Influence of the crushing process of recycled aggregates on concrete properties

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Keywords: Recycled aggregates; performance; crushing process; precasting.

Abstract: This work intends to evaluate the (mechanical and durability) performance of concrete made with coarse recycled concrete aggregates (CRCA) obtained using two crushing processes: primary crushing (PC) and primary plus secondary crushing (PSC). This analysis intends to select the most efficient production process of recycled aggregates (RA). The RA used here resulted from precast products (P), with strength classes of 20 MPa, 45 MPa and 65 MPa, and from laboratory-made concrete (L) with the same compressive strengths. The evaluation of concrete was made with the following tests: compressive strength; splitting tensile strength; modulus of elasticity; carbonation resistance; chloride penetration resistance; capillary water absorption; and water absorption by immersion. These findings contribute to a solid and innovative basis that allows the precasting industry to use without restrictions the waste it generates.

Introduction

Modern Society, more qualified in every knowledge area, has demanded that the construction industry adopts new practices and processes to minimize its negative impacts on the environment. Concerns relative to the exhaustion of raw materials, the high cement consumption (associated to the high energy consumption and carbon dioxide emissions) and the so-called construction and demolition waste (CDW) have been in the agenda of developed countries.

Recycling the generated waste was identified as the most viable way of minimizing the risks associated with the issues aforementioned [1]. In this context, dumping CDW in landfills is one of the major environmental problems of the European Union (EU), since it is estimated that around 160 Mton or 480 kg/person of CDW are generated yearly in the EU [2].

This growing concern with environment preservation and sustainable development has led to the development of CDW recycling systems. Presently the production and use of RA, materials whose properties started to be studied 70 years ago [3], are common practice in the construction industry of various countries. For example, the Construction Materials Recycling Association (CMRA) reports that 140 Mton of concrete waste are annually recycled in the USA [4]. The annual report of the European Aggregates Association [5] shows that the RA generated represent around 5% of the EU's aggregates production. The same report refers that Germany is the biggest RA producer (approximately 60 Mton). The UK follows with around 49 Mton, the Netherlands produce around 20 Mton and France 17 Mton. In Australia more than 50% of the overall concrete waste generated by construction and demolition activities is recycled and the remaining part dumped [6]. In Japan the processing of concrete waste for RA reached a ratio of 98% [7]. However, there are other countries where the conscientiousness level towards recycling for production and application of RA is still low [8].

Therefore various Governments around the world promote policies aimed at reducing the use of raw materials and increase reuse and recycling.

Various applications are already known for recycled concrete aggregates (RCA), guaranteeing compliance with every specification, namely in foundations, pavements, reinforced concrete, among others [9, 10].

Literature review

Recently the properties of RCA and the effects of their incorporation in concrete have deserved the attention of various researchers [1, 3, 6-10]. Notwithstanding its obvious environmental advantages, this material has distinct properties from those of natural aggregates (NA) that have hindered their more regular use. Furthermore, the quality of the RA varies significantly according to the source concrete, with enormous influence on the performance of the future concrete [11].

The main difference in physical terms between RCA and NA is the adhered mortar on the former's surface. The presence of this mortar is one of the main reasons for the quality losses relative to the NA.

This is explained by the porosity of the adhered mortar [12-15] coupled with many micro-cracks [14]. The RCA are thus characterized by lower particles density, higher water absorption and lower mechanical strength than the NA [16]. In the production of new concrete these characteristics of the RCA may have an adverse effect on the interfacial bond between them and the cement paste. According to Tam et al. [14], the presence of pores and cracks in the mortar next to the interfacial transition zone (ITZ) causes a weak link in the microstructure of concrete, affecting the global strength.

Topçu and Sengel [17] analysed the influence of the RCA incorporation on concrete mixes with replacement ratios up to 100%. The results show a decrease of the density with the incorporation of this waste but the difference is not as significant as the one in water absorption. Limbachiya et al. [18] reached similar conclusions.

There is therefore a greater water demand in concrete made with RCA (RCAC), causing a significant increase of the w/c ratio [19]. Some researchers resorted to the use of superplasticizers with the objective of maintaining the water content below reasonable limits [19, 20].

As a consequence of the greater absorption of these aggregates, the fresh-state concrete workability is also affected, showing worse performance for the same water content when RCA are incorporated, especially for replacement ratios above 50% [17]. In the Poon et al. [21] research, intended to improve the workability of RCAC, it is suggested to change the humidity use conditions of the RCA.

According to the literature, the conclusions concerning the mechanical performance of RCAC are identical, i.e. there is a decay of the properties when NA's are replaced by RCA. Rahal [22], Tabsh et al. [23] and Rao et al. [24] found losses of the compressive strength and modulus of elasticity of around 10-25% and 5-35%, respectively, for full replacement of the coarse aggregates.

In order to optimize the properties of concrete with RA, some authors suggest the use of admixtures (superplasticizers) and additions (fly ash, silica fume, among others). In the work of Berndt [25], it is observed that concrete with RA (full replacement of the coarse fraction) and 50% replacement of 50% of the cement by fly ash showed higher compressive and tensile strength values and lower modulus of elasticity than concrete with 100% coarse RA and 100% cement. Kou and Poon [26] obtained similar results for 25% replacement of cement by fly ash. However, for 35% replacement the compressive strength of the RCAC was significantly reduced. These results suggest that for a high volume of fly ash there is a strength decrease of the RCAC. As for the incorporation of silica fume and superplasticizer, it is suggested that the properties of RCAC can be significantly improved [27].

It is found that the durability of RCAC also suffers when the content of RA increases [20, 24]. Rao et al. [24] obtained increases of 33% and 14% in water absorption and chloride penetration resistance, respectively, when 100% of the coarse NA's were replaced. Ravindrajah et al. [28] registered increases of creep of around 30-60%, relative to the reference concrete (RC), in mixes with incorporation of coarse RCA. Katz [16] concluded that the use of RCA led to shrinkage values between 0.55 mm/m and 0.80 mm/m, at 91 days, which compared with 0.30 mm/m for the RC.

Since the shape of the RA influences the performance of the new concrete, Nagataki et al. [29] evaluated various crushing processes. They concluded that the compressive and flexural strength of RCAC were lower when the aggregates were subjected to one crushing cycle instead of two.

Tests sequence

The set of tests performed aimed at evaluating the viability of reintroducing RCA in the precast concrete industry. Coarse recycled aggregates (CRA) were used, from crushing precast elements and laboratory-made concrete.

All the RA used resulted from concrete with compressive strength classes of 20 MPa, 45 MPa and 65 MPa. In order to guarantee a quality adequate to fulfil the technical demands of the precasting industry, this work tried to optimize the crushing process used to obtain the RA.

The mechanical and durability performance of concrete made with CRA obtained using the current crushing method for RA (primary crushing only) was evaluated and compared with that of concrete with RA obtained through a two-stage crushing process (primary plus secondary crushing), similar to the one used to produce stone NA.

18 concrete mixes were produced in this experimental program. 12 mixes with CRA were prepared, considering the two crushing processes and trying to replicate the strength of the source concrete mixes (20 MPa, 45 MPa and 65 MPa), using aggregates both from laboratory and precast elements. Six RC mixes were produced, also combining crushing processes and target strengths.

The 20 MPa, 45 MPa and 65 MPa target strength RC with PC NA were named RC20PC, RC45PC and RC65PC. The RAC with PC RA from the L and P source concretes were named C100LC20PC; C100L45PC; C100L65PC; C100P20PC; C100P45PC; C100P65PC. The mixes with PSC aggregates adopted similar designations.

Materials

The various mixes (using NA only or RA) were produced according to the Faury's methodology [30], and only the mixes with slump values within the range 125 ± 15 mm were accepted.

The RCAC needed higher water contents to compensate the CRA's higher absorption capacity. By adding extra mixing water a correct hydration process was guaranteed, without compromising the concrete performance.

Two w/c ratios were determined: the apparent w/c ratio, i.e. the ratio between the overall water content in the mix and the binder content (which is particularly relevant to the study of concrete mixes) and the effective w/c ratio that consists on the ratio between the free water content and the binder content (essential to understand the concrete performance).

The following materials were used in the concrete mixes' composition: fine NA (sand river), coarse NA (crushed limestone), coarse RA (from concrete produced in laboratory and precast elements of various strength levels), cement and tap water.

CEM I 42.5R was used at 210 kg/m^3, 280 kg/m^3 and 350 kg/m^3 for the mixes with target strength of 20 MPa, 45 MPa and 65 MPa, respectively. In the 65 MPa mixes a superplasticizer (SikaPlast 898) was used at 1% by cement weight, within the range recommended by the manufacturer.

Only full replacement of coarse NA by coarse RCA was considered in the RCAC mixes.

Results and discussion

This section presents and comments the results of the hardened concrete properties (mechanical and durability characteristics).

Compressive strength

The compressive strength test was performed at 28 days, according to standard NP EN 12390-3 (2011). Figure 1 presents the results obtained.

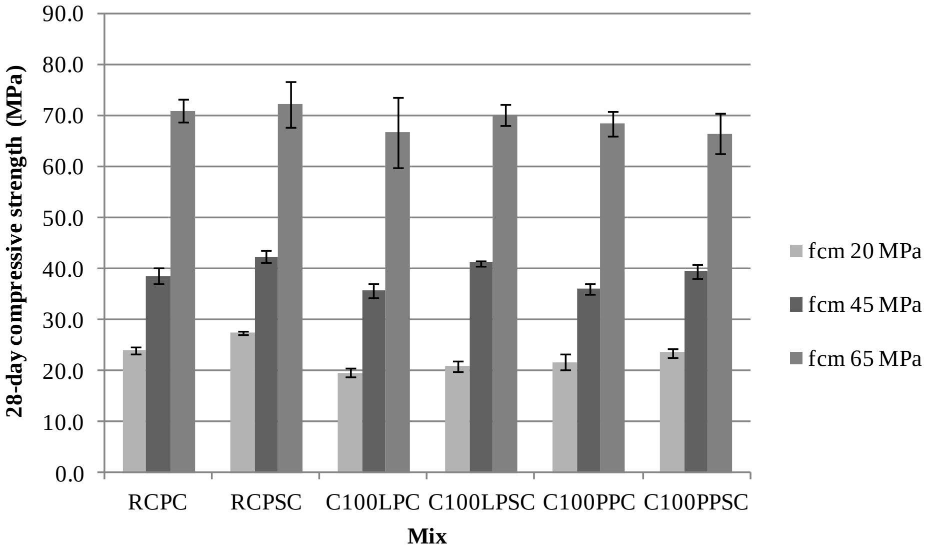

Figure 1 - 28.day compressive strength

It is observed that the replacement of coarse NA by coarse RCA causes strength losses relative to the RC of 9.0-17.7%, 3.2-7.6% and 3.0-8.1% for the 20 MPa, 45 MPa and 65 MPa mixes, respectively. This is due to the adhered mortar on the RA's surface, responsible for increasing their absorption and decreasing their particles density. The greatest loss occurred for the 20 MPa mixes because of the differences in failure mechanisms. In this worst quality RA the failure seems to occur in the interface between the original NA and the adhered mortar or through the mortar itself, unlike the mixes where better quality RA are used, in which the interface between the RA and the new mortar is the weakest zone.

It is found that the RA from the PSC process led to better performances, and that similar trends concerning this parameter occurred in the RCAC and RC. For the 20 MPa and 45 MPa target strength mixes the use of PSC RA is responsible for performance gains between 6.7% and 15.1%, relative to the PC RA mixes. This gain decreased to 5% in the 65 MPA mixes. In this program the objective was to replicate in the new concrete mixes the strength class of the source concrete (SC) mixes. Therefore, in the 20 MPa family the worst quality RA were used, contrasting with the 65 MPa mixes produced with the best RA. So the influence of the crushing process on the performance should increase from the RA from stronger SC to the weaker ones. In fact the greatest difference occurred for the RA from the intermediate strength SC. Two effects may explain this situation: the PC process may eliminate such an important part of the adhered mortar that the second crushing stage has only a small additional effect; in the RA with stronger mortar the second crushing stage may not be sufficient to detach an important part of the adhered mortar and cause the negative effect of causing micro-cracking of the mortar that remains attached to the original NA.

These results agree with those of Rahal [22], who found compressive strength losses of approximately 10%. Rao et al. [24] obtained similar losses, around 13%.

Splitting tensile strength

The splitting tensile strength test was performed at 28 days, according to standard EN 12390-6 (2011). Figure 2 shows the results obtained.

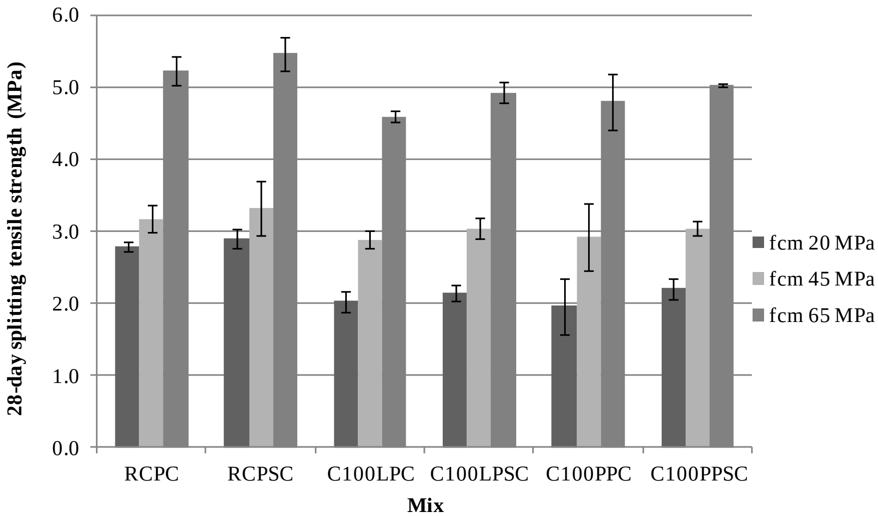

Figure 2 - 28-day splitting tensile strength

The splitting tensile strength decreases for full incorporation of RA. The greatest losses, around 25%, occur in the weakest mixes. On the other hand, the 45 MPa and 65 MPa mixes show losses of approximately 10%. This trend is also due to the worst quality of the RA in the first mixes, where failure occurs in the interface between the original NA and the adhered mortar or though the mortar itself, emphasizing the differences between the RC and the RCAC.

The crushing process has a similar influence on the RC and RCAC. The trends are also similar for all levels of the target strength. The secondary crushing of the aggregates leads to better results, by 4-7%. This is justified by the lower adhered mortar content achieved by PSC *versus* PC.

The maximum loss due to the replacement of NA by RA was 24%. These results agree with those of Rao et al. [24], who found tensile strength losses of approximately 24%. In the Tabsh et al. [23] research, the losses for mix 1 (30 MPa concrete) were the same, around 25%. However, for mix 2 (50 MPa concrete), almost the same strength occurred in the RC and RAC (similarly to what happened here with the C100L65PSC mix).

Modulus of elasticity

This test was performed at 28 days based on standard LNEC E-397 (1993). Figure 3 presents the results. There is a decrease with the incorporation of coarse RCA, reaching approximately 22%, 19% and 15% in the 20 MPa, 45 MPa and 65 MPa families, respectively. These results agree with Eurocode 2, i.e. concrete elastic deformations depend greatly on its composition.

It is concluded that the mixes with aggregates from the PSC process had better performances. However, the greatest difference registered in the various families was only 2%.

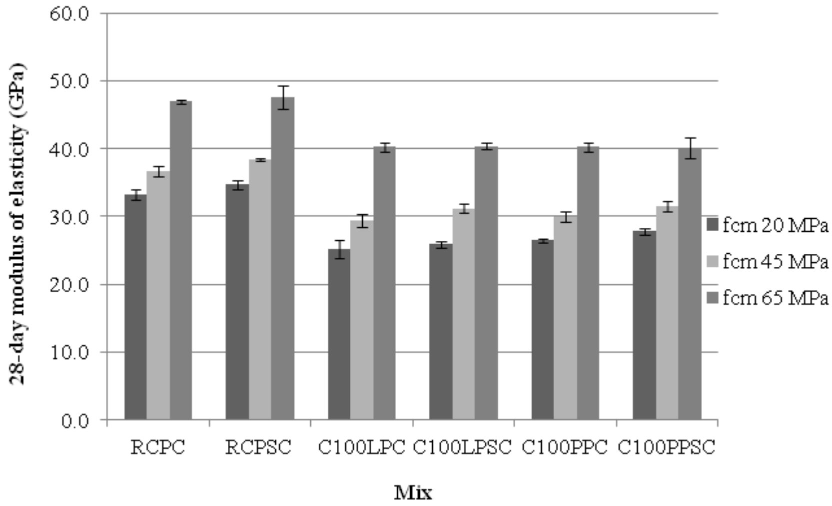

Figure 3 - 28-day modulus of elasticity

These results show that this property is influenced by the cement paste, aggregate type, the bond and distribution of the concrete constituents, i.e. the factors that affect the overall deformability of the composite.

The losses registered due to the incorporation of RA were around 20%. This is less than the Rao et al. [24] values, around 35%. This may explained by the level of modulus of elasticity of the RA used. In the study of Kheder et Al-Windawi [32], the losses were closer to ours, between 20% and 25%.

Water absorption by immersion

The water absorption by immersion test was performed at 28 days, according to standard LNEC E394-1993. Figure 4 shows the results obtained.

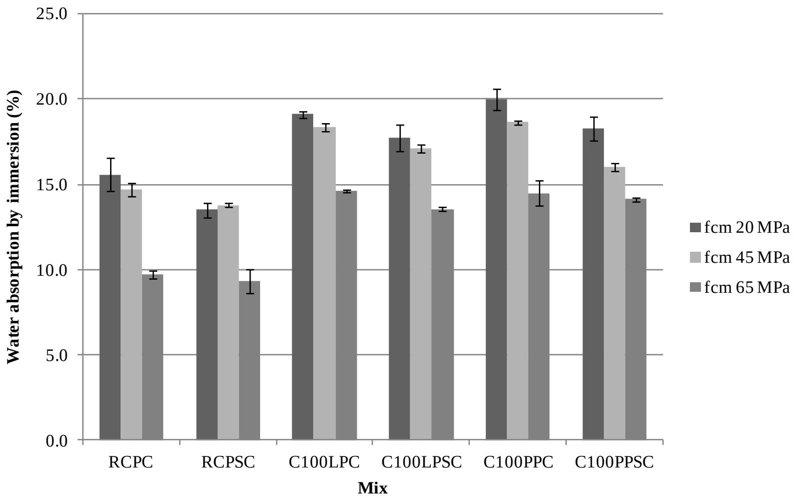

Figure 4 - Water absorption by immersion

The mixes that had the best mechanical performance were the ones that obtained the most satisfactory results in this property, i.e. the 65 MPa family performed better, followed by the 45 MPa and the 20 MPa families.

Figure 4 shows that in all families the mixes with RA had greater water absorption by immersion than the corresponding RC.

It is also concluded that the PC process leads to worse results than the PSC process.

Finally, it is concluded that the effects of replacing NA by RA are more significant in the high target strength families, with maximum variations relative to the corresponding RC of approximately 50%, 27% and 35% for the 65 MPa, 45 MPa and 20 MPa families, respectively.

With the exception of the 65 MPa family, these results agree with the literature, i.e. increases of the water absorption between 15% and 30% [24, 33]. Rao et al. [24] justified their results with the high water absorption of the CRA (around 3.5 times that of the NA).

Water absorption by capillarity

This test was performed 42 days after mixing according to standard LNEC E393-1993. Figure 5 presents the results obtained.

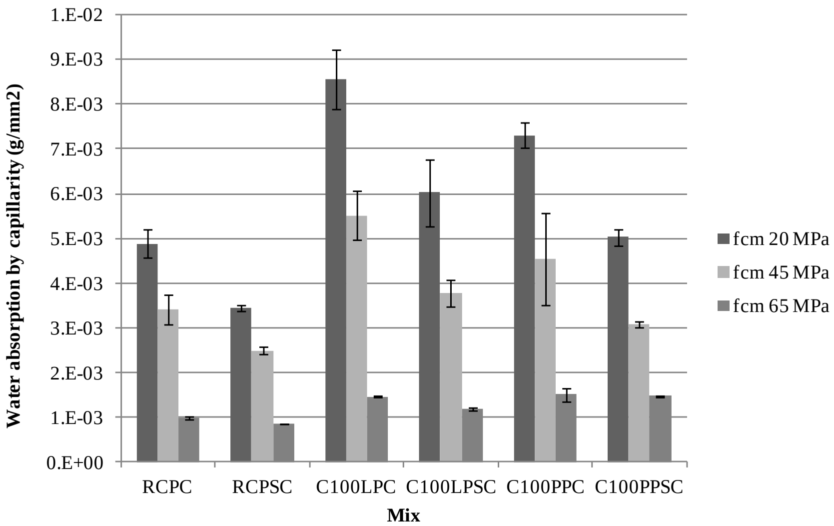

Figure 5 - Water absorption by capillarity

The absorption increases with the replacement of NA by RCA. The mixes with PSC aggregates showed better results than the mixes with PC aggregates. These conclusions agree with the ones drawn for water absorption by immersion.

As expected, in the Kou and Poon [26] study the water absorption of the RAC was significantly greater (by 65%) than that of the RC. This value falls within the range detected in our research. As for water absorption by immersion, the results of the various researches are justified by the higher water absorption of the RA relative to that of the NA.

Carbonation resistance

The carbonation resistance test was performed at 7, 28, 56 and 91 days, according to standard

LNEC E-391-1993. Figures 6 to 8 present the results obtained. At 91 days, the carbonation depths of the low target strength family had already reached the specimen's thickness (50 mm).

The carbonation front depth increases over time for all mixes, as expected. The graphs show a notorious difference between the carbonation depths of the various families, with greater values in the families with lower target strengths, again as expected.

At 56 days, the full replacement 20 MPa and 45 MPa mixes registered carbonation depth increases of approximately 15%. Even though the percentage variation is higher for the 65 MPa mixes, the difference in absolute terms is very small.

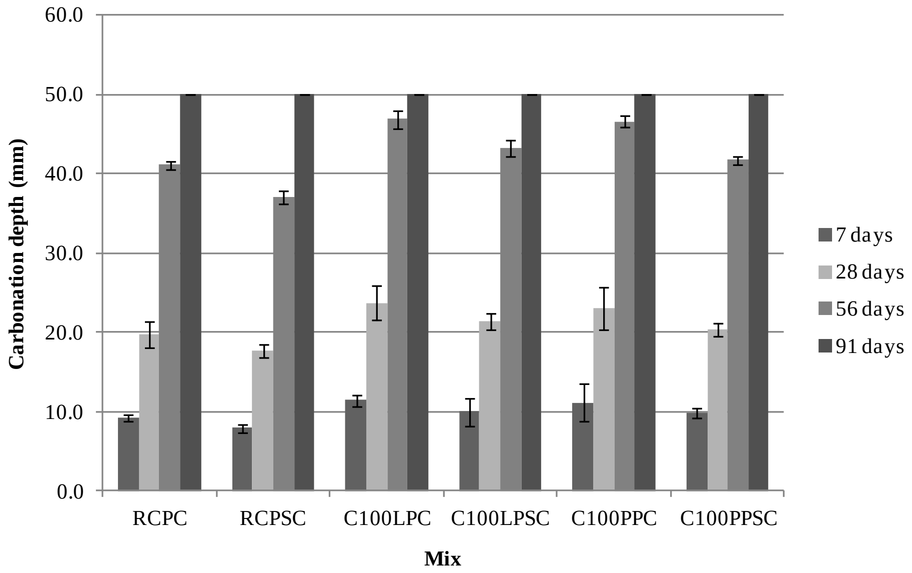

Figure 6 - Carbonation depth over time of the 20 MPa family mixes

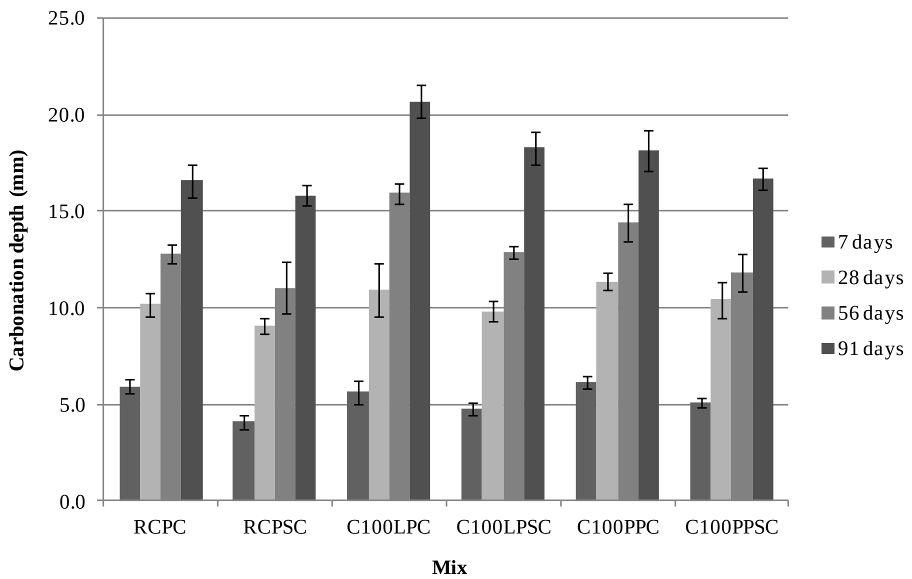

Figure 7 - Carbonation depth over time of the 45 MPa family mixes

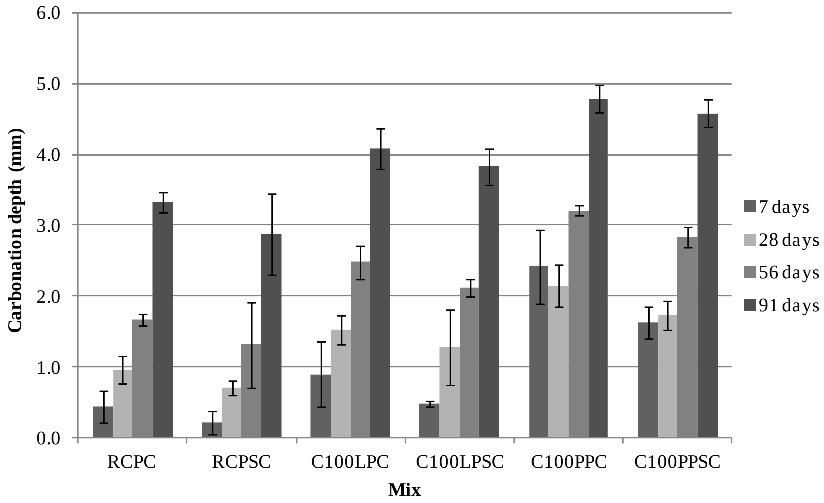

Figure 8 - Carbonation depth over time of the 65 MPa family mixes

The increase of carbonation depth due to the incorporation of RA was expected, since the capillary absorption and the chloride penetration follow the same trend. Kou and Poon [26] registered at 90 days increases between 20% and 35%, inside the range obtained in our study.

Again better results were obtained in the mixes using PSC RA. The worse performance of the PC process occur because it comprises only one crushing stage, leading to more porous aggregates and with clearer weak plans in the interface between aggregate and cement paste.

Chloride penetration resistance

This test was performed at 28 and 91 days according to standard LNEC E463-2004. Figures 9 and 10 present the results obtained.

It is found that the mixes' performance tends to improve from 28 to 91 days, given the decrease of the chloride diffusion coefficients. This trend is explained by the longer curing time of the specimens, responsible for hydrating larger cement contents and thus reducing the voids volume. However, according to standard LNEC E-465, more significant reductions were expected, i.e. the chloride diffusion coefficient at 91 days should be around 60% of the one registered at 28 days.

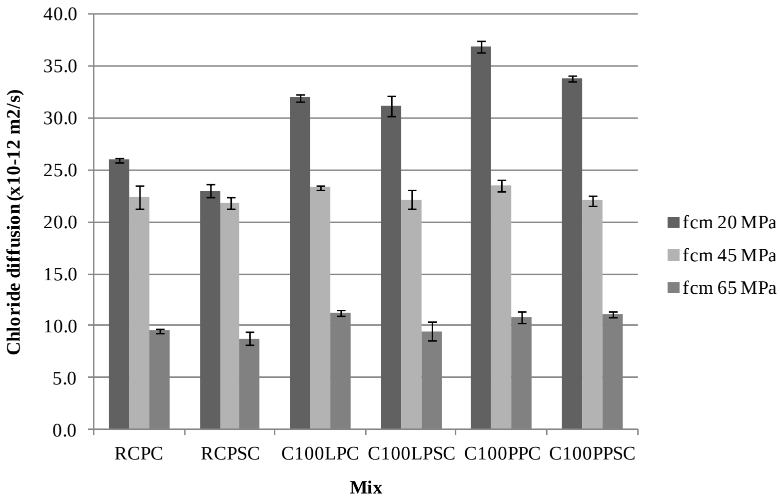

Figure 9 - 28-day chloride penetration resistance

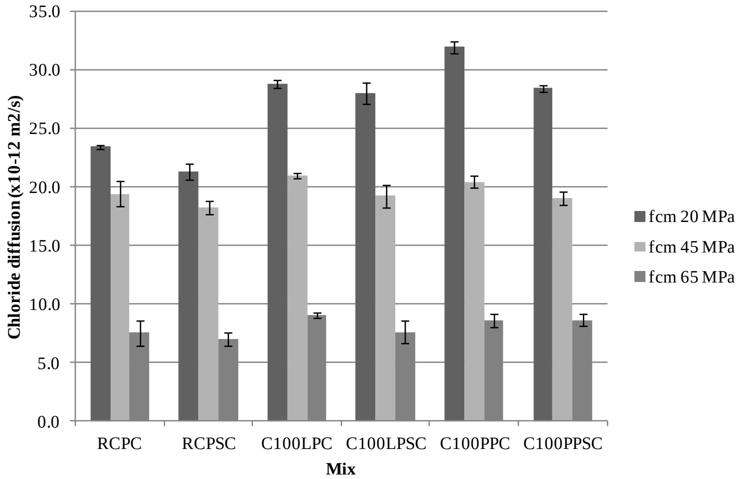

Figure 10 - 91-day chloride penetration resistance

In the various families the mixes produced with PSC aggregates showed better results.

The variation found in the diffusion coefficients was expected, since the mechanism of penetration of the chloride ions inside concrete is directly related with its porosity [31].

Rao et al. [24] and Kou and Poon [26] also observed an increase in penetration depth (around 14% and 12, respectively) due to the incorporation of RA. These results are coherent with the ones obtained here, i.e. variations between approximately 5% and 25%. Kou and Poon [26] also found that the resistance improved as the curing time increased from 28 to 90 days and explained the trend with the increase of the volume of the hydration products. The decreases observed of the diffusion coefficients were around 20%, again below that predicted by standard LNEC E-465.

Conclusions

Based on these results, it is concluded that:

1. The compressive strength of concrete decreases around 8% when coarse NA's are fully replaced by coarse RCA. The mixes made with PSC aggregates registered better results;
2. The splitting tensile strength also showed performance losses (a maximum of 25%) because of the incorporation of coarse RCA. The mixes with PSC aggregates showed the highest results;
3. The modulus of elasticity followed the trend of the previous properties (decreases of around 20%). However, no significant differences were found between mixes using PC aggregates and PSC aggregates;
4. Concrete performance losses were registered by the mixes with RCA, in terms of water absorption by immersion and capillarity. The mixes with PSC aggregates had lower losses, especially in the capillary absorption;
5. The incorporation of RA decreased the carbonation and chloride penetration resistances. Again, the losses were lower in the mixes with PSC aggregates;
6. In sum, the replacement of NA by RCA is responsible for performance losses in concrete, which are greater when aggregates with primary crushing only are used. Given the scale of the losses measured here, it is perfectly viable to offset these losses through the addition of additions or admixtures.

Acknowledgments

The authors gratefully acknowledge the support of the ICIST research centre, IST, University of Lisbon and FCT (Fundação para a Ciência e Tecnologia).

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