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ORIGINAL ARTICLE

Performance of concrete made with aggregates recycled from precasting industry waste: influence of the crushing process

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Abstract The aim of this paper is to evaluate the influence of the crushing process used to obtain recycled concrete aggregates on the performance of concrete made with those aggregates. Two crushing methods were considered: primary crushing, using a jaw crusher, and primary plus secondary crushing (PSC), using a jaw crusher followed by a hammer mill. Besides natural aggregates (NA), these two processes were also used to crush three types of concrete made in laboratory (L20, L45 e L65) and three more others from the precast industry (P20, P45 e P65). The coarse natural aggregates were totally replaced by coarse recycled concrete aggregates. The recycled aggregates concrete mixes were compared with reference concrete mixes made using only NA, and the following properties related to the mechanical and durability performance were tested: compressive strength; splitting tensile strength; modulus of elasticity; carbonation resistance; chloride penetration resistance; water absorption by capillarity; water absorption by immersion; and shrinkage. The results show that the PSC process leads to better performances, especially in the durability properties.

Keywords Concrete · Recycled aggregates · Crushing process · Source concrete · Mechanical and durability performance

Abbreviations

CDW	Construction and demolition waste
CNA	Coarse natural aggregates
CRCA	Coarse recycled concrete aggregates
f_{cm} 20 MPa	Concrete family with 20 MPa target strength
f_{cm} 45 MPa	Concrete family with 45 MPa target strength
f_{cm} 65 MPa	Concrete family with 65 MPa target strength
FNA	Fine natural aggregates
NA	Natural aggregates
PC	Primary crushing
PSC	Primary plus secondary crushing
RA	Recycled aggregates
RAC	Recycled aggregates concrete
RC	Reference concrete
RCA	Recycled concrete aggregates
RCAC	Recycled concrete aggregates concrete
SC	Source concrete
w/c ratio	Water/cement ratio

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1 Introduction

Concerns about the depletion of natural resources and the disposal of construction and demolition waste (CDW) have led to the development of methods/systems to use recycled aggregates (RA).

Even though much is already known about the use of RA in concrete our knowledge is still insufficient and more data will be needed, in particular on specific parameters such as the crushing process.

Eloranta [10] developed existing knowledge on natural stone crushing, using rotating and cone crushes. The author concluded that the feeding characteristics of the equipment are a determining factor for the final result, i.e. the crushed products. Therefore, even though the quality of the final product may be improved by changing operating parameters (course, speed, tuning), they can hardly compensate an incorrect feeding.

Concerning the TA processing, in the literature survey performed it was found that most studies on RAC either do not refer the crushing process or use a single crushing step. However, this is a fundamental aspect, since it changes the adhered mortar content, to which most of the concerns about the use of RA are associated. As a matter of fact, this material is responsible for decreasing the particles density and increasing the water absorption and porosity of the RA relative to the natural aggregates (NA) [40, 47]. The quality of the adhered mortar depends on the w/c ratio used in the source concrete and its content depends on the crushing process and the concrete's strength [17].

In the Florea and Brouwers [14] study, laboratory made concrete was used to mimic the recycling process. Aggregates RC-1 and RC-2 were crushed with a jaw crusher one and 10 times, respectively. To crush aggregate RC-3 a prototype specially conceived for this effect was used. The results showed a much higher cement paste content in the prototype's output aggregate (RC-3). For the same particles size, the cement paste differs by 50 % when aggregates RC-3 and RC-1 are compared. The authors also detected an 80 % improvement in cement paste content for particles lower than 10 and 11 mm of the RC-1 and RC-2, respectively. Aggregates RC-3 reached the same ratio for particles below 8 mm.

In the Etxeberria et al. [11] work, it was found that the particles size is a factor that influences the adhered mortar content, which can vary between 20 and 40 % the aggregates' mass. Hansen [16] reported an adhered mortar content up to 60 % in the 4–8 mm fraction and of 65 % in the 0–0.3 mm fraction. These results agree with those of Juan and Gutiérrez [19] that reached adhered mortar contents 23–44 % in the 8/16 mm fraction and of 33–55 % in the 4/8 mm fraction.

As for the smaller particles (lower than 2 mm), many researchers consider their use inadequate for concrete [16, 40]. This is explained by their high adhered mortar content.

Juan and Gutiérrez [19] established that the adhered mortar content should not be higher than 44 %. These authors consider that with this criterion it is possible to get recycled aggregates with absorption lower than 8 % and particles density higher than 2,160 kg/m^3 According to the Building Contractors Society of Japan [7], these values are adequate for RA use in concrete production.

Therefore in our research only coarse aggregates will be used to evaluate the influence of the crushing process on concrete's properties. In the literature survey performed, it was found that most of the works on RAC either did not refer the crushing process or used only one crushing stage. It is also stressed that no study was found in which an exhaustive evaluation was performed, analysing the influence of this parameter in terms of the mechanical and durability performance of the resulting concrete. In this context the works of Nagataki and Lida [34], Nagataki et al. [33] and Matias et al. [31] are highlighted.

Nagataki and Lida [34] studied the influence on the RAC's performance of various processes used to crush the RA. The SC were subjected to primary crushing using a jaw crusher and secondary crushing using an impact crusher, and these operations were called level 1 crushing. If an improved impact crusher was used once afterwards it was called level 2 crushing, and if it was used twice it was called level 3 crushing. The SC tested included several strength ranges (high—60.7 MPa; medium—49.0 MPa and low—28.3 MPa), and each was crushed at three ages (1 month, 1 year and 2 years). These results show that the influence of the crushing process grows as the target strength of the SC increases. The dynamic modulus of elasticity after freeze–thaw cycles also revealed the influence of the crushing process. The mixes with crushing levels 1 and 2 aggregates from the 60.7 MPa SC both showed a value of 77 % relative to the value before the cycles, whilst the mix with crushing level 3 aggregates from the same SC

Table 1 Composition of the concrete mixes (m^3)

Mix	Fine natural aggregates (kg)	Coarse natural aggregates (kg)	Coarse recycled aggregates (kg)		Cement CEM I 42.5R (kg)	Water (l)	w/c ratio	a/c_{ef} ratio	Superplasticizer (kg)
RC20PC	938	958	0		210	180.6	0.86	0.86	0
RC45PC	870	956			280	182.0	0.65	0.65	0
RC65PC	863	1,002			350	143.5	0.41	0.41	3.5
C100L20PC	929	0	L20PC	966	210	214.2	1.02	0.87	0
C100L45PC	866	0	L45PC	940	280	196.0	0.70	0.66	0
C100L65PC	858	0	L65PC	974	350	161.0	0.46	0.42	3.5
C100P20PC	932	0	P20PC	970	210	212.1	1.01	0.86	0
C100P45PC	870	0	P45PC	970	280	193.2	0.69	0.65	0
C100P65PC	858	0	P65PC	1,029	350	157.5	0.45	0.42	3.5
RC20PSC	946	1,019	0		210	170.1	0.81	0.81	0
RC45PSC	877	1,011			280	176.4	0.63	0.63	0
RC65PSC	868	1,057			350	140.0	0.40	0.40	3.5
C100L20PSC	938	0	L20PSC	953	210	207.9	0.99	0.84	0
C100L45PSC	877	0	L45PSC	988	280	187.6	0.67	0.63	0
C100L65PSC	868	0	L65PSC	982	350	150.5	0.43	0.40	3.5
C100P20PSC	943	0	P20PSC	977	210	205.8	0.98	0.82	0
C100P45PSC	873	0	P45PSC	962	280	190.4	0.68	0.64	0
C100P65PSC	858	0	P65PSC	1,016	350	157.5	0.45	0.42	3.5

reached 85 %. As for the 49.0 and 28.3 MPa SCs, the values obtained for levels 1, 2 and 3 were 71, 67 and 82 % and 76, 68 and 80 %, respectively. These values refer to the maximum number of cycles studied (400), for which crushing level 3 always yielded the best results. In this study, even though the freeze–thaw resistance decreased with the incorporation of RA, regardless of the crushing process, the results were generally regarded as satisfactory since the durability factor was always greater than 70 % after 300 cycles.

Nagataki et al. [33] found that the extent of the crushing process caused no significant changes in the compressive strength of concrete with RA. A similar trend was found for the splitting tensile strength. According to these researchers, unusual mechanical performance and porosity of concrete mixes with RA may be easily explained by changes in the microstructural profile of the SC aggregates caused by the crushing process. Furthermore, the mechanical compatibility of the system made of the original NA and the adhered cementitious matrix is another important condition for the good mechanical performance of concrete with CRCA.

In the Matias et al. [31] study some preliminary tests were performed to understand how the crushing process of natural and recycled aggregates influences the properties of concrete made with them. The authors found no meaningful differences in the compressive strength of mixes made with the same crushing process (primary or primary plus secondary), i.e. the crushing process made a difference but the type of aggregate used (NA vs. CRCA) did not.

2 Experimental programme

2.1 Materials

The concrete mixes composition (Table 1) includes the following materials: fine natural aggregates (river sand), coarse natural aggregates (crushed limestone), coarse recycled concrete aggregates, cement and water. The RA came from rejected precast elements (P), with strength classes of around 20, 45 and 65 MPa, and concrete made in the laboratory (L), with the same target strength classes. Table 2 presents their properties.

Cement CEM I 42.5R was used in a content of 210, 280 and 350 kg/m^3 for the laboratory mixes with target strength of 20, 45 and 65 MPa, respectively. In

Table 2 Aggregates' properties

Aggregates	Crushing process	Name	Particle density (kg/m^3)			Water absorption (%)
			Apparent	Oven-dry	Saturated surface dry	
Coarse	PC	NAPC	2,590.5	2,503.7	2,537.2	1.3
		L20PC	2,760.6	2,275.0	2,451.2	7.8
		L45PC	2,640.8	2,231.8	2,386.6	6.9
		L65PC	2,504.7	2,266.3	2,361.5	4.2
		P20PC	2,754.9	2,283.9	2,455.9	7.5
		P45PC	2,708.8	2,306.4	2,454.9	6.4
		P65PC	2,664.3	2,395.1	2,496.1	4.2
	PSC	NAPSC	2,708.8	2,639.1	2,664.8	1.0
		L20PSC	2,686.3	2,231.4	2,400.8	7.6
		L45PSC	2,701.7	2,356.1	2,484.0	5.4
		L65PSC	2,484.9	2,280.4	2,362.7	3.6
		P20PSC	2,719.8	2,288.1	2,446.8	6.9
		P45PSC	2,686.6	2,322.4	2,458	5.8
		P65PSC	2,614.1	2,371.6	2,464.3	3.9
Fine	–	FNA	2,637.8	2,625.0	2,630.0	0.1

the 65 MPa mixes a superplasticizer (SikaPlast 898) was added at 1 % per mass of cement, diluted in the mixing water (tap water).

In the concrete mixes with incorporation of CRCA (RAC) the only replacement ratio of CNA by CRCA considered was 100 %.

All the aggregates (natural and recycled) were sieved mechanically and only the 0–22.4 mm fraction was used. After being dried and separated by size the aggregates were stored in airtight containers to prevent humidity exchange with the environment. Even though it might be difficult to implement this procedure on an industrial scale, it allows comparing the mixes with exactly the same size distribution, eliminating this entropy factor in the results.

2.2 Preparation of the concrete mixes

The various concrete mixes were produced according to Faury's [12] method, all within the target slump range of 125 ± 15 mm. This corresponds approximately to the average of the range of the S3 slump class (NP EN 206-1 [38]. The composition of the mixes was defined for the reference concrete (RC) mixes made with natural aggregates (NA) only. Then it was adapted for the remaining mixes, bearing in mind that the w/c ratio tends to increase with the incorporation of RA, because of the greater absorption of the CRCA. In this research the mixing water compensation method was used in order to control the effects of this greater water absorption. This method yields better results than the RA pre-saturation process [13].

The objective of this study was to replicate the strength class of the source concrete (SC) of the RA to be used: 20, 45 and 65 MPa, for both the lab-made SCs and those from precast products. In other words, the mixes with target strength of 20 MPa were made with RA from 20 MPa SC, and so forth.

The experimental programme comprised two stages: in the first the mechanical performance of mixes with CRCA subjected to various crushing processes was evaluated; in the second their durability was analysed.

2.3 Tests

For the evaluation of the mechanical properties, compressive strength tests were performed on five 150 mm cubes per mix, according to NP EN 12390-3 [36]. The specimens were subjected to 28 days of curing in a wet chamber. For the splitting tensile strength and modulus of elasticity tests, four 150 mm diameter 300 mm thick cylinders per mix were tested

Table 3 28-Day compressive strength and splitting tensile strength

Family		f_{cm} 20 MPa			f_{cm} 45 MPa			f_{cm} 65 MPa		
Mix	Properties	μ (MPa)	σ (MPa)	Δ (%)	μ (MPa)	σ (MPa)	Δ (%)	μ (MPa)	σ (MPa)	Δ (%)
RCPC	Compressive strength	23.9	0.7	0.0	38.7	1.6	0.0	71.1	2.3	0.0
	Splitting tensile strength	2.8	0.1	0.0	3.2	0.2	0.0	5.2	0.2	0.0
RCPSC	Compressive strength	27.5	0.4	15.1	42.4	1.2	9.8	72.3	4.4	1.8
	Splitting tensile strength	2.9	0.1	4.2	3.3	0.4	4.4	5.5	0.2	4.5
C100LPC	Compressive strength	19.7	0.8	0.0	35.7	1.4	0.0	66.8	7.0	0.0
	Splitting tensile strength	2.0	0.2	0.0	2.9	0.1	0.0	4.6	0.1	0.0
C100LPSC	Compressive strength	21.0	1.0	6.7	41.1	0.6	15.0	70.2	2.0	5.1
	Splitting tensile strength	2.1	0.1	5.6	3.0	0.1	5.4	4.9	0.1	7.3
C100PPC	Compressive strength	21.8	1.6	0.0	36.1	1.1	0.0	68.5	2.5	0.0
	Splitting tensile strength	2.0	0.4	0.0	2.9	0.5	0.0	4.8	0.4	0.0
C100PPSC	Compressive strength	23.6	0.9	8.5	39.7	1.4	9.9	66.5	4.0	−3.0
	Splitting tensile strength	2.2	0.1	12.4	3.0	0.1	3.9	5.0	0.1	4.9

after 28 days of curing in a wet chamber, according to NP EN 12390-6 [37] and LNEC E397 [29], respectively.

For durability performance, water absorption by immersion tests were performed in four 100 mm cubes, according to LNEC E394 [28]. The water absorption by capillarity was determined in three 150 mm diameter 100 mm thick cylinders per mix, according to LNEC E393 [27]. The tests were performed at 42 days and the specimens were positioned in a tray in contact with water 5 ± 1 mm deep at a constant relative humidity of 60 % and temperature of 20 °C. The specimens were weighed to determine the amount of water absorbed after 3, 6, 24 and 72 h. The carbonation resistance test was performed after 7, 28, 56 and 91 days, according to LNEC E391 [25]. The process was artificially accelerated by positioning 12 specimens per mix in a carbonation chamber with 5 % concentration of CO_2. For every test age and mix type each specimen was broken into four pieces and immediately sprayed with a phenolphthalein solution to measure the carbonation depth. The chloride penetration resistance test was performed on three specimens per mix and test age, according to LNEC E463 [26], which corresponds to a non-stationary accelerated migration test, adapted from the procedures of NT-Build-492 [39].

The shrinkage test was performed according to LNEC E398 [30] on two 150 × 150 × 600 mm specimens per mix, subjected to controlled relative humidity and temperature conditions (60 % and 20 °C, respectively), and length changes were registered at 91 days.

3 Results and discussion

3.1 Compressive strength

The 28-day compressive strength results for the two crushing processes are presented in Table 3. For RCAC with replacement ratios of 100 %, the compressive strength fell relative to the RC by 9.0–17.7 %, 3.2–7.6 % and 3.0–8.1 %, for the 20, 45 and 65 MPa target strengths, respectively. The poorest RCAC performances are related to the presence of adhered mortar in the RA, responsible for an increase of weak planes [22]. Another important aspect is the greater strength loss of the 20 MPa mixes, explained by the poorer quality of the RA. Poon et al. [41] also observed that high-performance RA tend to create a stronger bond in the interfacial matrix-aggregate zone. Therefore, for worse quality RA, rupture occurs either in the interface between the original NA and the adhered mortar or through the adhered mortar itself, which does not happen in concrete with better quality RA, for which the weakest link is the interface between the RA and the new mortar. In the first case the strength difference between RC and RCAC may be important and in the second case it is less so.

The losses found here are within the range of those found by Ravindrarajah and Tam [44], Bairagi et al. [4], Poon et al. [41], Rahal [42] and Etxeberria et al. [11], i.e. 8–24, 6–16, 15, 10 and 20–25 %, respectively.

Concerning the crushing process, the PSC aggregates led to the best performances, with similar trends in the RC and RCAC mixes. In the 20 and 45 MPa families, the use of PSC RA was responsible for performance improvements between 6.7 and 15.1 %, relative to PC RA. In the 65 MPa family, the changes did not reach 5 %. For the same SC the better quality of the PSC RA is explained by the lower mortar content adhered to its surface, because of the extra crushing stage.

Therefore, the difference in performance due to the crushing process should increase from the RA from stronger SC to those from weaker SC. However, the greatest difference occurred for the RA from intermediate strength SC. Two effects may explain this, both leading to small differences in compressive strength between PC RA and PSC RA mixes: for the RA with weaker mortar the PC process may at once eliminate such an important part of the mortar that the next crushing stage has only a small additional effect; for the RA with stronger mortar the second stage of the PSC process may not detach much more of the strongly attached mortar. On the other hand, there were small decreases in the effective w/c ratio of the RCAC mixes with RA from weaker SC when the crushing process was PSC rather than PC. These trends agree with the aggregates properties (Table 2), where the RA subjected to secondary crushing show slightly lower water absorption values.

Even though the Nagataki and Lida [34] study did not intend to replicate the strength of RA SCs, it nonetheless found that the greatest changes induced by the crushing process occurred when weaker aggregates were used. There were differences of 25 % for the 28.3 MPa SC, with the mixes using RA subjected to levels 1 and 3 having values of approximately 60 and 80 MPa, respectively. For better quality SCs the variations were only 6–12 %. Smaller impacts of the crushing process were also reported by Matias et al. [31] and Nagataki et al. [33]. Matias et al. [31] obtained values of 50 and 51 MPa for PC and PSC RA respectively. The greatest variation registered by Nagataki et al. [33] was 4 %, with all RCAC having values in the 44–46 MPa range.

We also found that the change of compressive strength from 7 to 91 days due to the crushing process is very similar. For each target strength, the RC and the RCAC mixes had similar strength gains over time, in agreement with the Rahal's [42] study. However, a steeper strength growth of the RCAC mixes was expected at early ages because of the higher absorption capacity of the adhered mortar and the presence of non-hydrated cement in the RA, which helps increase the strength at early ages but whose effect is lost later on [11, 46].

3.2 Splitting tensile strength

The splitting tensile strength test results are presented in Table 3. This table shows that the splitting tensile strength decreases for the maximum NA by RA replacement ratio. The greatest losses, around 25 %, occur in the weakest mixes. On the other hand, the 45 and 65 MPa mixes showed decreases of around 10 %. These results are also related to the poorer quality of the RA from the first mixes, where rupture occurs in the interface between the original NA and the adhered mortar or through the adhered mortar itself, emphasizing the differences between RC and RCAC mixes. Comparing our findings with those of Rao et al. [43], Tabsh and Abdelfatah [49] and Yang et al. [52], we see that this property always decreases with RA incorporation. The variations are within the same range (14–30 %), thus validating the results obtained now.

Concerning the crushing process, the RC and RCAC mixes show similar behaviour. The trends are also similar for each target strength. The PSC process leads to better results, with improvements around 4–7 % relative to the PC process. This is justified by the reduction of the adhered mortar and consequent decrease of the absorption of the aggregates produced by primary and secondary crushing. Finally, Nagataki et al. [33] obtained similar results, i.e. they found variations linked to the crushing process of around 7 % for high and medium quality aggregates.

3.3 Modulus of elasticity

The results of the modulus of elasticity test are presented in Table 4. They are similar in terms of CRAC within each family: approximately 26, 30 and

Table 4 28-Day modulus of elasticity

Family	f_{cm} 20 MPa			f_{cm} 45 MPa			f_{cm} 65 MPa		
Mix	μ (GPa)	σ (GPa)	Δ (%)	μ (GPa)	σ (GPa)	Δ (%)	μ (GPa)	σ (GPa)	Δ (%)
RCPC	33.3	0.8	0.0	36.7	0.8	0.0	46.9	0.3	0.0
RCPSC	34.7	0.7	4.7	38.3	0.2	4.6	47.6	1.6	1.4
C100LPC	25.2	1.3	0.0	29.5	0.9	0.0	40.3	0.7	0.0
C100LPSC	25.9	0.5	2.8	31.2	0.7	5.9	40.4	0.5	0.3
C100PPC	26.5	0.3	0.0	30.0	0.7	0.0	40.3	0.7	0.0
C100PPSC	27.8	0.5	5.0	31.5	0.7	4.9	40.2	1.5	−0.3

40 GPa, for the low, intermediate and high strength families, respectively. The RC mixes values were 34, 38 and 47 GPa, respectively, i.e. relative losses were 22, 19 and 15 %.

These results are justified by the differences in modulus of elasticity between the cement paste and the NA. These variations might have been more significant if the mixes produced had not aimed at replicating the strength of the RA SCs. The lower decrease of the modulus of elasticity of the 65 MPa mixes (15 %) is justified by the greater strength of the aggregate-matrix interface [35].

Andreu and Miren [3] observed that mixes replicating the strength of the RA SCs, around 100 MPa, showed a drop in the modulus of elasticity of around 10 %. However, for lower quality RA this difference increased to 30 %.

For the various families, it is concluded that, even though the performance losses of the RCAC are very similar in terms of how the aggregates are crushed (variations of 2 %), the mixes with PSC aggregates had slightly better results.

According to Neville [35], this property is related to the stiffness of the coarse aggregates and the mortar, their porosity and binding capacity. Thus, for each concrete family, the PC RA lead to weaker interfaces between the original NA and the old and new cement pastes.

Adjusting the size distribution of the RCAC to comply with the Faury's method (i.e. the aggregates of all the mixes have exactly the same size distribution) may have mitigated the variations caused by the crushing process, not only for the modulus of elasticity but for the other properties, too. Concerning the replacement of fine natural aggregates (FNA) with RA, Solyman [48] concluded this adjustment could indeed slow down the decline of the modulus of elasticity.

3.4 Water absorption by immersion

The results of the water absorption by immersion test are presented in Table 5. These results showed performance losses caused by the incorporation of RA that reached 27, 35 and 50 % for the various target strengths. This property is related to the concrete's open porosity, i.e. the voids that are connected by capillaries of varying diameter. Therefore, considering the greater porosity and absorption of the RA relative to the NA, the RCAC were expected to show higher values for water absorption by immersion. The values in Tables 2 and 5 support this theory. Comparing the values we report here with those found by Levy and Helene [23], Rao et al. [43] and Thomas et al. [51], it is concluded that these researchers found similar absorption increases for the same RA incorporation ratio.

The values with the best mechanical performance, i.e. in descending order the f_{cm} 65 MPa, the f_{cm} 45 MPa and the f_{cm} 20 MPa families, were in fact those with the most satisfactory results for this property, Therefore, the lower target strength mixes had very significant decreases of compacity and increases of voids volume. Satisfactory correlations between water absorption by immersion and compressive strength ($R^2 = 0.71$–0.74) were obtained in the various families, showing that these properties are indeed related.

Better results are found for the mixes produced with PSC aggregates. The performance improvements due to the crushing process were 3–14 %. The behaviour of the RC and RCAC mixes is similar from this point

Table 5 Water absorption by immersion

Family	f_{cm} 20 MPa			f_{cm} 45 MPa			f_{cm} 65 MPa		
Mix	μ (%)	σ (%)	Δ (%)	μ (%)	σ (%)	Δ (%)	μ (%)	σ (%)	Δ (%)
RCPC	15.6	1.0	0.0	14.7	0.4	0.0	9.7	0.2	0.0
RCPSC	13.5	0.4	−13.3	13.8	0.1	−6.1	9.4	0.7	−3.7
C100LPC	19.1	0.2	0.0	18.3	0.2	0.0	14.6	0.1	0.0
C100LPSC	17.7	0.8	−7.2	17.1	0.2	−6.8	13.5	0.1	−7.2
C100PPC	20.0	0.7	0.0	18.7	0.1	0.0	14.5	0.8	0.0
C100PPSC	18.3	0.7	−8.6	16.0	0.3	−14.1	14.1	0.1	−2.6

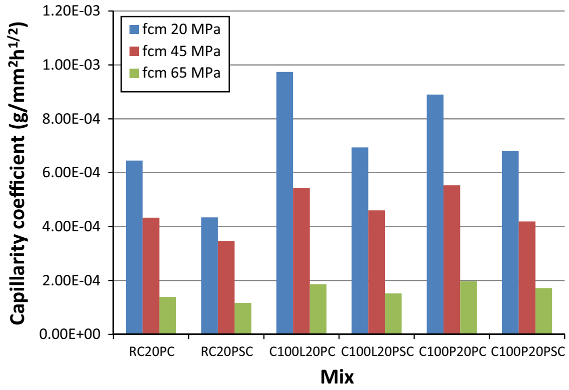

Fig. 1 Capillarity coefficient

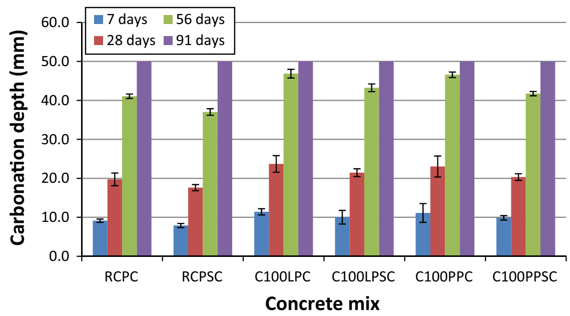

Fig. 2 Carbonation depth of the f_{cm} 20 MPa family

of view. These results may be explained by the lower absorption and adhered mortar content of the PSC aggregates, which also led to lower effective w/c ratios and, therefore, better performance. For the NA, the PSC process indirectly improves the concrete quality because of the rounder shape of the aggregates [31].

3.5 Water absorption by capillarity

The results of the water absorption by capillarity test are presented in Fig. 1. It was found that mixes from the low-strength family and those with PC aggregates have the worst results. The values show that the RA incorporation caused increases in the capillarity coefficient of 38–60, 21–32 and 30–47 %, for the 20, 45 and 65 MPa target strengths, respectively. The different porous structures of the concrete mixes can be explained by the water content of each family and the source of the aggregates because the adhered mortar of each of the RA types is also affected by the different w/c ratios of the SC (different porosity indexes).

In terms of the crushing process, the PSC process led to mixes with less absorption. Regarding the PC process, decreases of 24–33, 15–24 and 13–18 % occurred %, for the 20, 45 and 65 MPa target strengths, respectively. As with the previous property, these results are explained by the lower content of mortar adhered to the RA, which is responsible for the reduction of the absorption capacity of these aggregates.

3.6 Carbonation resistance

The results of the carbonation resistance test are presented in Figs. 2, 3, and 4. As with water absorption, the mechanical properties have a significant correlation with carbonation, i.e. the best carbonation results were those of the highest compressive strength mixes. In the 65 MPa family (Fig. 4) the high scatter registered is essentially due to the fact that the absolute values are very low, which makes slight absolute variations to correspond to big relative changes.

This trend is explained by the lower w/c ratio of the higher target strength families and by their higher

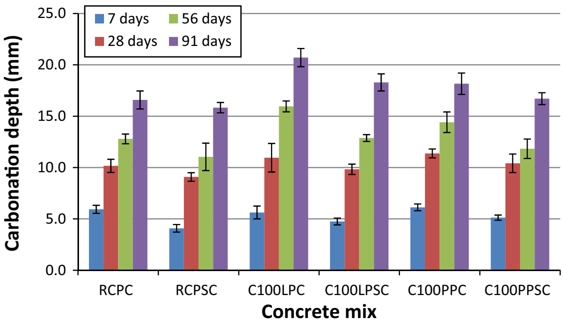

Fig. 3 Carbonation depth of the f_{cm} 45 MPa family

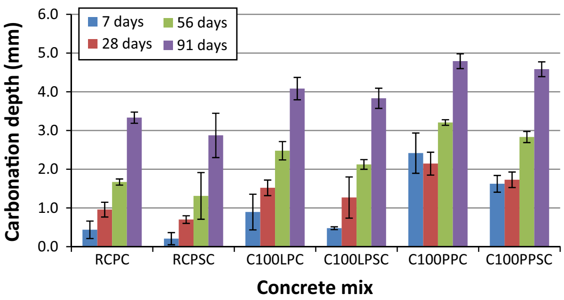

Fig. 4 Carbonation depth of the f_{cm} 65 MPa family

cement content, which increases the alkali reserves available in the hydrated cement matrix and delays of the carbonation progress [32].

Since carbonation is prompted by the reaction of CO_2 with the hydrated cement products, it depends on the concrete quality (internal factors) and the exposure conditions (external factors). In this study the external factors were constant, i.e. all tests were performed under controlled conditions of CO_2, temperature and relative humidity.

Table 6 presents the carbonation coefficient values (k), determined by the equation $x = k\sqrt{t}$, where x is the carbonation depth and t is the time of exposure to the aggressive element. These results show that in the 20 and 45 MPa target strength mixes there were carbonation increases caused by RA incorporation of approximately 15 %, for a replacement ratio of 100 %. Even though the percentile variation is higher in the mixes with 65 MPa target strength (34.2–88.9 %), the differences in absolute terms are small (0.23–0.43 mm/day$^{1/2}$). The worst performance observed for the maximum incorporation of RA is

Table 6 Carbonation coefficients (mm/day$^{1/2}$)

Family	f_{cm} 20 MPa		f_{cm} 45 MPa		f_{cm} 65 MPa	
Mix	(mm/day$^{1/2}$)	Δ (%)	(mm/day$^{1/2}$)	Δ (%)	(mm/day$^{1/2}$)	Δ (%)
RCPC	4.79	0.0	1.78	0.0	0.28	0.0
RCPSC	4.30	−10.2	1.61	−9.6	0.23	−18.0
C100LPC	5.57	0.0	2.14	0.0	0.37	0.0
C100LPSC	5.10	−8.4	1.84	−14.0	0.33	−11.0
C100PPC	5.49	0.0	1.96	0.0	0.48	0.0
C100PPSC	4.90	−10.8	1.74	−11.5	0.43	−10.4

explained by the greater porosity of the adhered mortar. Therefore, and as found in the previous properties, the RCAC mixes show greater absorption and porosity and consequently greater carbonation, leading to greater losses of alkalinity and corrosion liability which compromises their durability.

Concerning the crushing process, better results are again observed for the mixes where PSC aggregates are used. For the 100 % replacement ratio, the carbonation coefficient values in the various target strengths varied between 9 and 18 %, because of the crushing process. The PC process performed worst because it only involves one crushing stage, so the aggregates are more porous and the aggregate–cement paste interface has weak planes, both of which increase the rate of penetration of CO_2 into concrete.

Table 6 shows that at all ages the low-strength family has the highest k values, between 3.0 and 6.2 mm/day$^{1/2}$, followed by the intermediate strength family with 1.7–2.2 mm/day$^{1/2}$ and the high-strength family with 0.1–0.6 mm/day$^{1/2}$. However, it must be stated that applying the model $x = k\sqrt{t}$ has some limitations since the simplifications used in its deduction based on the first Fick's law are not really accurate [50]. The CO_2 diffusion coefficient of a concrete depends on many parameters, and is not constant over the exposure period, as assumed in the deduction of the model. These effects are more pronounced in weaker mixes.

To the best of the authors' knowledge, the literature contains no studies concerning the influence of the crushing process on the carbonation resistance of concrete. Furthermore, overall knowledge about the effects of the replacement of NA with RA on this property is not only scarce, but often contradictory. According to Limbachiya et al. [24], concrete with RA has distinct behaviour, while Levy and Helene [23]

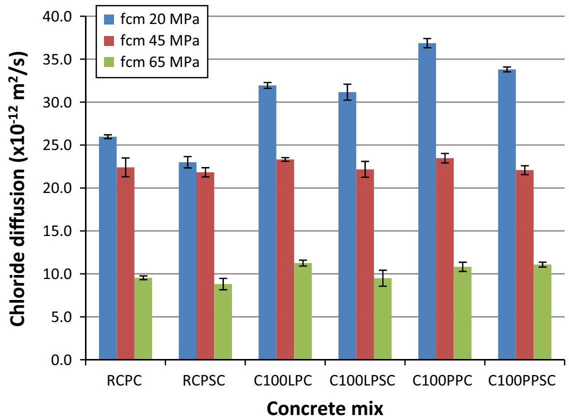

Fig. 5 Chloride diffusion test results at 28 days

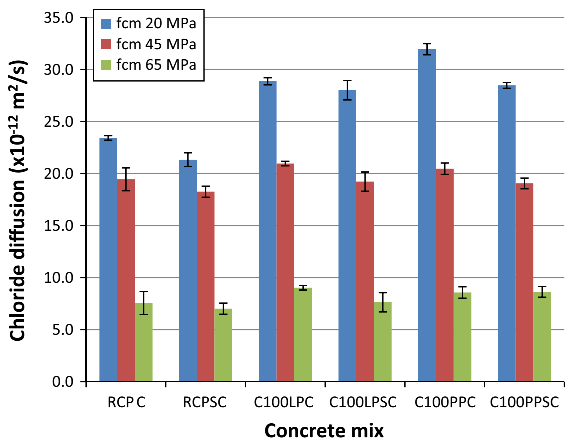

Fig. 6 Chloride diffusion test results at 91 days

found that the carbonation depth decreases when the RA content increases. But Kou and Poon [21] and Amorim et al. [2] found a worsening carbonation performance as the replacement ratio increased.

3.7 Chloride penetration resistance

The results of the chloride diffusion test for all concrete mixes are presented in Figs. 5 (28 days) and 6 (91 days). On average, at 28 days the RC mixes had values of 26.0, 22.4 and 9.5 $\times$ 10^{-12} m^2/s, for the PC process for the 20, 45 and 65 MPa target strengths, respectively. For the PSC process, the RC had the following corresponding values: 23.0, 21.8 and 8.8 $\times$ 10^{-12} m^2/s. For the RCAC the values were 31.9–36.9, 23.3–23.5 and 10.8–11.3 $\times$ 10^{-12} m^2/s (PC process), and 31.2–33.8, 22.1–22.2 and 9.5–11.1 $\times$ 10^{-12} m^2/s (PSC process).

These results show resistance loss due to the replacement of NA with RA. The 20 MPa family had a wide range of values, with variations relative to the RC of 11 $\times$ 10^{-12} m^2/s, for 100 % replacement ratio. For the 45 and 65 MPa concrete mixes, the variations were below 2.3 $\times$ 10^{-12} m^2/s. The absolute values (RCAC vs. RC) of the coefficients are explained by the more permeable nature of the RCAC, linked to the porous adhered mortar and the original RA/SC paste interface. Similar decreases were reported for mixes with 100 % of CRA in the studies of Rao et al. [43], Kou and Poon [21] and Limbachiya et al. [24].

In our research we found that the mixes made with PSC aggregates had better chloride penetration resistance. The increments attributable to the crushing process (PSC vs. PC) reached 3–15 %. The trends were similar in the various target strength families. These results are explained by the smaller number of pores and micro-cracks of the PSC RA, since they have less mortar adhered to their surface. Therefore the microstructure of the interfacial zone is improved, and so is the concrete performance [20].

Finally, as expected, the performance of the mixes tends to improve from 28 to 91 days, with a corresponding decrease of the chloride diffusion coefficients. For the various families there are values between 7.0 and 23.4 $\times$ 10^{-12} m^2/s for the RC and between 7.6 and 32.0 $\times$ 10^{-12} m^2/s for the RCAC.

Kou and Poon [21] reached similar conclusions, i.e. the resistance increases as concrete ages. This was explained by the longer curing time of the specimens which allowed the hydration of more of the cement content, which led to a decrease in the volume of voids.

3.8 Shrinkage

The results of the shrinkage test are presented in Figs. 7, 8, and 9. They show that deformation increases nonlinearly over time, as expected. This parameter increases very quickly in the first days and then tends progressively to stabilize. Modelling of the shrinkage evolution over time has been the object of various studies of greater and smaller complexity and sophistication [5, 6, 9, 18, 45]. Nevertheless, in practice it is usual to use simpler models, whose application is facilitated by equations easy to interpret.

ACI 209.2R [1] proposes a model expressed in Eq. 1, where shrinkage $(\varepsilon_{sh}(t, t_c))$ in a given time

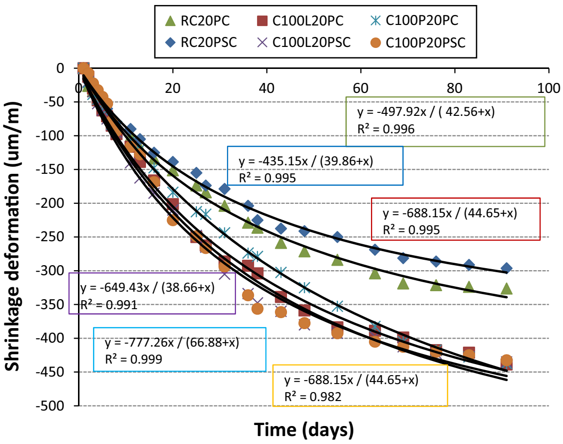

Fig. 7 Shrinkage deformation over time of the f_{cm} 20 MPa family

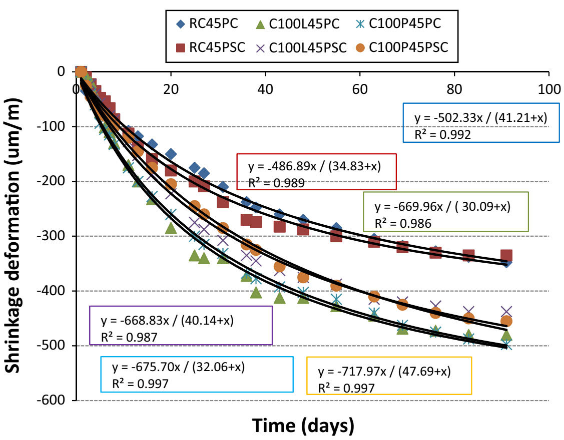

Fig. 8 Shrinkage deformation over time of the f_{cm} 45 MPa family

interval $(t - t_c)$ is a function of experimental parameters A and B.

$$\varepsilon_{sh}(t, t_c) = \frac{(t - t_c)}{B + (t - t_c)} A \quad (1)$$

Figures 7, 8, and 9 show there is a good fitting of the theoretical curve established by ACI 209.2R [1] with the values obtained, demonstrated by the high correlation factors.

It is also clear that shrinkage has a distinct behaviour at early and more advanced ages.

There are 7-day deformation variations of approximately 12, 31 and 21 %, for the f_{cm} 20, f_{cm} 45 and f_{cm} 65 MPa families. At 91 days the corresponding values are 47, 43 and 68 %.

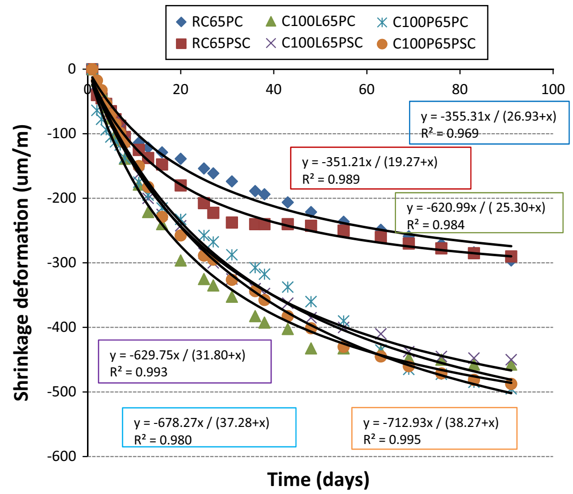

Fig. 9 Shrinkage deformation over time of the f_{cm} 65 MPa family

This irregular trend over time is explained by the internal curing of concrete, triggered by the RA, which compensates for the evaporation water with the water within the RCAC. Therefore, as long as there is water available within the RA, the dimensional variations are relatively small [8].

Regarding the RA's crushing process, PC leads to slightly poorer performances than PSC. This difference is greater at young ages but it tends to significantly decrease over time. This trend may be due to the greater adhered mortar content of the PC RCA which, on the one hand, is more deformable than the original NA [11] and, on the other hand, is still shrinking due to its age (less than 6 months).

4 Conclusions

Aggregates account for three-quarters of the overall concrete volume and therefore their characteristics have a strong influence on its performance. It is thus demanded of the aggregates that they comply with various geometric, physical and chemical properties. Parameters such as shape, size distribution, strength, chemical compatibility with the binder and external actions must be considered.

In this research, with the objective of limiting the number of variables to the analysis of the influence of the aggregates' crushing process, all aggregates were separated by size, thus enabling compositions with exactly the same size distribution.

It is found that the recycled concrete aggregates concrete (RCAC) mixes have higher w/c ratios than the reference concrete (RC) mixes. This trend is noticed equally in mixes made with primary crushing (PC) recycled aggregates (RA) and primary plus secondary crushing (PSC). The w/c ratio increases because of the high absorption of the recycled material and the flatter and more angular shape of the particles obtained by PC.

Therefore, if these particles are used the water content must be increased to keep the concrete workability constant (measured indirectly by slump values within the 125 $\pm$ 15 mm range), as was intended in this programme.

It is concluded that PSC leads to better mechanical performance by the recycled aggregates concrete (RAC) mixes. This trend can be explained by the lower w/c ratio of these PSC mixes, which is one of the factors responsible for the better quality of the interfacial zone between the original natural aggregate (NA) and the surrounding mortar. According to Guedes et al. [15], in the concrete microstructure this zone is responsible for regulating the mechanical strength properties. Moreover, less adhered mortar in the PSC RA will lead to a better mechanical performance of the RAC.

Even though there is a clear decrease in the modulus of elasticity when coarse natural aggregates (CNA) are replaced by coarse recycled concrete aggregates (CRCA), within the same RAC family the variation caused by the crushing process is not significant. This may be because the concrete modulus of elasticity depends on the aggregates' stiffness [35], which is not significantly affected by the crushing process.

It is also concluded that PSC gives better results in all durability-related properties. Furthermore, the incorporation of either PC or PSC RA causes more significant durability-related performance loss than mechanical performance loss.

The increase in water absorption by immersion and by capillarity may be attributed to the high absorption of the RA and the increase of porosity with the total replacement of CNA with CRA, since CRA are substantially more porous. PSC mitigates these drawbacks, relative to PC.

The greater porosity of the matrix of the RCAC mixes may help to accelerate the carbonation process and is more accentuated when PC RA are used because they are more porous and have clearly weak planes in the aggregate–cement paste interface.

The results of chloride penetration resistance obtained with PSC RA are explained by the lower permeability of the mixes made with these aggregates. Furthermore, the trends are similar to the ones found for carbonation, and for the same reasons.

Finally, the mixes made with PSC RA also showed better long-term shrinkage-related performances, because their lower w/c ratio means that less free is water available for drying evaporation.

The RC mixes with PSC NA (natural aggregates only, primary plus secondary crushed aggregates) from each family perform best, which demonstrates the influence of both the aggregate type and the crushing process.

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