Permeability properties of self-compacting concrete with coarse recycled aggregates

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HIGHLIGHTS

- Permeability properties of SCC with 20%, 40% and 100% of coarse recycled aggregates were studied.
- According to the air permeability method applied, the SCC mixtures are considered airtight.
- The recycled coarse aggregate incorporation did not significantly affect the water permeability.
- Water capillarity coefficient is slightly decreased when 100% of coarse recycled aggregate is used.
- Water penetration depth is reduced with the increasing of the recycled aggregate in SCC.

ABSTRACT

This article addresses to the issue of durability related properties of self-compacting concrete (SCC) with the use of coarse recycled aggregates obtained from demolition of concrete structures. The objective was to verify the influence of recycled aggregates on SCC permeability properties. For this purpose four different types of concrete mixes were produced, one of them used as reference with natural coarse aggregates and the others prepared with 20%, 40% and 100% of recycled coarse aggregates. The properties related to the durability of SCC, as air and water permeability and capillary absorption were determined on concrete specimens with and without preconditioning. The results from fresh and hardened concrete properties lead to the conclusion that it is viable to replace natural coarse aggregates by recycled coarse aggregates since the present research does not show any detrimental to the SCC permeability properties.

Keywords:
Capillary water absorption
Coarse recycled aggregate
Concrete permeability
Self-compacting concrete

1. Introduction

The potential use of recycled aggregates in the self-compacting concrete composition increases the ecological value and partly solves the issues of waste disposal sites generated by construction and demolition of structures. In the last two decades, the properties of normal concrete with recycled aggregates were extensively studied [1–6]. From these studies it is known that, comparing with the natural aggregates, the recycled aggregates density is lower and the water absorption is higher. These differences are due to the incrustation of cement paste on the recycled aggregates surfaces. Thus, the increased of the content of recycled aggregates in normal vibrated concrete, both coarse and fine, causes a loss of the mechanical properties. Furthermore, the coarse recycled aggregate shows a greater negative influence than the recycled fine aggregate [7–9]. Also the durability of the recycled aggregates concrete can be strongly affected by the porosity and the high water absorption of the recycled aggregates [10]. The cause is usually associated to the fact that, to reach the same workability, the water demand to produce concrete with recycled aggregates is higher compared to natural aggregates, leading to the increase of the water/cement ratio, thereby, also increasing the porosity of the cementing matrix [8]. The use of water-reducing admixtures may minimize this effect, since they may provide workability to the mixture without increasing the water/cement ratio. The relatively poorer durability properties of recycled aggregates concrete can be adequately compensated by the use of fly ash, either as a replacement of cement or addition, in the concrete mix design [7].

When compared with normal vibrated concrete, the SCC mixtures usually exhibit a better durability potential, even when the mixtures have larger water contents. This is due to increased fines content in SCC, that refines the microstructure and hence the pore network of the material [11]. It is the capillary porosity that greatly affects the permeability of concrete [12]. The permeability of SCC is typically lower than that of ordinary concrete. This is mostly attributed to the superior flow properties, dense microstructure and refined pore. Good flow properties result in superb packing condition due to better consolidation, and thus contribute to reduce the permeability of concrete [13]. So, the SCC mixtures...
could be considered as a good receptor of recycled aggregates. In fact, according to Gredic et al. [14], when coarse recycled aggregate of good quality is used, the total replacement of the natural coarse aggregate by recycled aggregate from demolition of concrete structures has a marginal effect on the compressive and tensile strength reduction. The authors found a reduction of 9% for compressive strength and 13% for tensile strength, at 28 days. Despite the relatively high water absorption of coarse recycled aggregates, they also observed a marginal increasing of recycled aggregates SCC water absorption of 0.4% when compared with control concrete.

In Portugal, the most used demolition processes is based on the simultaneous destruction of the entire building, which results in waste rather heterogeneous. Taking into account the construction demolition wastes heterogeneity, the Portuguese recommendation E 471/2009 [15] limit the incorporation of recycled coarse aggregate in structural concrete production. The replacement of natural aggregates by recycled aggregates is limited by this document in order to avoid large variations of the elastic modulus, creep, shrinkage and durability. The limit is 25% of aggregates composed of 90% minimum of particles from concrete demolition (ARB1) that can be used up to concrete strength class C40/50. When the recycled aggregates composition has a value between 90% and 70% of particles from concrete demolition (ARB2), this can be used up to concrete class C35/45. Regarding that this recommendation was elaborated for normal concrete and there are few studies about SCC with recycled aggregates, hence, in this work, both physical and mechanical properties of SCC specimens have been studied. The results of this research, indeed may serve to guide practical recommendations for recycled aggregates use in SCC mixtures.

A piece of data which is important for the design of SCC mixture with recycled coarse aggregates is the quantity of water absorbed by the recycled aggregate, which is always higher in comparison to the same fraction of the natural coarse aggregate. Normally, the water requirement of normal concrete with recycled aggregates is increased, resulting in significant high total water/cement ratio (W/C), regardless of the use of water-reducing admixtures [16]. The amount of water absorbed by the aggregate was taken into account separately by some researchers [17], in addition to its wetness before mixing and the free water that formed part of the mixture. Other researchers [16,18] consider the total water content for W/C ratio, because it is impossible to separate the effective water content (water absorbed by recycled aggregate and mixing water) from the total water content in the fresh concrete, especially in the case of recycled sand. In the case of SCC with recycled aggregate, Gredic et al. [14] observed small variations in the quantity of water for SCC mixtures to achieve the equal consistency. From the point of view of the concrete durability properties, it is believed that an analogous advantage could result with the use of dry recycled coarse aggregate, since it was observed an highest porosity of the concrete ITZ microstructure around the pre-soaked lightweight aggregate compared with the dry aggregate [19]. Some authors [20,21] argue that this difference on ITZ microstructure of good quality is used, the total replacement of the natural coarse aggregate by recycled aggregate from demolition of concrete structures has a marginal effect on the compressive and tensile strength reduction. The authors found a reduction of 9% for compressive strength and 13% for tensile strength, at 28 days. Despite the relatively high water absorption of coarse recycled aggregates, they also observed a marginal increasing of recycled aggregates SCC water absorption of 0.4% when compared with control concrete.

2. Materials and methods

2.1. Materials

A Portland cement type CEM I 42.5R with density of 3140 kg/m³ and a mineral addition of limestone powder with density of 2720 kg/m³ were used as powder materials in the SCC mixtures. The granular skeleton for the fine and the coarse aggregates were defined taking into account the grading reference curves proposed by Nepomuceno and Pereira-de-Oliveira [22]. The fine aggregates mix was done with the proportion in absolute volume being 82% for natural sand (S1) and 18% for natural sand (S2). Fig. 1 shows the resultant grading curve of fine aggregates mix, which was kept constant for all the mixtures produced. Two natural coarse aggregates of crushed granite, CA1 and CA2, were combined on the proportions in absolute volume of 68% (CA1) and 32% (CA2). Two coarse recycled aggregates, RA1 and RA2, classified according EN471 as ARB1 aggregates, were sourced from a local construction and demolition waste recycling facility and were combined on proportions in absolute volume of 90% (RA1) and 10% (RA2). Table 1 shows the individual aggregate characteristics. The natural and recycled coarse aggregates have the same maximum size with a very slightly difference in the fineness modulus. It can be also observed in Fig. 1 that the grading curves of coarse aggregates mix were quite similar. Only a slight deviation from general tendency occurs on the grading curve with 100% of recycled coarse aggregate. It means that the particle size of recycled aggregates is slightly higher than other coarse aggregates compositions. These similar coarse aggregates grading curves were used to enable replacement without changing significantly the concrete granular skeleton.

A modified polycarboxylate based superplasticizer, with a density of 1050 kg/m³, was used to help the concrete mixtures attain self-compacting rheological desired characteristics.

2.2. Mix design of self-compacting concrete mixtures

The methodology of SCC mix design applied in this study was developed by Nepomuceno et al. [23,24] and considers the concrete as a two phase material: the matrix (mortar phase) and the incorporation of coarse aggregates on the matrix (concrete phase). The design parameters of the mortars phase should be defined to obtain simultaneously the desired fresh and hardened properties of self-compacting concrete. For each of these two phases, an adequate reference curve of granular skeleton was defined. Thus the general approach consists of the following stages: selection of the materials; definition of the reference grading curves for the fine and coarse aggregates; studies in mortars and studies on concretes.

At the first stage, the powder materials (cement and additions) should be selected taking into account the level of compressive strength to achieve on hardened concrete. The fine and coarse aggregates should have adequate grading curves to enable the best approximation to the proposed reference curves. Preferably, a modified polycarboxylate based superplasticizer should be selected. On the second stage, the unit volume percentage of fine aggregates and the unit volume percentage of coarse aggregates must be determined separately.

The third stage corresponds to the definition of the adequate parameters for the mortar phase, that includes the unit volume percentage of each powder material in the total volume of the blend of powder materials (Vp), unit volume percentage of each fine aggregate in the total volume of fine aggregates (Vs), as previously defined on the second stage, Vp/Vs (ratio in absolute volume between powder materials and fine aggregates), Vw/Vp (ratio in absolute volume between water and powder materials) and Sp/p% (ratio in percentage between the amounts in mass of superplasticizer and powder materials). For the mortar phase, an interval of variation was defined for the parameters that characterize the flow behavior of mortars (Gm, Rm), in such a way that it leads to self-compacting concrete. The Gm parameter is measured on mortar spread test and Rm is measured on a v-funnel test. Adequate correlations between concrete compressive strength and water to cement ratio is proposed for two types of cement. Since the water to cement ratio is the same for concrete and mortar phases, this parameter can be defined on the mortar phase design. The Vp/Vs ratio should be defined from 0.6 to 0.8, but a value between 0.7 and 0.8 is recommended. Correlations are proposed to estimate the percentage of cement replacement by the addition for different combinations of powder materials as a function of the Vp/Vs ratio and the water to cement ratio previously established. The Vw/Vp and the Sp/p% ratios can be also estimated for preliminary tests based on proposed correlations. However, since the superplasticizer can differ from different suppliers, the water content Vw/Vp and the superplasticizer dosage Sp/p% have to be experimentally adjusted until the mortar presents the adequate flow properties, evaluated in terms of relative spread area (Cφ) and the relative flow velocity (Rφ). Usually only superplasticizer dosage needs to be adjusted.
On the fourth stage the design parameters of concrete are completed by the definition of the unit volume percentage of each coarse aggregate in the total volume of coarse aggregates (Vg) as previously defined on the second stage, the volume of voids (Vv) and the Vm/Vg ratio (where Vm is the volume of mortar excluding air and Vg is the volume of coarse aggregate). For this purpose, a mathematical model was developed to estimate the adequate Vm/Vg ratio, which takes into account the properties of the mortar phase (Vp/Vs) and the fresh desired properties for concrete (H2O/H1 in a box test and Dm in slump-flow test) and assuming that (G) in the v-funnel test for concrete is between 10 and 20 s. The Vm/Vg can vary from 2.00 to 2.60. For the volume of voids it is proposed a constant value of 0.030 m³ per cubic meter, when no air entrainment agent is used.

Based in this mix design method, in this research work four different concretes were produced: a reference mixture SCC produced only with natural aggregates, SCC20, SCC40 and SCC100, i.e. self-compacting concrete with 20%, 40% and 100% of natural coarse aggregates replaced by recycled coarse aggregates. To observe the effect of recycled aggregates water absorption on the SCC water and superplasticizer demand, the recycled aggregates were used on dry conditions. Thus, the fine and coarse aggregates were previously dried on laboratory environment. The reference SCC mix was designed in order to comply with EN 206-9 [25] and fits in a concrete strength class C45/50 and in accordance with the requirements concerning the properties of fresh concrete of the same standard. It should be noted that the SCC strength class chosen is the maximum strength class permitted, on the recommendation E471, for the application of recycled aggregates from concrete demolition.

Table 1 shows the final proportions of SCC mixtures.

<table>
<thead>
<tr>
<th>Notation</th>
<th>Maximum size D (mm)</th>
<th>Fineness modulus</th>
<th>Density (kg/m³)</th>
<th>Water absorption (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>1.2</td>
<td>1.95</td>
<td>2570</td>
<td>0.30</td>
</tr>
<tr>
<td>S2</td>
<td>4.8</td>
<td>3.27</td>
<td>2610</td>
<td>0.40</td>
</tr>
<tr>
<td>CA1</td>
<td>9.5</td>
<td>5.27</td>
<td>2710</td>
<td>0.15</td>
</tr>
<tr>
<td>CA2</td>
<td>15.0</td>
<td>6.82</td>
<td>2700</td>
<td>0.14</td>
</tr>
<tr>
<td>RA1</td>
<td>9.5</td>
<td>5.78</td>
<td>2509</td>
<td>4.10</td>
</tr>
<tr>
<td>RA2</td>
<td>15.0</td>
<td>6.52</td>
<td>2485</td>
<td>4.05</td>
</tr>
</tbody>
</table>

2.3. Methods

In order to evaluate the rheological properties in fresh concrete, the following methods were used: slump-flow test according to EN 12350-8/2010 [26] and v-funnel test according to EN 12350-9/2010 [27].

The self-compactability properties were evaluated indirectly by means of slump-flow test and v-funnel test, respectively, expressed in the relative spread (Dm) and in the relative flow velocity (Rc). The value for (Gc) is obtained by Eq. (1) [28], whereas (Rc) is obtained by Eq. (2) [28]. The acronym (Dm) stands for the average spread diameter, in mm; the acronym (Rc) stands for the initial diameter at the base of the cone, in mm, whereas (t) stands for the time of flow, in seconds. The variation interval admissible for Gc and Rc was defined by Gc values between 8.0 and 11.3 and Rc values between 0.5 and 1.0 s⁻¹ [22].

\[
G_c = \frac{D_m}{10}^2 - 1 
\]

\[
R_c = \frac{10}{t} 
\]

The mechanical properties of hardened concrete were evaluated by density, compressive strength and dynamic elastic modulus (ultrasonic pulse velocity method) measurements according to the following standards: EN 12390-7/2003 [29], EN 12390-3/2003 [30] and BS 1881-203:1986 [31], respectively, at 7 and 28 days. All SCC mechanical hardened properties were determined in 3 concrete specimens for each age and mixture.

SCC properties related to durability, such as capillary water absorption, water and air permeability were determined in cored cylindrical specimens, while the depth of water penetration was determined in molded cubic specimens. All tests were carried on at 28 days curing age. Determination of capillary water absorption was done according to EN 12390-7/2003 [29], as recommended for concrete in sets of two cylindrical specimens with 10 cm high and 10 cm diameter. After drying in oven at a temperature of 40 ± 5 °C during 14 days, the samples were weighed and placed in a recipient in contact with a level of water capable to submerge them about 5 ± 1 mm. After a predefined period of time, the samples were removed from the recipient to proceed to weight registration. Immediately after weighed, the samples were placed again in the recipient till reach the following measuring time. The procedure was consecutively repeated at 3, 6, 24 and 72 h. Capillarity coefficient was obtained according to ISO 15148 standards [33]. The capillarity coefficient [kg m⁻² min⁻⁰.⁵] determination requires the graphical interpretation of the cumulative inflow curve and is defined as the slope of the first stage of the cumulative inflow curve as a function of square root of time.

Air and water permeability were obtained using sets of five cylindrical specimens of 4 cm high and 5 cm diameter. Air permeability was tested using pressure values up to 3.5 bar. The water permeability test was carried for a period of 60 min and pressure of 2.5 bar. The details of the equipment used and experimental procedures for each of these tests, here briefly described, was also discussed in [34].

Water penetration depth was measured according to NP EN 12390-8/2003 [35]. The test was carried on in standard moulded cubic specimens of 15 cm size, by applying a 5 bar water pressure for 72 h. All SCC properties related to durability were determined in 4 concrete specimens for each age and mixture.

2.3.1. Air permeability test

The permeability cell used to determine air and water permeability of concretes is shown in Fig. 2.

The permeability cell works with oxygen. It allows submitting samples, with the referred dimensions, to a certain pressure, guaranteeing that the flow of oxygen through the sample is uniaxial. After a certain period of time elapsed during the test, the flow can be considered to be laminar (i.e. smooth and uninterrupted). This way, the results obtained with this equipment can be explained based on Darcy’s law. The intrinsic air permeability (being μ oxygen dynamic viscosity = 1.92 × 10⁻⁵ N s m⁻²), can be determined by the following equation [36]:

\[
\mu \text{ (kg/m/s)} = \frac{\text{Air permeability (cm³/s/10⁻³ bar)}}{(\text{Relative permeability of concrete})} 
\]

![Fig. 2. Air and water permeability cells used in this work.](image)
\[ K = \frac{4.04 \times R \times L \times 10^{-16}}{A \times (P_2 - 1)} \]  

(3)

where: \( K \) – Intrinsic air permeability (m²), \( R \) – Oxygen flow through the specimen (cm³ s⁻¹), \( L \) – Thickness of the test specimen (m), \( A \) – Area of the section crossed by oxygen (m²), \( P_2 \) – Oxygen pressure at the forefront of specimen (bar), being the outlet pressure of 1 bar.

2.3.2. Water permeability test

The water permeability test can take place after the air permeability test, in a similar way and within the same specimen. With the test specimens placed inside the permeability cell, the water is introduced on the top of the cell and the pressure is applied in a way to force the water to penetrate through the sample. The measurement of the permeability is carried out by a method based on water penetration depth. It is introduced water with a color indicator that helps to determine the border of penetration depth. The water permeability coefficient is determined then by the expression 4 presented as follows, that takes in consideration the penetration depth [37],

\[ k_w = \frac{d_p^2 \times \delta}{2 \times h \times t} \]  

(4)

where \( k_w \) – Water permeability coefficient (m s⁻¹), \( d_p \) – Water penetration depth (m), \( \delta \) – Water absorption of the test specimen (open porosity), \( t \) – Time that took to penetrate to the depth \( d_p \), \( h \) – Height of water column (m), 1 bar = 10.207 m of water column.

To convert the water permeability coefficient, expressed in m s⁻¹, in intrinsic permeability \( k_{aw} \), expressed in m², which is independent from the properties of the liquid, the following expression (5) is used [34]:

\[ k_w = k_{aw} \times \frac{\eta}{\rho \times g} \]  

(5)

being \( k_w \) – Water intrinsic permeability (m²), \( \eta \) – Viscosity of the solution, to 20 °C, \( \rho \) – Density of the water (1000 kg m⁻³), \( g \) – Gravity (9.8 m s⁻¹⁻²).

In case that is just used water, the expression (5) becomes the expression (6) and, in the case of using a phenolphthalein indicator (a mixture of 5 ml of phenolphthalein in 500 ml of ethanol with 500 ml of water) the expression (5) becomes the expression (7). The expressions [34] are different considering the dynamic viscosity of the solution with the indicator.

\[ k_w = 1.02 \times 10^{-7} \times k_{aw} \]  

(6)

\[ k_w = 1.3 \times 10^{-7} \times k_{aw} \]  

(7)

2.3.3. Preconditioning specimens prior to testing

According to the procedure given in RILEM TC 116-PCD [38], before carrying out air permeability and capillary absorption tests, concrete specimens should first reach an intermediate average moisture concentration. With this procedure it is intended that a uniform distribution of the evaporable water in the test specimens can be formed. The preconditioning procedure itself consists of a pre-drying step and a subsequent moisture redistribution phase and may take up to 35 days. Thus, it consists of a long term conditioning period and offers a relatively complex preconditioning procedure. This however is unavoidable if a uniform moisture distribution in the concrete specimen is sought, as is specified prior to undertaking concrete absorption and air permeability tests. In this study, the preconditioning was done by a simplified procedure, which provides RILEM TC 116-PCD similar values. In the simplified procedure the specimens were dried at 50 °C in a ventilated oven for 24 h and thereafter placed in a sealed box having 75% RH for three weeks [39]. However, tests were also carried on without preconditioning specimens, i.e. part of specimens was dried at 50 °C in a ventilated oven for 24 h prior to testing. The results obtained with and without preconditioning specimens are compared.

2.3.4. Water penetration test

The water penetration depth apparatus used in this work is shown in Fig. 3.

The water penetration test determines the initial absorption at concrete surface. Although the test measures surface absorption, it does not represent permeability of concrete and mechanisms of penetration of aggressive agents in concrete. Essentially, the test characterizes the surface cover of concrete when it is submitted to water pressure, namely rainwater fall.

The test consists of applying water under pressure in one side of the specimen surface, within a 10 cm diameter area confined by a watertight rubber ring. The test can be carried on in standard moulded cubic specimens of 15 cm size. It consists of applying a 5 bar water pressure for 72 h and measuring afterwards the water penetration depth. Prior to the test, the surface of the specimen, which will be in contact with water, must be brushed with a wire brush.

3. Results and discussion

3.1. Fresh properties of self-compacting concrete

Fig. 4 shows that the final mix proportions presented in Table 2 are within the limits imposed by \( G_c \) and \( R_c \) rheological parameters described in Section 2.3, which slump-flow and v-funnel results are shown in Table 3. As it was explained in Section 2.3, the concrete mix design was developed taking as goal two fresh properties parameters: a relative spread area \( G_c \) and relative flow velocity \( R_c \). A self-compactability target was defined for all mixtures by the range values of \( G_c \) between 8.0 and 11.3 and \( R_c \) between 0.5 and 1.0 s⁻¹⁻¹. It was observed that the W/C ratio and SP content to achieve this target was dependent of the coarse recycled aggregates amount. To keep a quasi-constant W/C ratio for all the mixtures, a gradually increase of superplasticizer dosage was necessary as the coarse aggregates replacement increases from 0 to 100%, as shown in Table 2.

Overall, the W/C ratio increased only around 1% in SCC20 and SCC100 mixtures, but a significant amount of superplasticizer was added to the mixtures with recycled aggregates incorporation. This supplementary addition of superplasticizer that attained 2.2% of cement content represents an increase of 75% when the total natural coarse aggregates are replaced by the recycled aggregates. This can be justified by the higher water absorption of recycled
aggregates, shown in Table 1, which reduce the available water necessary to lubricate the mixture.

Regarding the slump-flow and flow time presented in Table 3, it is observed that all mixtures attained the values previously defined as indicator of the self-compactability. It is noted in the case of the mixture SCC40, where the superplasticizer amount is slightly lower than that used in SCC20, that the flow time in v-funnel test was increased by around 30%. The v-funnel results can apparently lead to a contradiction between the SCC40 and SCC100 results. However, crossing these results with the information in Table 2, it is possible indeed to confirm that the recycled aggregates affect adversely the concrete workability. One can also observe that the flow time is strongly affected by the W/C ratio. In fact, the higher v-funnel value was obtained for SCC40, which has the lower W/C ratio. Thus, a reduction of the solids surface wetting in this mixture was expected. Anyway, to control the flow time when natural aggregate was totally replaced by the recycled aggregates in the mixtures of similar W/C ratio, an increase of superplasticizer amount was necessary.

### 3.2. Physical and mechanical properties of self-compacting concrete

Table 4 presents the average density values as a function of the recycled aggregate percentages, the compressive strength and dynamic modulus of elasticity values at 7 and 28 days. Analyzing the results, it appears that the SCC density decreases as the rate of natural coarse aggregates replacement by recycled coarse aggregates increases. This was expected, since the recycled coarse aggregate presents a lower density compared to the natural coarse aggregates. This was expected, since the recycled coarse aggregate percentage and the increase in dynamic modulus of elasticity between 7 and 28 days was unable to be established since there is an uneven variation in the different concretes. In general, after seven days, the concrete results analysis showed a modulus of about 80% of the value measured at 28 days. It is possible to verify, especially for 28 days, that the average value of dynamic modulus of elasticity increase with the compressive strength, particularly when SCC is compared with SCC100.

### 3.3. Durability properties of self-compacting concrete

Table 5 presents the average and standard deviation results of water permeability, capillarity coefficients and water penetration results.

Concerning to the air permeability of SCC mixtures tested at 28 days, it was not possible to register any value even over a pressure of 3.5 bar, for both with or without preconditioning methods. Thus, according to the air permeability method applied, the mixtures are considered airtight.

The water permeability results show in general a very low permeability coefficient if compared with the normal concrete that typically is in the range of $5 \times 10^{-12}$ m$^2$. Measured in dry state, i.e. without pre-conditioning. In these results a trend was observed when the natural coarse aggregate is replaced by 20% of recycled aggregate.

However, this trend is not clear for 40% and total replacement. By the other hand, it seems that the recycled aggregate increasing is responsible by a kind of growing disturbance on the concrete skeleton modifying their porosity. This disturbance could be expressed by high variation obtained during the tests of four samples of SCC100 mixture, in order of 57%, whereas for SCC20, SCC40 and SCC this variation is in order of 17% till 22%. Then, comparing with the self-compacting concrete with natural coarse aggregate, it is concluded that recycled aggregate incorporation did not significantly affect the water permeability, but could promote a large variation around an average value. Even in this situation,

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### Table 3

<table>
<thead>
<tr>
<th>Mix</th>
<th>Slump-flow test Dm (mm)</th>
<th>V-funnel test time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SCC</td>
<td>650</td>
<td>13.0</td>
</tr>
<tr>
<td>SCC20</td>
<td>650</td>
<td>13.8</td>
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<tr>
<td>SCC40</td>
<td>670</td>
<td>17.2</td>
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<tr>
<td>SCC100</td>
<td>675</td>
<td>14.4</td>
</tr>
</tbody>
</table>

### Table 4

<table>
<thead>
<tr>
<th>Mix</th>
<th>Density (kg/m$^3$)</th>
<th>Compressive strength (MPa)</th>
<th>Dynamic modulus of elasticity (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SCC</td>
<td>2370</td>
<td>44</td>
<td>32</td>
</tr>
<tr>
<td>SCC20</td>
<td>2354</td>
<td>43</td>
<td>30</td>
</tr>
<tr>
<td>SCC40</td>
<td>2351</td>
<td>42</td>
<td>31</td>
</tr>
<tr>
<td>SCC100</td>
<td>-</td>
<td>2282</td>
<td>-</td>
</tr>
</tbody>
</table>

---
the values obtained with the total coarse aggregate replacement are of the same magnitude to those observed in concrete of similar strength class.

The capillary water absorption determined at 3, 6, 24 and 72 h as function of square root of time in minutes are shown in Fig. 5. A similar behavior, as shown in Fig. 5, was observed for all mixtures. As the capillary water absorption is dependent of matrix porosity and pores interconnectivity, the incorporation of recycled aggregates seems not significantly modify the evolution of the capillary water absorption on time. Concerning the water capillarity coefficient, shown in Fig. 6, it was observed a decreasing of values from 5% up to 13% when the natural coarse aggregate is totally replaced by the recycled aggregate. In this case, even assuming the skeleton disturbance provoked by the recycled aggregate physical particularities, their addition is favorable to build some barriers or voids in the porous structure reducing the water movement.

The comparison between the values of water capillarity coefficients obtained on samples with and without preconditioning indicates that the values are highest to preconditioning samples, as shown in Fig. 7. This trend was also observed by Castro Gomes et al. [39] in tests on normal concrete. It means that a certain degree of humidity distributed on samples could change the tests results.

Taking into account the standard deviations of the water permeability coefficients, as shown in Fig. 8, it is confirmed that any significant difference was observed to be caused by the preconditioning.

Fig. 9 shows that the effect of the preconditioning procedure on the water permeability results is not significant. In this case it was expected because the water inside the porous is on pressure. The depth of water penetration is normally used to evaluate the concrete superficial porosity. Fig. 10 indicates that the water penetration depth on concrete becomes shorter when the percentages of incorporation of the recycled aggregate in concrete are significant (up to 40%). At 28 days age, the water penetration depth slightly increases for the SCC20 mixture, and reduces around 30% for SCC40 and 25% for SCC100. These results show that the recycled aggregate incorporation in SCC mixtures has any prejudicial effect into water penetration of the concrete.

### Table 5
Results of related durability properties of SCC.

<table>
<thead>
<tr>
<th>Mixture</th>
<th>Water permeability coefficient ( \times 10^{-18} ) (m²)</th>
<th>Capillarity coefficient ( \times 10^{-2} ) (kg/m² min⁻⁰·⁵)</th>
<th>Water penetration (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean value SD</td>
<td>Mean value SD</td>
<td>Mean value SD</td>
</tr>
<tr>
<td>SCC</td>
<td>4.23 0.95</td>
<td>1.43 0.0438</td>
<td>13.9 2.1</td>
</tr>
<tr>
<td>SCC20</td>
<td>2.61 0.46</td>
<td>1.36 0.0587</td>
<td>16.8 0.0</td>
</tr>
<tr>
<td>SCC40</td>
<td>2.83 0.63</td>
<td>1.34 0.0007</td>
<td>9.8 0.8</td>
</tr>
<tr>
<td>SCC100</td>
<td>3.62 2.07</td>
<td>1.24 0.0028</td>
<td>10.6 0.6</td>
</tr>
</tbody>
</table>

\( \text{SD} \) – Standard deviation.
According to the air permeability method applied, the SCC mixtures are considered airtight. However, it is concluded that recycled aggregate incorporation did not significantly affect the SCC water permeability, but could promote a large variation around an average value.

The SCC water capillarity coefficients obtained on samples with and without preconditioning indicate that the values are higher to preconditioning samples. It means that a certain degree of humidity distributed on samples influence the tests results. As the water penetration depth is dependent of concrete superficial layer, normally composed exclusively of mortar, the recycled aggregate incorporation in SCC mixtures has any prejudicial effect into water penetration of the concrete.

Taking into account the research done, the type of recycled aggregate used and their marginal effect on SCC properties, it is possible to conclude that, in general, the SCC incorporating local recycled coarse aggregates is a viable material with good potential to be used in the construction industry. Concerning coarse recycled aggregates from concrete demolition, it is also possible in the case of SCC to extent the limit percentage incorporation imposed by the current recommendation. Naturally, this extent limit needs to be confirmed, for each individual case, by an SCC mix design study.

Finally, the possibility to increase the use of recycled aggregates volume in self-compacting concrete may be regarded as a great environmental and economical benefit.

4. Conclusions

With respect to the fresh concrete properties, the particularity noted during the tests was the need to add more superplasticizer amount for concretes with recycled aggregates. Nevertheless, the increase of superplasticizer could be considered minor, around 2% of cement content for total natural aggregate replacement, against the environmental benefits here involved. This additional quantity is necessary because there is a water fraction that concerns the high values of water absorption showed by recycled aggregates if compared with the natural aggregates.

For the densities of the hardened concrete, there was a small weight loss by increasing the incorporation of recycled aggregates. This loss can be explained from the low density values of the recycled aggregates, when compared with natural aggregates.

Regarding the compressive strength, it was observed only 3.3% of strength loss with the maximum recycled aggregate incorporation. The incorporation of recycled aggregate reduced the concrete dynamic modulus of elasticity around 8.0% when compared with the natural coarse aggregate self-compacting concrete.

References


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