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Influence of the use of recycled concrete aggregates from different sources on structural concrete

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HIGHLIGHTS

- Source of recycled concrete aggregates (RCA) highly influences concrete properties.
- RCA from medium/high strength concrete have little influences on concrete properties.
- Lab-sourced RCA are equivalent to equal strength precast elements-sourced RCA.
- This proves the reliability of previous researches made with lab-sourced RCA.

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ABSTRACT

This paper intends to evaluate the capacity of producing concrete with a pre-established performance (in terms of mechanical strength) incorporating recycled concrete aggregates (RCA) from different sources. To this purpose, rejected products from the precasting industry and concrete produced in laboratory were used. The appraisal of the self-replication capacity was made for three strength ranges: 15–25 MPa, 35–45 MPa and 65–75 MPa. The mixes produced tried to replicate the strength of the source concrete (SC) of the RA. Only total (100%) replacement of coarse natural aggregates (CNA) by coarse recycled concrete aggregates (CRCA) was tested. The results show that, both in mechanical and durability terms, there were no significant differences between aggregates from controlled sources and those from precast rejects for the highest levels of the target strength. Furthermore, the performance losses resulting from the RA's incorporation are substantially reduced when used medium or high strength SC's.

1. Introduction

The construction industry is one of the most important economic sectors in most countries, involving a great flux of material and human resources. In the European Union (EU), the sector is responsible for 28% of the employment and 7% of the economic production [1].

In environmental terms, the sector is the third biggest emissary of CO_2 from the industrial cluster [2], with around 10% of all emissions. Furthermore, it is responsible for a very significant use of natural resources, causing societal concerns inherent to their exhaustion.

In order to conciliate economic growth with preservation of the natural heritage, many solutions have been sought. An example of this is European Directive 2008/98/CE, where a target for 2020 was defined: 70% of all construction and demolition waste (CDW) must be recycled.

In this sustainability context, this work tried to establish a sound and innovative basis to allow the precast concrete industry to use without restrictions the waste that it generates. Unlike CDW, which have a wide variety in terms of nature and size, the precast rejects result from certified products, thus decreasing the difficulties in managing them.

Abbreviations: CDW, construction and demolition waste; CNA, coarse natural aggregates; CRCA, coarse recycled concrete aggregates; LC, laboratory-produced concrete (source concrete); NA, natural aggregates; PC, precast elements concrete (source concrete); RA, recycled aggregates; RAC, recycled aggregates concrete; RC, reference concrete; RCA, recycled concrete aggregates; SC, source concrete; T1, primary crushing; T2, primary plus secondary crushing; *w/c* Ratio, water/cement ratio.

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This research comprises an extensive experimental campaign, considering three types of concrete made in laboratory (LC20, LC45 and LC65) and three others from rejects of the precast concrete industry (PC20, PC45 and PC65). The recycled aggregates (RA) were obtained by two distinct crushing processes: primary crushing (T1) and primary plus secondary crushing (T2).

2. State of the art

In the last years the properties of the recycled concrete aggregates (RCA) and the effects of their incorporation in concrete have drawn the attention of various researchers [3–8]. Despite the obvious environmental advantages, this material has distinct properties from those of natural aggregates (NA) that have hindered their regular use.

In physical terms, the main difference between RCA and NA is the mortar adhered to the surface of the original NA in the RCA, which is one of the main reasons for the losses of quality of the RCA relative to the NA.

This is explained by the porosity of the adhered mortar [9–11]. The RCA are characterized by lower particle density, much higher water absorption and lower mechanical strength than the NA [12].

Topçu and Sengel [13] tried to analyse the influence of the incorporation of coarse recycled concrete aggregates (CRCA), by producing concrete mixes with replacement ratios up to 100%. The fresh-state results show, as expected, a decrease of the density and workability caused by the replacement of the NA by CRCA. In the mixes with target strength of 16 MPa (in cylinders) it was found for the maximum replacement ratio that the density decreased from approximately 2500 kg/m^3 to 2350 kg/m^3. In the mixes with target strength of 20 MPa, the reduction was from 2350 kg/m^3 to 2325 kg/m^3. As for workability, the decrease from the reference concrete (RC), without CRCA, and the mix with 100% of CRCA was 15–20%. This was justified by the absorption of the CRCA, around 7%, well above 1.5% for the NA. Limbachiya et al. [14] found that the variation of the particle density of the RA is not as significant as that of the water absorption. They found water absorption values of 5.2% for the RA and 1.7% for the NA (a ratio of approximately three to one). In terms of particle density the RA showed values 7–9% lower than that of the NA.

The variability of the results for the RA in these researchers [13,14] is stressed. There was a 35% difference in the water absorption values between these two studies.

Gonzalez and Etxeberria [15] produced high-performance concrete mixes using RA from various sources. The water absorption of the aggregates from the 40 MPa, 60 MPa and 100 MPa SC's was 5.91%, 4.90% and 3.74%, respectively, i.e., a maximum variation of 58%. In terms of particle density, the variation was only 7%. In order to evaluate the influence of the SC on the performance of concrete, they made mechanical and durability tests. All mixes with RA from the 60 MPa and 100 MPa SC's reached values of compressive strength for the maximum replacement ratio identical to that of the RC (around 100 MPa). However, for the RA from the 40 MPa SC, this only occurred for ratios of 20% and 50%. For the 100% ratio the strength variation between the mixes using RA from the 40 MPa SC and the 100 MPa SC was approximately 20%.

The modulus of elasticity of the mixes with 100% incorporation of RA from the 100 MPa, 60 MPa and 40 MPa SC's were 46 GPa, 40 GPa and 37 GPa, respectively. The RC reached 50 GPa.

Tabsh and Abdelfatah [16] also produced mixes with SC and RA of known (50 MPa and 30 MPa) and unknown strengths. The concrete mixes produced had target strengths of 30 MPa (family 1) and 50 MPa (family 2). In family 1 the strength of the mix made with RA from the 50 MPa SC was the same as that of the RC. However, the mixes with low-strength RA had worse performance: 30% for the mix with RA from the 30 MPa SC and 40% for the one with RA from SC with unknown strength. In family 2 a similar pattern occurred, i.e., the strength losses for the mix with RA from the 30 MPa SC and the one with RA from SC with unknown strength were respectively 10% and 15%. The different strengths in the families were obtained by changing the cement content and maintaining the coarse aggregates' content.

The Gonzalez and Etxeberria [15] study concerning durability showed that the capillary water absorption of the recycled aggregates concrete (RAC) is not always higher than that of the RC. Because of the low *w*/*c* ratio of the mixes produced, the increase of the water content (in weight) in the first 30 min, relative to the oven dried weight of the samples, was less than 0.05%. After 48 h, the weight of all samples increased approximately 0.11% relative to the initial weight. Therefore, the behaviour of all mixes was considered adequate.

Comparing the electric resistivity values obtained with the limit ranges of Langford and Broomfield [17], it was concluded that the mixes generally showed a low to moderate corrosion risk. The best performance occurred in the RAC with 20% RA from the 100 MPa SC (33,000 $\Omega*$cm) and the worst one in the RAC with 100% RA from the 40 MPa SC (10,000 $\Omega*$cm), i.e., the worst results coincided with the highest replacement ratios and the RA from the lowest quality SC.

Gonzalez and Etxeberria [15] show that chloride penetration resistance decreases with the incorporation of RA, with similar trends to those for electric resistivity.

Through these researches, it is found that the RA's quality significantly changes according to the SC, thus influencing the performance of concrete made with them. Silva et al. [18] proposed a classification system of RA based on their physical properties, namely water absorption and oven dried particle density. Based on this system, in another work [19] these authors performed a statistical analysis of over 700 concrete mixes and found that the worst quality aggregates (class D) led to the greatest compressive strength losses. For 100% replacement ratio the RA from classes A–D are responsible for strength losses of 21%, 38%, 54% and 65%, respectively.

The literature shows that even for good quality SC's the incorporation of RA necessarily leads to a greater need of mixing water, i.e., an increase of the *w*/*c* ratio to maintain the workability [20]. Therefore, some researchers resorted to superplasticizers to keep the water content within acceptable limits [6,8,20].

In order to improve the workability of RAC, Poon et al. [21] suggested changing the humidity conditions in which the RA are kept. When RA kept outdoors were used as replacement of NA, the fresh concrete workability and the hardened concrete compressive strength were only slightly changed when compared with those of the RC. However, when the RA's were used in oven dried or saturated surface dry conditions (extreme cases), the workability and compressive strength were more affected.

These results agree with those of Ferreira et al. [22], where the influence of the pre-saturation of CRCA was compared with that of the mixing water compensation method. By analysing the evolution of the water absorption of the CRCA over time, it was found that 70% of its potential value was reached in the first minute and 90% after 5 min.

The authors concluded also that the pre-saturation of the CRCA was slightly detrimental to the concrete mechanical performance and especially the durability performance, by comparison with the mixing water compensation method.

3. Research significance

After an exhaustive collection of information, several contradictory results were found in the results relative to the incorporation of RA. For instance, for 100% replacement of CNA by CRCA, compressive strength decreases between 6% and 25% were registered [21,23–25]. For splitting tensile strength both significant decreases [26] and approximately 9% increases [27] occurred. The greatest variations were observed for the modulus of elasticity, between 11% and 80% losses [26–29]. In terms of durability-related aspects, similar increases of water absorption by immersion (between 33% and 38% [26,30,31]) and by capillarity (between 75% and 85% [32,33]) were registered. A wide range of carbonation resistance values was found, from 3% increases [31] to 67% decreases [32]. Finally, chloride penetration resistance decreases between 10% and 32% were registered [26,32,34].

This paper intends to find explanations for the significant range of values registered. It is believed that this is due to the influence and variability of the SC's from which the RA are obtained. For this purpose, an extensive experimental campaign was developed, including, among others, water absorption by immersion, carbonation resistance and shrinkage tests, which had not been performed so far within the SC influence context [15,16]. Furthermore, this research intends to complete the evaluation matrix of Gonzalez and Etxeberria [15], i.e., evaluate in mechanical and durability terms concrete mixes with the target strength as the SC's from the RA used. Except for one family, these authors only evaluate high-strength mixes using low-strength RA.

4. Experimental programme

4.1. Materials

In the composition of the concrete mixes (Table 1), the following materials were used: fine natural aggregates (river sand), coarse natural aggregates (crushed limestone), coarse recycled concrete aggregates, cement and water. The RA resulted from precast rejects (PC), with target strengths of 20 MPa, 45 MPa and 65 MPa, and laboratory made concrete mixes (LC) with the same target strengths.

The determination of the strength of the PC mixes was made by extracting cores. That process complied with standard EN 12504-1 [35], and the issues concerning shape, size and other requirements specified for the test specimens followed standard EN 12390-1 [36]. The *in situ* strength of cubes was estimated according to the British Standards [37–39] suitable for cores without reinforcement. As for the mixes produced in laboratory, cubes were made and conventionally tested at 28 days. Table 2 provides the results of these tests.

The coarse aggregates (natural and recycled) were subjected to two crushing processes: primary crushing (T1), using an impact crusher (Fig. 1), and primary plus secondary crushing (T2), using an impact crusher followed by a hammer mill (Fig. 2). Process T1 occurred at the Construction Laboratory of Instituto Superior Técnico, while process T2 was performed in a Portuguese stone quarry, reproducing the industrial method that is used to produce NA. Table 3 presents the aggregates' properties.

Both NA and RA were separated in terms of their size, by mechanical sieving, using only the 0–22.4 mm fractions. After sieving, the aggregates were stored in airtight containers to prevent humidity exchanges with the environment. Even though this procedure may be difficult to implement at an industrial scale, it allows the comparison of mixes with exactly the same aggregates' size grading, eliminating this entropic factor from all subsequent results.

Cement CEM I 42.5R was used with contents of 210 kg/m^3, 280 kg/m^3 and 350 kg/m^3 for the mixes with target strengths of 20 MPa, 45 MPa and 65 MPa, respectively. In the mixes with 65 MPa target strength a superplasticizer (SikaPlast 898) was used at 1% per weight of cement, diluted in the mixing water (from the tap).

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

4.2. Preparation of the concrete mixes

The various mixes were designed according to the Faury methodology [40], and they were calibrated to comply with the 125 ± 15 mm slump range. The compositions were designed for the RC mixes. Then they were adapted for the remaining mixes, taking into account the effective *w*/*c* ratios, which tended to increase with the incorporation of RA [22]. Considering the RC mixes, 18 types of concrete mixes were evaluated in terms of their performance.

The 20 MPa, 45 MPa and 65 MPa target strength RC with T1 NA were named RC-20-T1, RC-45-T1 and RC-65-T1. The RAC with T1 RA from the LC and PC source concretes (SC) were named RAC-LC20-T1; RAC-LC45-T1; RAC-LC65-T1; RAC-PC20-T1; RAC-PC45-T1; RAC-PC65-T1. The mixes with T2 aggregates adopted similar designations.

4.3. Tests

To evaluate the mechanical properties of each mix, compressive strength tests were performed according to standard EN 12390-3 [41]. A total of eleven 150 mm cubes were used per mix, subjected to wet curing: 3 at 7 days, 5 at 28 days and 3 at 56 days. At 28 days two 150 mm diameter 300 mm high cylinders per mix were also tested. The method described in standard LNEC E397 [42] was used to determine the modulus of elasticity. This test was made on two 150 mm diameter 300 mm high cylinders per mix, after wet curing.

As for durability, every mix was tested for water absorption by immersion in four 100 mm cubes, according to standard LNEC E394 [43]. The carbonation resistance test was performed at 7, 28, 56 and 91 days, according to standard LNEC E391 [44]. In this accelerated test, 12 specimens per mix were positioned inside a carbonation chamber at a 5% CO_2 concentration. For each testing age and mix type, three of these specimens were split into four parts that were sprayed with a phenolphthalein solution at 1%, in order to measure the carbonation depth. The chloride penetration resistance test, an accelerated migration test in non-stationary regime with procedures adapted from standard NT Build 492 [45], was performed on three specimens per testing age and mix type, according to standard LNEC E463 [46]. Shrinkage was measured according to standard LNEC E398 [47], in two

Table 1
Composition of the mixes tested.

Concrete mix	Fine natural aggregates (kg)	Coarse natural aggregates (kg)	Coarse recycled aggregates (kg)		Cement CEM I 42.5R (kg)	Water (l)	*w*/*c* ratio	Effective *w*/*c* ratio	Superplasticizer (kg)
RC-20-T1	938	958	0		210	180.6	0.86	0.86	0
RC-45-T1	870	956			280	182.0	0.65	0.65	0
RC-65-T1	863	1002			350	143.5	0.41	0.41	3.5
RAC-LC20-T1	929	0	LC20-T1	966	210	214.2	1.02	0.87	0
RAC-LC45-T1	866	0	LC45-T1	940	280	196.0	0.70	0.66	0
RAC-LC65-T1	858	0	LC65-T1	974	350	161.0	0.46	0.42	3.5
RAC-PC20-T1	932	0	PF20-T1	970	210	212.1	1.01	0.86	0
RAC-PC45-T1	870	0	PF45-T1	970	280	193.2	0.69	0.65	0
RAC-PC65-T1	858	0	PF65-T1	1029	350	157.5	0.45	0.42	3.5
RC-20-T2	946	1019	0		210	170.1	0.81	0.81	0
RC-45-T2	877	1011			280	176.4	0.63	0.63	0
RC-65-T2	868	1057			350	140.0	0.40	0.40	3.5
RAC-LC20-T2	938	0	LC20-T2	953	210	207.9	0.99	0.84	0
RAC-LC45-T2	877	0	LC45-T2	988	280	187.6	0.67	0.63	0
RAC-LC65-T2	868	0	LC65-T2	982	350	150.5	0.43	0.40	3.5
RAC-PC20-T2	943	0	PF20-T2	977	210	205.8	0.98	0.82	0
RAC-PC45-T2	873	0	PF45-T2	962	280	190.4	0.68	0.64	0
RAC-PC65-T2	858	0	PF65-T2	1016	350	157.5	0.45	0.42	3.5

Table 2
Properties of the source concrete mixes.

Type	Slump (mm)	Density (fresh-state) (kg/m^3)	Compressive strength (MPa)	Water absorption by immersion (%)
LC20	95	2388.4	21.6	12.7
LC45	150	2370.3	37.2	13.6
LC65	200	2370.6	73.2	10.3
PC20	–	–	21.4	–
PC45	–	–	41.0	–
PC65	–	–	74.5	–

Fig. 1. Primary crushing equipment: impact crusher.

Fig. 2. Primary plus secondary crushing equipment: impact crusher + hammer mill.

0.15 × 0.15 × 0.60 m^3 specimens per mix, subjected to controlled temperature and humidity conditions (RH of 60% and temperature of 20 °C). The length variations were measured at 91 days.

5. Results and discussions

5.1. Compressive strength in cubes

The compressive strength (at 7, 28 and 56 days) results of all the mixes, organized by target strength families, are presented in Figs. 3–5.

At 28 days, the RC from the 20 MPa, 45 MPa and 65 MPa's families reached values of 23.9–27.5 MPa, 38.7–42.4 MPa and 71.1–72.3 MPa, respectively. The compressive strength of the low-strength RAC using LC RA varied between 19.7 MPa and 21.0 MPa, and the ones using PC RA between 21.8 MPa and 23.6 MPa. In the intermediate strength family the RAC using LC RA and PC RA reached values of 35.7–41.1 MPa and 36.1–39.7 MPa, respectively. Finally, in the high-strength family the compressive strength varied from 66.5 MPa to 70.2 MPa, for both RA SC's.

The replacement of CNA by CRCA causes compressive strength losses relative to the RC of 9.0–17.7%, 3.2–7.6% and 3.0–8.1% in the low, intermediate and high target strength families, respectively (Figs. 6 and 7). The losses are similar at 7, 28 and 56 days and are due to the mortar adhered to the surface of the original NA within the RA, responsible for increasing the aggregates' absorption and decreasing their particle density [48,49].

The greatest loss occurs in the 20 MPa's family. This may be justified by the low quality of the RA used. In this research, the mixes intended to replicate the strength class of the SC. Therefore in the 20 MPa's family the lower quality RA's were used, contrarily to the 65 MPa's family where the best RA's were used. However, within the families there were differences in the failure mechanisms of the specimens under compression. In fact, the structure of the RCA is more complex than that of the RC. In the RC there is only one type of Interfacial Transition Zone (ITZ), i.e., between the

Table 3
Properties of the aggregates.

Aggregates	Crushing process	Name	Particle density (kg/m^3)			Water absorption (%)
			Apparent	Oven dried	Saturated surface dry	
Coarse	T1	NA-T1	2590.5	2503.7	2537.2	1.3
		LC20-T1	2760.6	2275.0	2451.2	7.8
		LC45-T1	2640.8	2231.8	2386.6	6.9
		LC65-T1	2504.7	2266.3	2361.5	4.2
		PC20-T1	2754.9	2283.9	2455.9	7.5
		PC45-T1	2708.8	2306.4	2454.9	6.4
		PC65-T1	2664.3	2395.1	2496.1	4.2
	T2	NA-T2	2708.8	2639.1	2664.8	1.0
		LC20-T2	2686.3	2231.4	2400.8	7.6
		LC45-T2	2701.7	2356.1	2484.0	5.4
		LC65-T2	2484.9	2280.4	2362.7	3.6
		PC20-T2	2719.8	2288.1	2446.8	6.9
		PC45-T2	2686.6	2322.4	2458	5.8
		PC65-T2	2614.1	2371.6	2464.3	3.9
Fine	–	FNA	2637.8	2625.0	2630.0	0.1

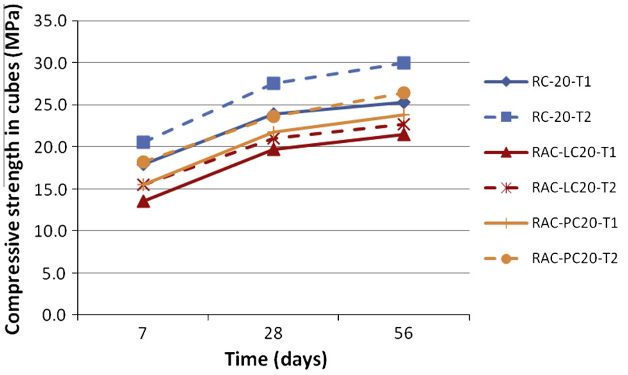

Fig. 3. Compressive strength in cubes at 7, 28 and 56 days of the 20 MPa's family.

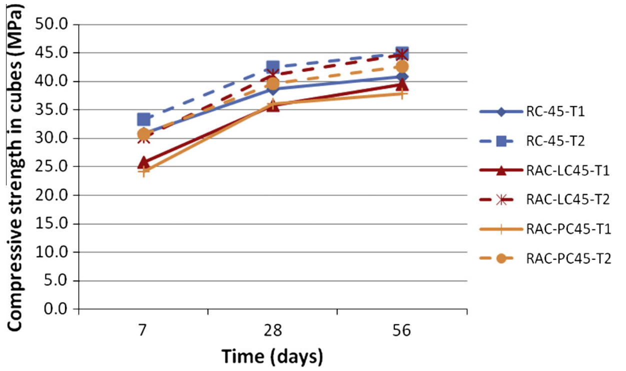

Fig. 4. Compressive strength in cubes at 7, 28 and 56 days of the 45 MPa's family.

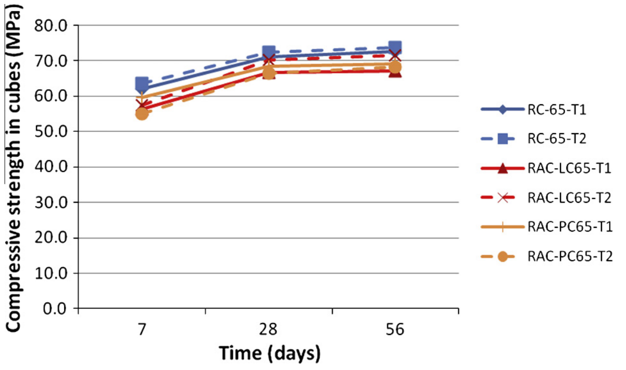

Fig. 5. Compressive strength in cubes at 7, 28 and 56 days of the 65 MPa's family.

CNA and the cement paste, while in the RCA there are two: one between the RA and the new cement paste and the other between the RA and the adhered mortar from the SC. These frontier zones significantly condition the concrete's performance [7].

Taking into account these differences in the concrete's microstructure, the greater strength losses in the 20 MPa's family seem to be caused by the fact that failure of the RAC mixes occurs in the ITZ between the original NA and the adhered mortar or through the mortar itself, contrarily to what happens in RAC mixes with RA from better quality SC's, where the weakest zone is the interface between the RA and the new paste.

Tabsh and Abdelfatah [16] obtained similar results. When they tried to replicate the SC's strength of 30 MPa, the RAC exhibited a loss of performance relative to the RC of approximately 30%. However, when the replicated strength was 50 MPa, the RAC showed a performance similar to that of the RC, with a loss of only 2%.

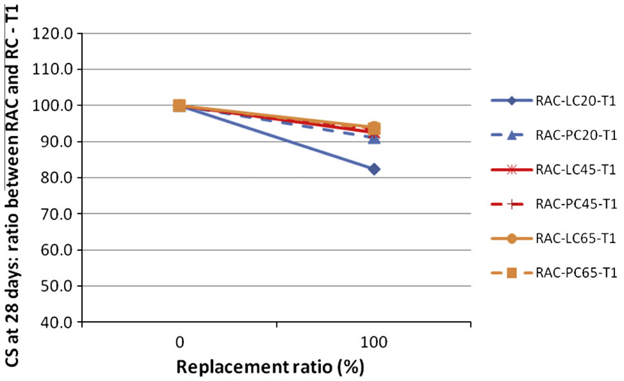

Fig. 6. Compressive strength at 28 days: ratio between RAC and RC (T1 crushing process).

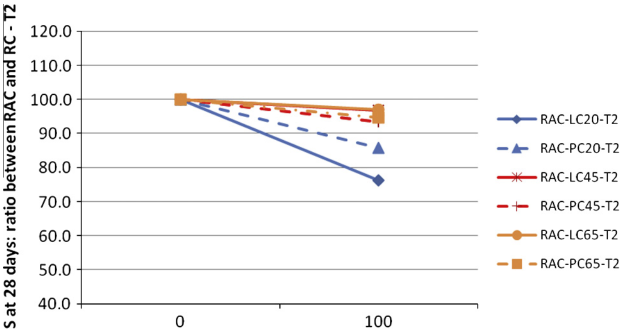

Fig. 7. Compressive strength at 28 days: ratio between RAC and RC (T2 crushing process).

Gonzalez and Etxeberria [15] also concluded that RCA mixes with RA from a 100 MPa SC reached identical values to the RC (around 100 MPa), even for total aggregates' replacement.

In our work it is found that for the same strength level the variations due to the use of LC or PC RA are higher in weaker mixes. Maximum differences reach 11%, 4% and 6% for the low, intermediate and high strength families, respectively. Therefore, for stronger SC's, the various mixes show more similar results, without significant differences caused by RA from different crushing processes (LC and PC). This may be related with the fact that the failure of the weaker mixes is different and may occur in two distinct zones, as explained above.

Finally, looking at the evolution of this property over time, it is concluded that strength develops faster in the better performance mixes. All mixes from the 65 MPa's family have at 7 days more than 80% of the 28-day strength, while in the lower strength family this ratio varies from 65% to 71%. On the other hand, it is also found that the greatest increase of the ultimate stress occurs in the first 7 days, reaching on average 67.4%, 69.7% and 83.7% of the 56-day ultimate stress for the 20 MPa, 45 MPa and 65 MPa's families, respectively.

5.2. Compressive strength in cylinders

The 28-day compressive strength in cylinders of the mixes is presented in Figs. 8 and 9. It is found that the RC's reach values of 19.6–22.8 MPa, 29.7–33.1 MPa and 58.0–59.4 MPa for the low, intermediate and high strength families, respectively. In the low strength RAC's the values are 14.7–16.9 MPa when LC RA are used and 16.3–18.7 MPa when PC RA are used. The corresponding values in the intermediate strength RAC's are 28.2–32.9 MPa (LC RA) and

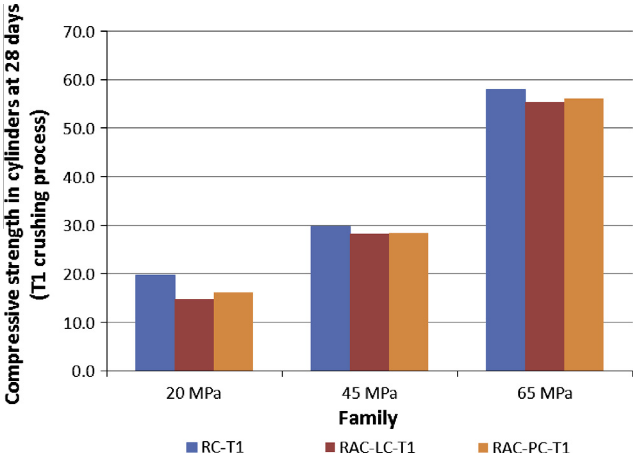

Fig. 8. Compressive strength in cylinders at 28 days (T1 crushing process).

28.5–31.5 MPa (PC RA). Finally, in the high strength family the corresponding values are 55.3–58.5 MPa (LC RA) and 56.1–55.0 MPa (PC RA).

In the 20 MPa's family, there are decreases of around 20% due to the incorporation of RA, while in the 45 MPa and 65 MPa's families the variation is only 5%. These results are justified by the same reasons as for cubes, i.e., the adhered mortar of the RA and the failure mechanism of the weaker mixes being different.

In the literature, there are strength losses between 3% and 20% in mixes with CNA replaced by CRCA [50–52]. These differences agree with the ones found here, demonstrating that the performance of RCA depends on various factors, namely the SC's quality.

As for the differences caused by using LC RA or PC RA, they reach 10% in the weaker mixes and 5% in the intermediate and high target strength mixes, again due to the differences in the failure mechanism.

When establishing a relationship between the cylinder and the cube strengths, it is found that at 28 days the ultimate stress in cylinders is on average 79.0%, 78.7% and 82.4% of the cubes stress, for the 20 MPa, 45 MPa and 65 MPa's families, respectively.

5.3. Modulus of elasticity

The results of the modulus of elasticity test are presented in Figs. 10 and 11. The RC registered values of 33.3–34.7 GPa, 36.7–38.3 GPa and 46.9–47.6 GPa for the 20 MPa, 45 MPa and 65 MPa's families, respectively. The RAC showed corresponding values of 25.2–25.9 GPa, 29.5–31.2 GPa and 40.3–40.4 GPa (for LC RA) and 26.5–27.8 GPa, 30.0–31.5 GPa and 40.2–40.3 GPa (for PC RA).

It is found that for an integral replacement of CNA by CRCA there were losses relative to the RC of 22%, 18% and 15% for the 20 MPa, 45 MPa and 65 MPa's families, respectively (Figs. 12 and 13). This is explained by the greater deformability of the RA

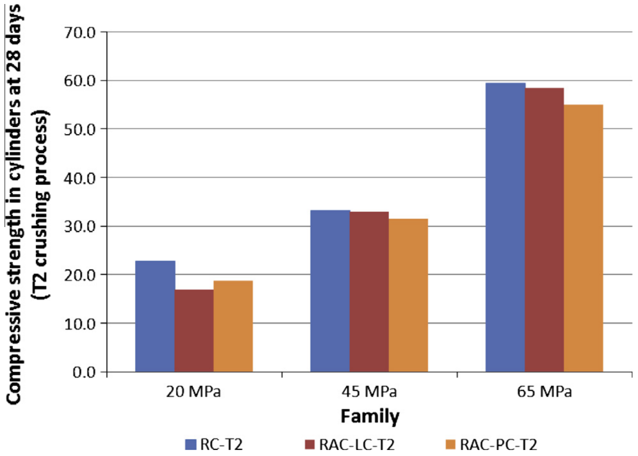

Fig. 9. Compressive strength in cylinders at 28 days (T2 crushing process).

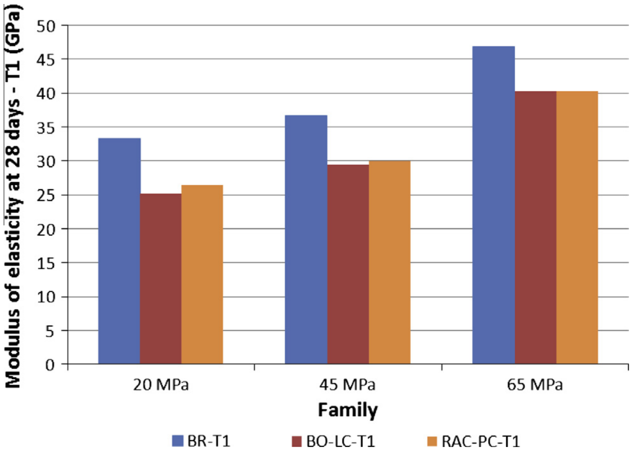

Fig. 10. Modulus of elasticity at 28 days (T1 crushing process).

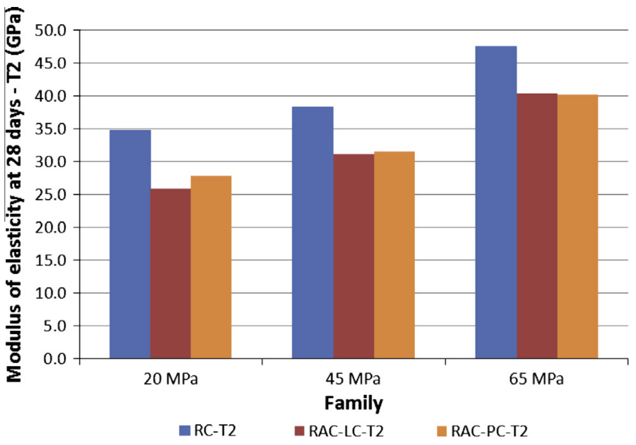

Fig. 11. Modulus of elasticity at 28 days (T2 crushing process).

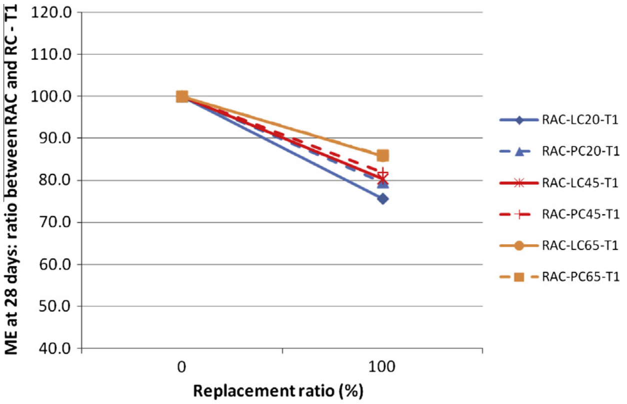

Fig. 12. Modulus of elasticity at 28 days: ratio between RAC and RC (T1 crushing process).

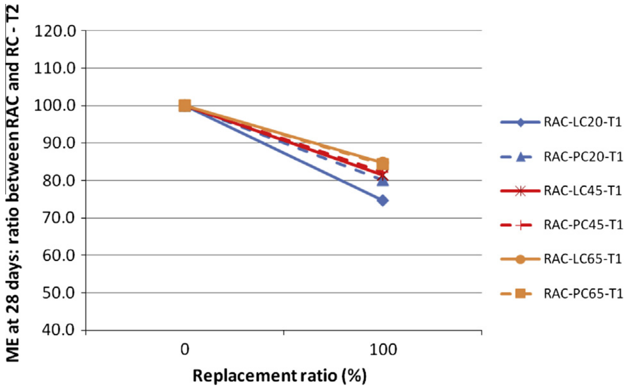

Fig. 13. Modulus of elasticity at 28 days: ratio between RAC and RC (T2 crushing process).

relative to the NA, caused by their lower modulus of elasticity [53] and by the strong dependence of the modulus of elasticity of concrete on the modulus of elasticity of the aggregates [54].

Similar losses, around 20%, were found in the study of Ajdukiewicz and Kliszczewicz [55]. Their results were explained by the lower mechanical characteristics of the RA *versus* the NA.

The lower losses found in the mixes with the best RA (around 15%) can be justified by the fact that these RA tend to have a stiffness much closer to that of the NA and therefore their influence on the modulus of elasticity of concrete (which depends on the stiffness of the paste and of the aggregates) is attenuated.

On the other hand, the worst quality RA's have markedly greater porosity and water absorption capacity, leading to lower stiffness of concrete.

Gonzalez and Etxeberria [15] also observed lower modulus of elasticity losses for high strength RA. They registered losses of around 11% when replicating the strength of a 100 MPa SC.

There were no significant differences caused by the use of LC RA instead of PC RA, in the medium and high strength families. However, for the weaker mixes, a maximum variation of around 6% is noticed. This is caused by the use of low quality RA, leading to greater variability in terms of their stiffness.

5.4. Water absorption by immersion

The results of the water absorption by immersion test presented in Table 4 comprise the average values (μ), the standard deviation (σ) and the variations relative to the incorporation of RA from several sources (Δ). The RC register values of 13.5–15.6%, 13.8–14.7% and 9.4–9.7% for the low, intermediate and high strength families, respectively. The RAC with LC RA showed corresponding values of 17.7–19.1%, 17.1–18.3% and 13.5–14.6% while those with PC RA had 18.3–20.0%, 16.0–18.7% and 14.1–14.5%. The incorporation of RA is responsible for the worse performance relative to the RC, namely absorption increases between 23% and 50% for the various target strengths. These results may be justified by the adhered mortar in the RA, responsible for their greater porosity and water absorption that strongly conditions the open porosity of the RAC. In this case the RA's absorption can be as high as 7 times that of the NA. Table 3 shows that, according to the SC, the RA's water absorption varied between 3.9% and 7.6%. These results compare well with those from the Thomas et al. [30] study.

According to Poon et al. [5], for a medium strength SC, the pores in the RA's adhered mortar fall essentially in the 0.01–1 μm range. However, in RA from high-performance concrete most pores' size is below 0.1 μm. Therefore, the best performance of the high-quality RA is achieved through a finer pores distribution.

The performance variations caused by the incorporation of RA from different crushing processes (LC or PC) did not exceed 6%, in all concrete families.

5.5. Chloride penetration resistance

The results of the chloride diffusion test for all mixes are presented in Table 5 (28 and 91 days). The 28-day diffusion coefficients of the RC were 23.0–26.0, 21.8–22.4 and 8.8–9.5 $\times 10^{-12}$ m^2/s for the low, intermediate and high strength families, respectively. The corresponding values of the RCA were 31.2–31.9, 22.2–23.3 and 9.5–11.3 $\times 10^{-12}$ m^2/s, for LC RA, and 33.8–36.9, 22.1–23.5 and 10.8–11.1 $\times 10^{-12}$ m^2/s, for PC RA.

The lower values always occurred in the RC's. The 20 MPa's family registered a wide range of values, with variations relative to the RC up to 11 $\times 10^{-12}$ m^2/s (100% replacement ratio). In the 45 MPa and 65 MPa's families, these variations did not exceed 2.3 $\times 10^{-12}$ m^2/s. The resistance losses due to the replacement of CNA by CRCA are justified by more permeable nature of the RAC, caused by the adhered mortar in the RA. As referred this feature of the RA leads to a more complex structure of the RCA than that of the RC. Thus, improving the microstructure of the transition zones may improve the concrete performance, since they contain a large number of pores and micro-cracks [56]. The greater chloride penetration rate shown by the 20 MPa's family is explained by the paste/aggregate interfacial effects and the existence of more internal cracks in the RA [57]. Another factor that may explain this situation is the size of the cracks of the weaker RA. Xiao et al. [58] concluded that the width of the cracks in the old adhered mortar is correlated with the chloride diffusion coefficient, i.e., the diffusivity rises as the width of the cracks increases.

It is thus concluded that, when producing concrete with low *w*/*c* ratios and with RA of average/high quality, it is possible that RCA show a performance similar to that of the RC. Gonzalez and Etxeberria [15] reached similar conclusions when trying to replicate a SC with compressive strength of 100 MPa. The mixes made with 20%, 50% and even 100% of CRCA from that SC fell very near the limit between very low and low corrosion risk, according to standard ASTM C1202 [59]. On the other hand, the resistance of mixes using RA from 40 MPa and 100 MPa differed approximately 20%, for the maximum replacement ratio.

Identical conclusions were registered by Limbachiya et al. [14], who observed for the strength range under analysis (50 MPa,

Table 4
Water absorption by immersion.

Family	20 MPa			45 MPa			65 MPa		
Concrete mix	μ (%)	σ (%)	Δ (%)	μ (%)	σ (%)	Δ (%)	μ (%)	σ (%)	Δ (%)
RC-T1	15.6	1.0	0.0	14.7	0.4	0.0	9.7	0.2	0.0
RC-T2	13.5	0.4	0.0	13.8	0.1	0.0	9.4	0.7	0.0
RAC-LC-T1	19.1	0.2	22.8	18.3	0.2	24.8	14.6	0.1	50.4
RAC-LC-T2	17.7	0.8	31.4	17.1	0.2	24.0	13.5	0.1	44.9
RAC-PC-T1	20.0	0.7	28.4	18.7	0.1	27.0	14.5	0.8	49.4
RAC-PC-T2	18.3	0.7	35.4	16.0	0.3	16.3	14.1	0.1	51.0

Table 5
Chloride diffusion results at 28 and 91 days.

Concrete mix	Family	20 MPa			45 MPa			65 MPa		
	Age (days)	μ (%)	σ (%)	Δ (%)	μ (%)	σ (%)	Δ (%)	μ (%)	σ (%)	Δ (%)
RC-T1	28	26.0	0.2	0.0	22.4	0.9	0.0	9.5	0.2	0.0
	91	23.4	0.6	0.0	19.5	0.9	0.0	7.6	1.1	0.0
RC-T2	28	23.0	0.4	0.0	21.8	1.0	0.0	8.8	0.7	0.0
	91	21.3	0.5	0.0	18.3	0.7	0.0	7.0	0.5	0.0
RAC-LC-T1	28	31.9	1.2	23.0	23.3	0.2	4.1	11.3	0.3	17.9
	91	28.9	3.1	23.2	21.0	1.7	7.8	9.0	0.2	19.5
RAC-LC-T2	28	31.2	1.9	35.5	22.2	1.1	1.6	9.5	0.9	7.8
	91	28.0	1.5	31.3	19.2	1.1	5.3	7.6	0.9	8.8
RAC-PC-T1	28	36.9	0.1	41.9	23.5	0.3	4.8	10.8	0.5	13.4
	91	32.0	0.9	36.4	20.5	0.5	5.2	8.6	0.5	13.4
RAC-PC-T2	28	33.8	1.9	47.0	22.1	1.7	1.1	11.1	0.3	25.7
	91	28.5	0.5	33.5	19.1	0.6	4.4	8.6	0.5	23.1

Table 6
Carbonation depth at 7, 28, 56 and 91 days.

Concrete mix	Family	20 MPa			45 MPa			65 MPa		
	Age (days)	μ (%)	σ (%)	Δ (%)	μ (%)	σ (%)	Δ (%)	μ (%)	σ (%)	Δ (%)
RC-T1	7	9.1	0.4	0.0	5.9	0.4	0.0	0.4	0.2	0.0
	28	19.8	1.6	0.0	10.2	0.6	0.0	1.0	0.2	0.0
	56	41.1	0.6	0.0	12.8	0.5	0.0	1.7	0.1	0.0
	91	50.0	0.0	0.0	16.6	0.9	0.0	3.3	0.1	0.0
RC-T2	7	7.9	0.5	0.0	4.1	0.4	0.0	0.2	0.2	0.0
	28	17.6	0.8	0.0	9.1	0.4	0.0	0.7	0.1	0.0
	56	37.0	0.8	0.0	11.0	1.3	0.0	1.3	0.6	0.0
	91	50.0	0.0	0.0	15.8	0.5	0.0	2.9	0.6	0.0
RAC-LC-T1	7	11.4	0.8	24.9	5.6	0.6	-5.3	0.9	0.5	104.8
	28	23.7	2.1	20.0	11.0	1.4	7.8	1.5	0.2	58.7
	56	46.9	1.1	14.1	16.0	0.5	24.8	2.5	0.2	48.4
	91	50.0	0.0	0.0	20.7	0.9	24.9	4.1	0.3	22.5
RAC-LC-T2	7	10.0	1.8	27.1	4.8	0.3	16.3	0.5	0.0	130.0
	28	21.5	1.0	21.7	9.8	0.5	8.3	1.3	0.5	81.2
	56	43.3	1.0	16.8	12.9	0.3	16.6	2.1	0.1	61.9
	91	50.0	0.0	0.0	18.3	0.8	15.5	3.8	0.3	33.3
RAC-PC-T1	7	11.1	2.4	21.7	6.1	0.3	3.2	2.4	0.5	452.4
	28	23.0	2.7	16.7	11.4	0.4	11.9	2.1	0.3	123.9
	56	46.6	0.7	13.4	14.4	1.0	12.7	3.2	0.1	92.0
	91	50.0	0.0	0.0	18.2	1.0	9.5	4.8	0.2	43.8
RAC-PC-T2	7	9.9	0.6	25.0	5.1	0.3	25.5	1.6	0.2	680.0
	28	20.3	0.9	15.4	10.4	0.9	14.7	1.7	0.2	146.5
	56	41.8	0.5	12.7	11.8	0.9	7.2	2.8	0.1	115.9
	91	50.0	0.0	0.0	16.7	0.6	5.5	4.6	0.2	59.4

Table 7
Carbonation coefficient.

Family	20 MPa		45 MPa		65 MPa	
Concrete mix	μ (%)	Δ (%)	μ (%)	Δ (%)	μ (%)	Δ (%)
RC-T1	4.8	0.0	1.8	0.0	0.3	0.0
RC-T2	4.3	0.0	1.6	0.0	0.2	0.0
RAC-LC-T1	5.6	16.1	2.1	20.5	0.4	34.2
RAC-LC-T2	5.1	18.5	1.8	14.7	0.3	45.6
RAC-PC-T1	5.5	14.6	2.0	10.6	0.5	72.9
RAC-PC-T2	4.9	14.0	1.7	8.2	0.4	88.9

60 MPa and 70 MPa) that the use of 100% of CRCA did not have any negative influence on chlorides' diffusion.

There are no significant differences in terms of chloride diffusion coefficient, in absolute terms and for the various families, between RAC mixes using LC RA and PC RA.

At 91 days, the coefficients decreased approximately 12% (relative to 28 days) for the 20 MPa and 45 MPa's families, and 20% for the 65 MPa's family. This may be explained by the greater curing time of the specimens, responsible for hydrating greater cement contents and thus decreasing the voids volume. However, according to standard LNEC E-465, more significant decreases between 28 and 91 days, around 40%, were expected.

5.6. Carbonation resistance

The average results of the carbonation resistance test are presented in Table 6. The carbonation coefficients were also determined using the following equation (Table 7):

$$x = k\sqrt{t} \tag{1}$$

where x is the carbonation depth (mm), k is the carbonation coefficient and t is time (days).

The carbonation depth increased with the replacement of NA by RA and with the decrease of the concrete's target strength. This is due to the lower w/c ratio of the higher strength families but also to their greater cement content, leading to a greater alkaline reserve available in the hydrated cement paste matrix. At 56 days, carbonations depths between 37.0 mm and 46.9 mm were registered for the low strength family, between 11.0 and 14.4 mm for the intermediate strength family and between 1.7 mm and 3.2 mm for the high strength family. At 91 days, the carbonation had already reached the maximum depth of the low strength family specimens (50 mm).

The carbonation coefficients of the RC were 4.30–4.79, 1.61–1.78 and 0.23–0.28 mm/day$^{1/2}$, for the 20 MPa, 45 MPa and 65 MPa's families, respectively. In the low strength family (Table 7), the RAC coefficients varied between 5.10 and 5.57 mm/day$^{1/2}$ (when using LC RA) and between 4.90 and 5.49 mm/day$^{1/2}$ (when using PC RA). In the intermediate strength family (Table 7), the corresponding ranges were 1.84–2.14 mm/day$^{1/2}$ (for LC RA) and 1.74–1.96 mm/day$^{1/2}$ (for PC RA). Finally, in the high strength family (Table 7), the corresponding ranges were 0.33–0.37 mm/day$^{1/2}$ (for LC RA) and 0.43–0.48 mm/day$^{1/2}$ (for PC RA). The carbonation depth increased approximately 15% due to full incorporation of RA in the 20 MPa and 45 MPa's families. In the 65 MPa's family, even though there is a greater percentage variation (34.2–88.9%), the difference in absolute terms is very small (0.23–0.43 mm/day$^{1/2}$).

The performance losses of the RAC are due to the greater porosity of these mixes. According to Kou and Poon [60], the total volume and average pores diameter increased with the RA incorporation. Therefore and as expected, the carbonation resistance follows a similar trend to those of the water absorption and chloride penetration.

The values obtained here are similar to those of Amorim et al. [4]. In that study there was an increase in carbonation of approximately 20% for full aggregates' replacement. The performance losses were justified by the RCA's porosity.

The maximum difference linked to the use of RA from different crushing processes (LC *versus* PC) was around 6% in the low and intermediate strength families. In the high strength mixes, because the absolute values were so low, more significant relative variations were observed, which do not correspond to established trends.

5.7. Shrinkage

The results of the shrinkage test are presented in Fig. 14. It is found that the deformation increases non-linearly over time, i.e., there is a rapid growth in the early days, and from then on there is a stabilizing trend.

At young ages (7 days) the RAC had maximum deformation increases relative to the RC of 12%, 31% and 21% for low, intermediate and high target strengths, while for older ages (91 days) these increases were 47%, 43% and 68%, respectively.

These values show that shrinkage is one of the properties most affected by CRCA incorporation. The worst RAC results meet expectations since this type of concrete, by having a lower internal restriction due to the RA's lesser modulus of elasticity, allows greater shrinkage deformations. Therefore, the greater voids content caused by the adhered mortar in the RA seems to lead to an increase of deformability and shrinkage of concrete.

The higher increases at 91 days of the RAC relative to the RC are justified by a phenomenon of internal curing promoted by the CRCA that allows the compensation of the evaporation water by water stored inside them. Therefore, as long as there is water available in the RA, the dimensional variations are relatively small [4].

Another important conclusion from this test is that, unlike in the other properties, the replacement of NA by RA of different SC's (i.e., different strength) has no significant consequences in

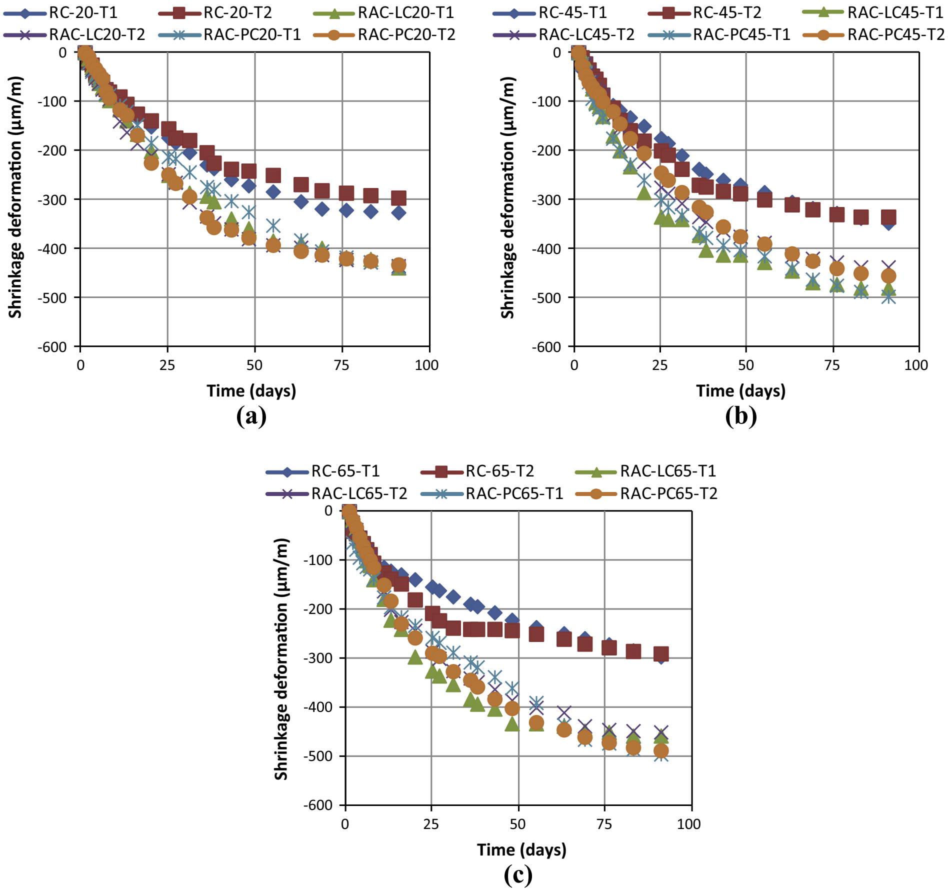

Fig. 14. Shrinkage deformation over time of the: (a) 20 MPa's family; (b) 45 MPa's family; and (c) 65 MPa's family.

absolute terms. This means that shrinkage seems to be conditioned almost exclusively by the incorporation of RA, independently of the quality of the SC and with little influence of the concrete composition.

Ajdukiewicz and Kliszczewicz [55] also found a significant influence of the RA incorporation: increases of 40% relative to the RC. Sagoe-Crentsil et al. [61] found increases of around 30% and justified these results with the lower restricting capacity of the RA.

6. Conclusions

From the results obtained in concrete mixes with target strengths of 20 MPa, 45 MPa and 65 MPa, where reference mixes were compared with others with CRCA from various sources and the objective was to replicate in the new mixes the strength of the source concretes, the following conclusions can be drawn:

- The compressive strength in cubes decreases around 8% for the 45 MPa and 65 MPa target strengths due to the incorporation of RA; for the 20 MPa target strength, the decrease is 20%; furthermore, for intermediate and high strength SC's, the influence of using laboratory-made SC's or precast-elements SC's is not significant.
- Similar trends were found for compressive strength in cylinders, with 3% losses for the 45 MPa and 65 MPa mixes and 14% for the 20 MPa mixes; the ultimate stress in cylinders is on average 79.0%, 78.7% and 82.4% that of cubes, for the 20 MPa, 45 MPa and 65 MPa target strength mixes, respectively.
- The modulus of elasticity of the RCA showed decreases of approximately 22%, 18% and 15% for the 20 MPa, 45 MPa and 65 MPa's families, respectively; the use of RA from SC's with low mechanical properties emphasizes the negative effects of the RA.
- The incorporation of CRCA is responsible for increases of the concrete's water absorption by immersion between 23% and 49%, due to the high water absorption of the RA; the quality of the SC plays a determinant role, leading to water absorption values of the RA ranging between 3.9% and 7.6%.
- The variability of chlorides diffusion within each mix is greater in the 20 MPa target strength mixes, which is also where the greatest performance loss at 91 days, around 30%, is found; however, in the 65 MPa mixes, where RA from high-quality SC were used, the performance is comparable to that of the RC; this trend agrees with those found in the mechanical properties.
- An identical situation occurs in the carbonation resistance; at 28 days the incorporation of RA represents a depth increment of approximately 18% and 10%, for the low and medium target strength families; for the 65 MPO target strength, higher relative increases occurred, but only because the absolute values were very small.
- Shrinkage is one of the properties most impaired by the incorporation of CRCA; at 91 days there were increases of 47%, 43% and 68%, relative to the RC; as for the SC's influence, there were no significant differences in the mixes using different RA, unlike in all the other properties; this lack of trend was not expected and needs to be further investigated.
- Except for shrinkage, the 65 MPa target strength mixes using RA from high-strength SC has a performance similar to that of the corresponding RC, a high-performance concrete.

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