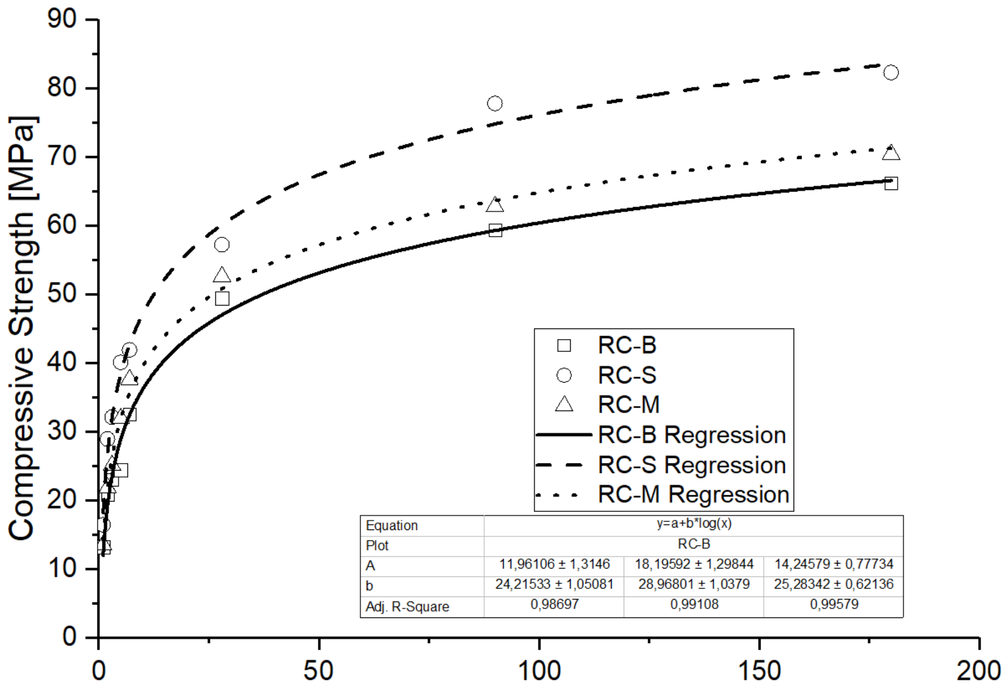
As can be expected, the values of the density are lower in the RC-S as a consequence of the lower density of its aggregates. The absorption and porosity are higher in the RC-S because of the higher absorption of the aggregates [55]. The RC-M properties are situated between the RC-B and RC-S ones as can be expected.

The values of the density and the absorption of the recycled concretes are similar values to other authors with a 100% of aggregate substitution [56].

#### 3.2.2. Mechanical properties

Table 6 show the results of the compressive strength test.

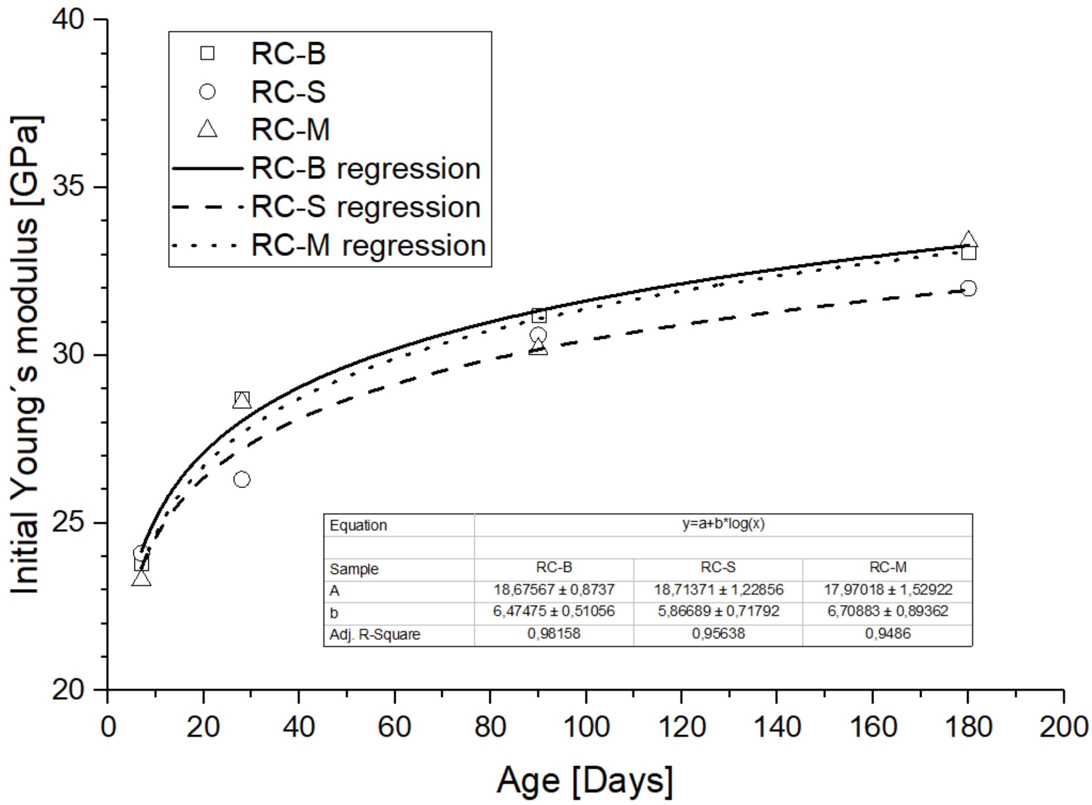
Table 6: Compressive strength values.



| Age [days] | RC-B [MPa] | RC-S [MPa] | RC-M [MPa] |
|---|---|---|---|
| 1 | 13.2 | 16.4 | 13.5 |
| 2 | 20.8 | 28.9 | 21.8 |
| 3 | 23.0 | 32.1 | 25.1 |
| 5 | 24.4 | 40.1 | 31.9 |
| 7 | 32.5 | 41.9 | 37.6 |
| 28 | 49.4 | 57.2 | 52.6 |
| 90 | 59.4 | 77.8 | 62.8 |
| 180 | 66.2 | 82.3 | 70.4 |

The most resistant is the RC-S one, due to the lower effective water/cement ratio of this dosage. The RC-B obtained the lower results although the exceptional tribological properties of these aggregates. The RC-M is between the RC-B and the RC-S as can be expected. All the mix proportions had being always above the 37 MPa at the age of 28 days, which is the requirement for slab track concrete [17]. In addition, it has been possible to raise this strength due to the good quality of the ballast and the sleepers [57].

Two different Young's modulus have been measured. The first and the third time that the samples are loaded. The results of the evolution of these parameters are shown in Table 7. There are no high differences between the different concretes. The Young's modulus of the RC-B is higher due to the greater stiffness of its aggregates. RC-S had similar values than other recycled concretes young modulus with the same water/cement ratio [58].



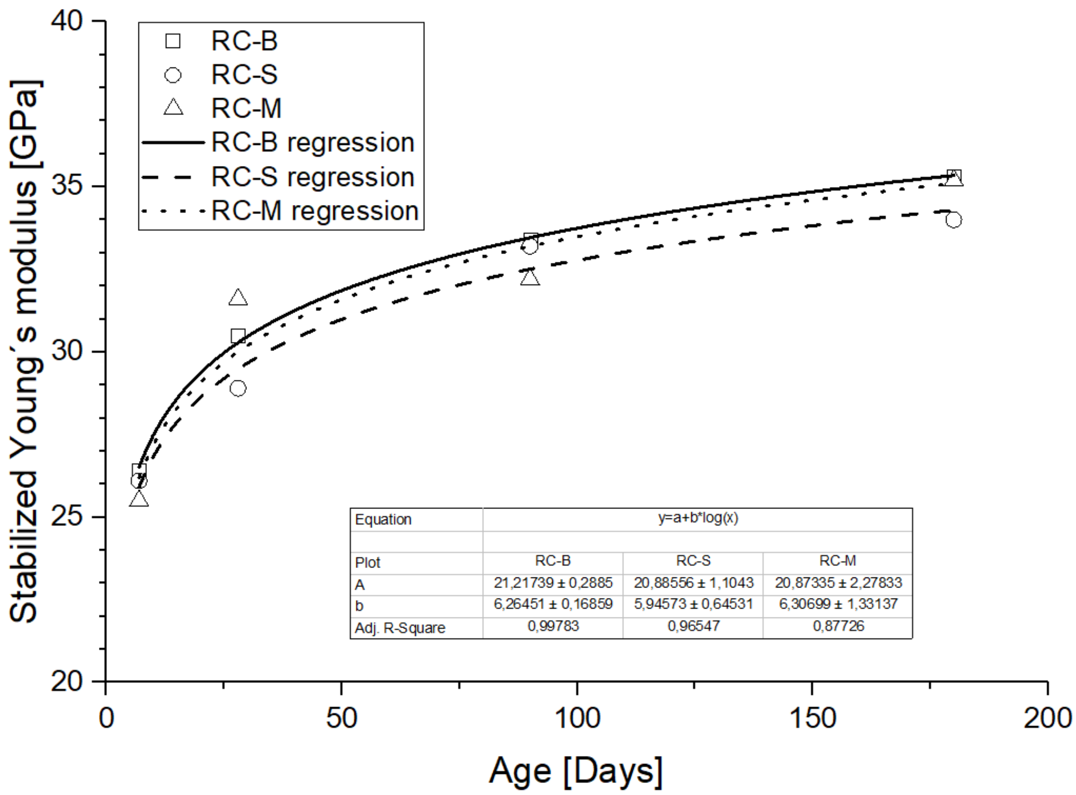



Table 7: Young's modulus values.

| Age [days] | RC-B [GPa] | RC-S [GPa] | RC-M [GPa] |
|---|---|---|---|
| **Starting Young's modulus** | | | |
| 7 | 23.8 | 24.1 | 23.3 |
| 28 | 28.7 | 26.3 | 28.6 |
| 90 | 31.2 | 30.6 | 30.2 |
| 180 | 33.1 | 32.0 | 33.4 |
| **Stabilized Young's modulus** | | | |
| 7 | 26.4 | 26.1 | 25.5 |
| 28 | 30.5 | 28.9 | 31.6 |
| 90 | 33.4 | 33.2 | 32.2 |
| 180 | 35.3 | 34.0 | 35.2 |

### 3.2.3. Wear resistance

The results are shown in Figure 7.

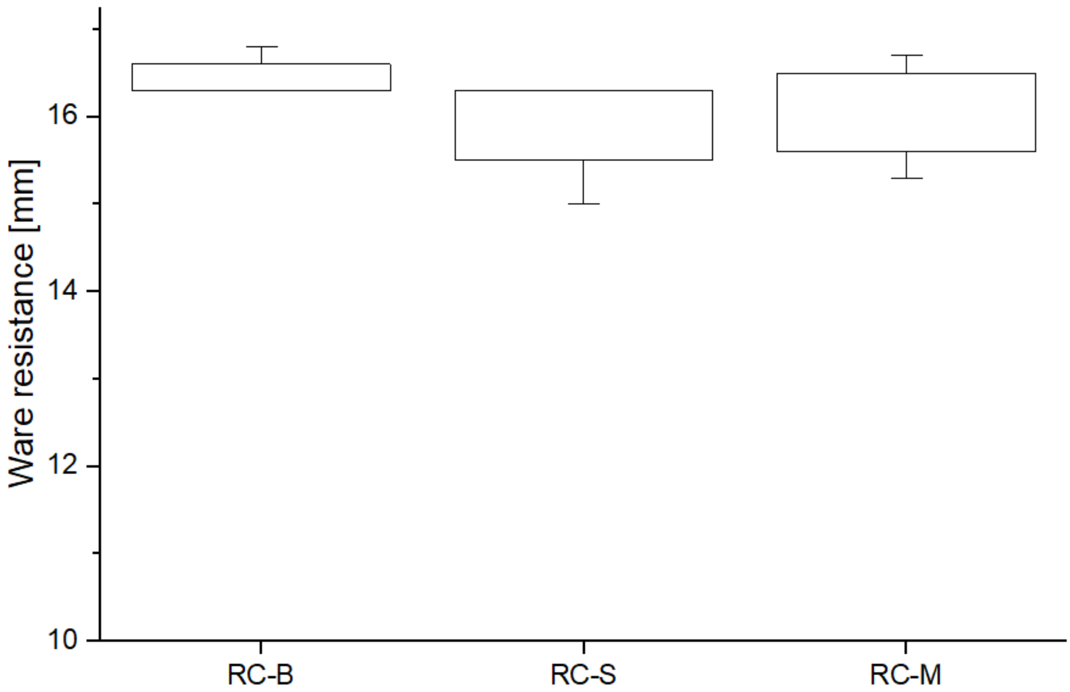



Figure 7: Wear resistance.

#### 3.2.4. Durability

The permeability is a great parameter to measure the durability of a concrete because it is the property responsible of the penetration of any agent that could damage the concrete. The results of both the oxygen permeability and the water permeability are shown in Table 8. The lower values of oxygen permeability are in the RC-S, and the higher ones are in the RC-B. It is well known that the presence of RA does not really affect the permeability of the concrete [59], and the lower water/cement ratio provides a lower permeability to RC-S. Anyway, it is well known that the use of fly ash will help to reduce the permeability of a concrete [43], so all the mix proportions obtained good results. These values of permeability are lower, so a good durability behaviour can be expected.

Table 8: Permeability results.

| **Concrete** | **Oxygen permeability coefficient** | **Water permeability** | |
|---|---|---|---|
| | **[$m^2$]** | **Max penetration [mm]** | **Mean penetration [mm]** |
| RC-B | 3.0 E-17 | 50 | 40 |
| RC-S | 1.5 E-17 | 20 | 20 |
| RC-M | 1.6 E-17 | 40 | 20 |

The water penetration in the RC-B is the higher one, actually, higher than expected. The reason of this high penetration is the presence of impurities and the higher effective water cement ratio.

The variation of the length of the concrete is plotted in .

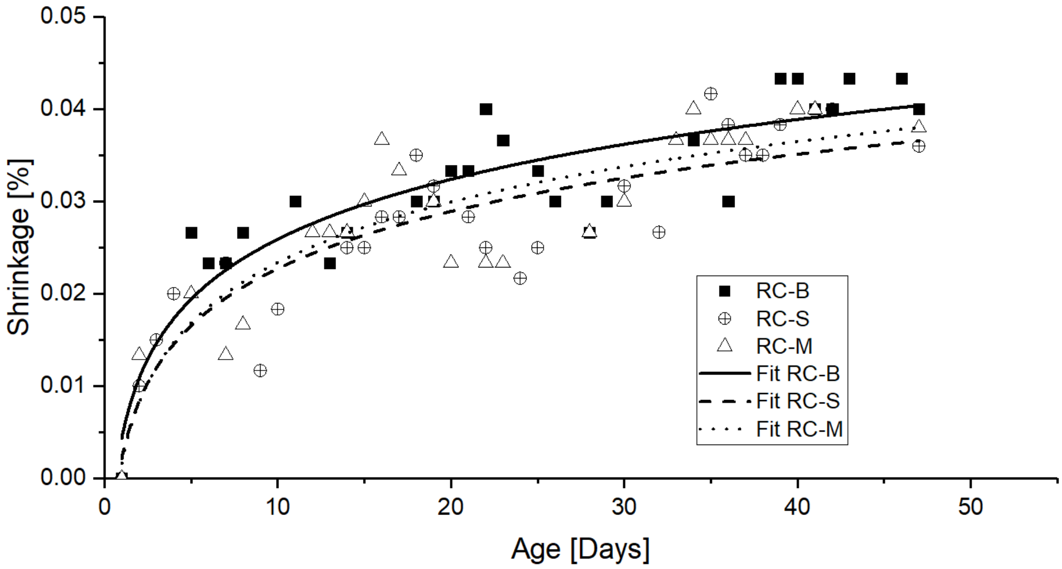



Figure 8: Shrinkage.

The RC-B samples suffer the higher strain and the RC-S the lower. Usually, the presence of aggregates from recycled concretes aggregates increases the shrinkage [60], but due to the higher water/cement ratio of these mixes [61].

Usually, the presence of aggregates from recycled concretes aggregates increases the shrinkage [60], but as can be noted from the above chart, the RC-B samples suffer more strain due to the higher water/cement ratio of these mixes [61].

The damage suffered by the samples after 56 frozen-thaw cycles is shown in Figure 9. In addition, as a quantitative parameter, the loss of mass is plotted in Figure 10, where it can be appreciated that the RC-S are the more resistant to these kinds of cycles. The RC-S have a better frozen-thaw behaviour due to the lower water/cement ratio [51].

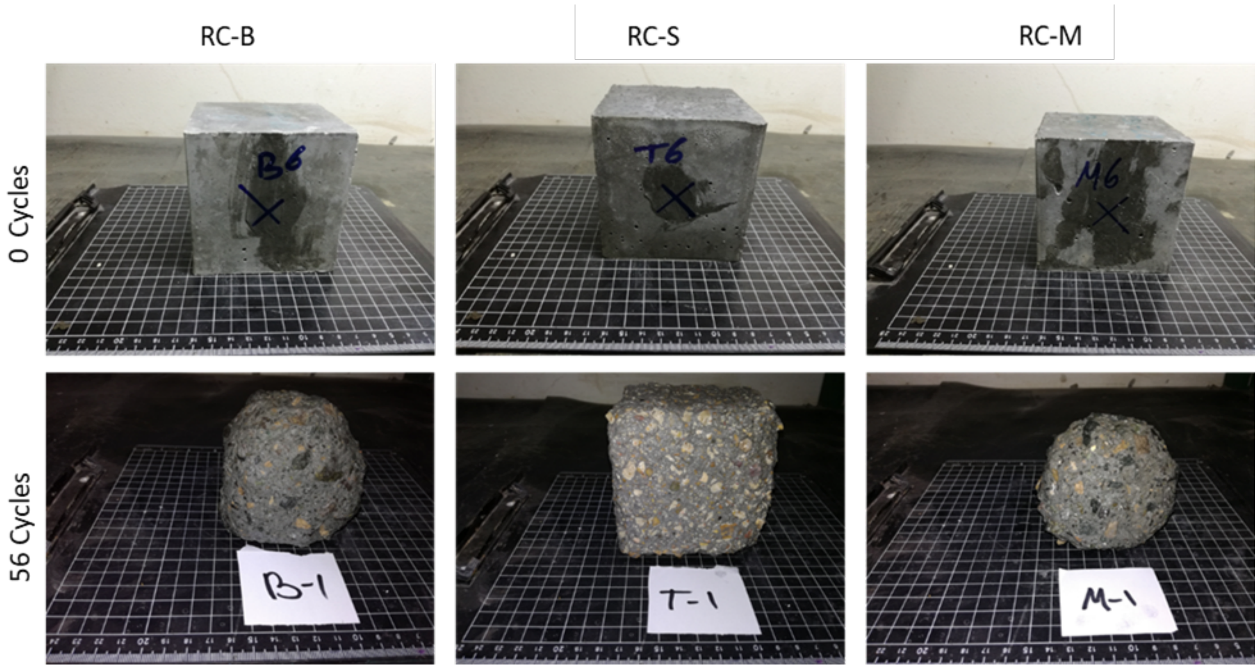



Figure 9: Frozen-thaw surface deterioration.

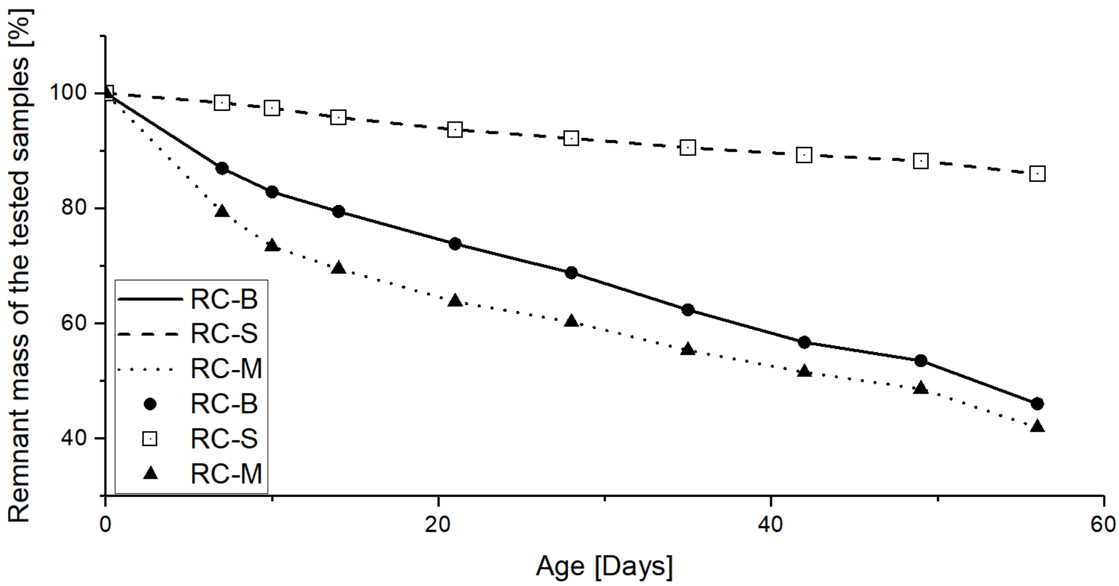



Figure 10: Frozen-thaw mass evolution.

The damage suffered by the samples after 100 drying-wetting cycles can be appreciated in Figure 11. Also, the evolution of the mass variation is plotted in Figure 12. At the end of the 100 cycles, the samples were tested and the loss in compressive strength was analysed. The results are shown in Table 9. Visually, there are no big difference after these 100 cycles in any of the samples, just a superficial deterioration.

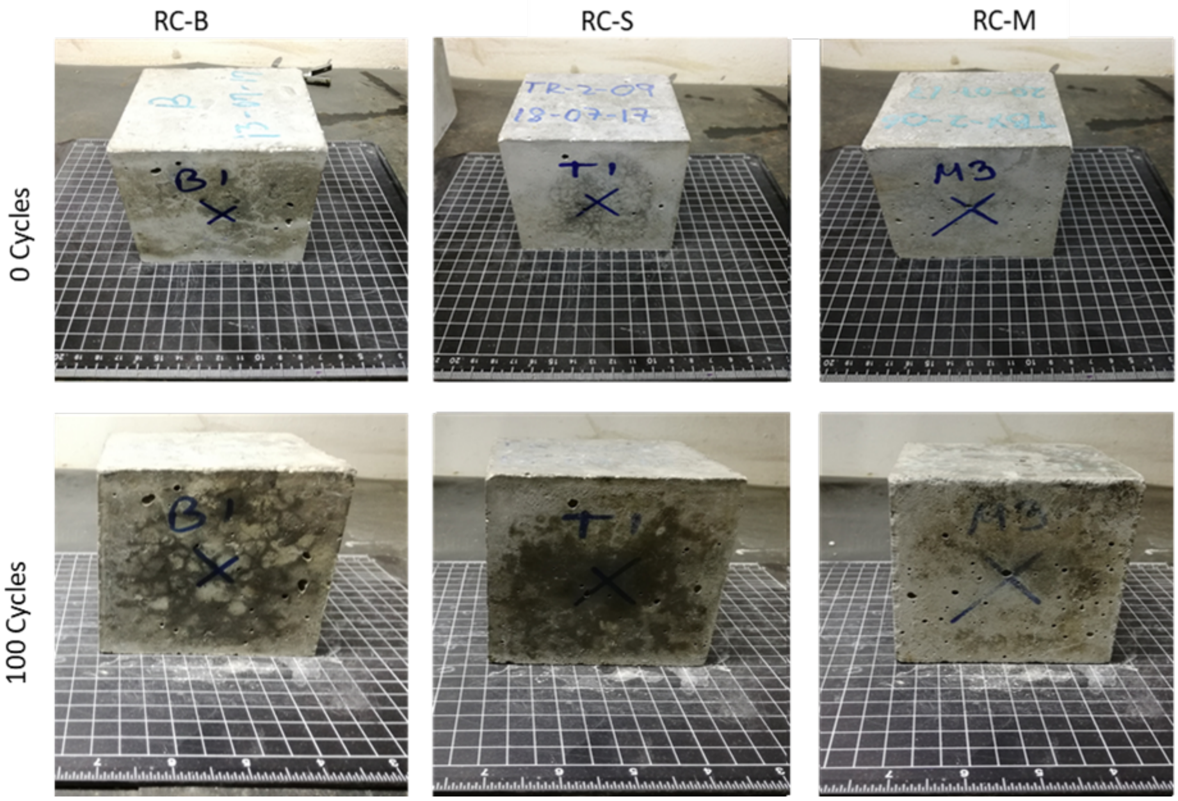



Figure 11. Drying-wetting test evolution.

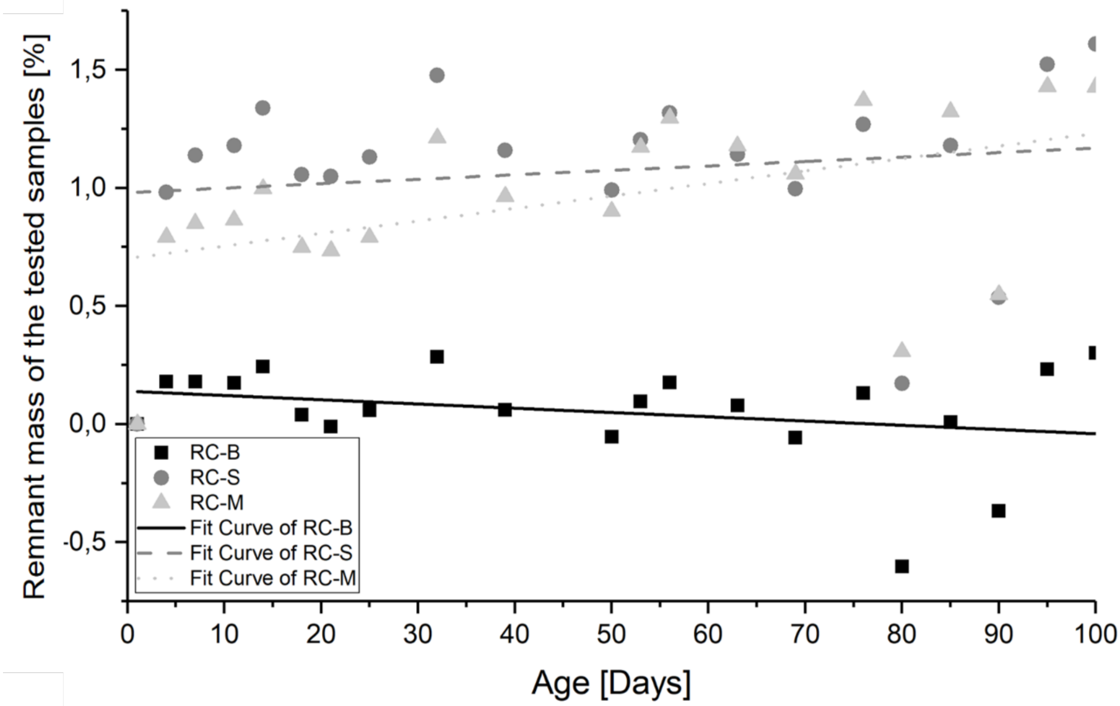



Figure 12. Drying-wetting test mass evolution.

Table 9: Loss of compressive strength after 100 cycles of drying-wetting.

| Concrete | Drying-wetting test [MPa] | Residual compressive strength [%] |
|---|---|---|

| | | |
|---|---|---|
| RC-B | 52.7 | 11.3 |
| RC-S | 62.3 | 19.9 |
| RC-M | 53.6 | 13.9 |

## 4. Conclusions

The recycled aggregate from the crushing of ballast and sleepers meet the requirements for the manufacture of structural concrete. Specifically, the evolution of the uniaxial resistance and the elastic modulus as a function of time was analysed. It was found that in the three cases analysed, mechanical properties were higher to the properties provided by the manufacturers of the main types of track.

It has been possible to manufacture self-compacting concretes that meet the mechanical criteria for the construction of slab track using, exclusively, recycled aggregate; that is, without the need to add any type of non recycled aggregate. This is due to the use of a type IV cement.

From the above results, the possibility of manufacturing a concrete with low $CO_2$ emissions is demonstrated.

The 3 characterized concretes correctly fulfil the durability requirements.

The importance of adjusting the water/cement ratio in the concrete has been proven. This may become more influential than the quality of the aggregate. This is clear when comparing the results of both the durability and the mechanical properties of recycled concrete from crushed ballast and recycled concrete from crushed sleepers.

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