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Influence of Recycled Precast Concrete Aggregate on Durability of Concrete's Physical Processes

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Featured Application: The results of this research have been followed for the use of recycled concrete at the ARTEPREF precast plant (Spain).

Abstract: The research presented in this article analysed the influence of incorporating precast concrete waste as an alternative to coarse aggregate in self-compacting concrete to generate new precast elements. The experimental study involved the characterization of recycled aggregate and the design of the mix of the new self-compacting concrete (SCC). The experimental study evaluates the physical processes that affect the durability of concrete with percentages of incorporation such as 20%, 50% and 100% of recycled aggregate. Two types of SCC were manufactured with minimum compressive strength of 30 MPa and 45 MPa. The properties analysed were density of hardened SCC, shrinkage cracking, freeze-thaw resistance, resistance to ageing by thermal shock and abrasion resistance. The results obtained were compared with those of the control concrete, observing great capacity of the SCC under physical aggressions that affect durability. The results of this research show that it is possible to use the recycled aggregate coming from precast pieces in order to the manufacture of self-compacting recycled concrete in the same precast industry. However, high loss of proprieties occurs for a 100% substitution, while for 20% and 50%, the variations with respect to control concrete are smaller. In addition, taking advantage of this waste to incorporate it back into the production chain contributes to more sustainable construction.

Keywords: recycled; precast; recycled concrete; recycled aggregate; durability; physical

1. Introduction

Although construction has existed since the origin of civilization (Greek and Roman temples serve as an example), construction with structural elements of precast concrete is more recent. The origins of these precast elements date back to the early nineteenth century when, in Chicago, the first blocks based on lime cements and limestone aggregates were used in masonry walls, as an alternative to natural stone. Prefabrication is the industrialized version for construction and its many advantages include greater reliability (quality), dimensional precision, speed of execution, optimization of sections, greater work safety and longer useful life. Hence, in recent decades, many countries, such as the USA, Japan or The Netherlands, are promoting the prefabrication industry, consolidating the use of precast elements. However, and as with other activities related to construction, the precast sector requires a large amount of natural resources, since almost 80% of the total volume of concrete is aggregates.

This is leading to a progressive depletion of natural resources, forcing all countries to adopt more sustainable construction. In this regard, it is worth highlighting the "Precast Sustainability Strategy and Charter" of the British Precast Concrete Federation [1] where measures to reduce energy consumption, eliminate waste and implement environmental and sustainable management systems were introduced. Furthermore, they have recently approved new targets in line with the Sustainable Concrete industry Strategy targets and the construction industry Low Carbon Route map to 2050.

Therefore, taking into account that construction and all activities related to cement consume a large amount of natural resources, the recovery of concrete and its subsequent treatment to re-incorporate as a substitute for natural aggregate has taken on great importance. Since 2011, all precast sector companies in the European Union, complying with EU Regulation 305/2011 [2] have had to use natural resources sustainably.

The use of recycled aggregates (RA) from concrete can be an alternative to natural aggregates for the manufacture of different types of concrete, which has a positive impact on the environment by reducing the continuous exploitation of natural aggregate quarries that produce an important environmental impact and also has a favourable impact on the economy. Numerous investigations have been carried out to find ways to use this type of RA in the manufacture of concrete [3–9], generally observing a decrease in the properties and durability of concrete. A possible cause of this reduction may be a consequence of the greater absorption of the recycled aggregate with respect to the natural aggregate, producing a reduction in the water/cement (*w/c*) ratio, which reduces the workability of the concrete and, therefore, its fresh properties. As has been shown in different studies, the use of superplasticizer additives can be an alternative to correct the workability and can be beneficial in terms of durability and mechanical resistance since it optimizes the *w/c* ratio [6]. In this regard, Sainz-Aja [10] analysed the optimal amount of superplasticizer additive in the manufacture for self-compacting concrete. Regarding the use of RA, Thomas et al. [8,11] analysed the possibility of incorporating multi-recycled aggregate for the manufacture of a multi-recycled concrete. The results showed that it was possible to incorporate this type of RA, but limiting recycling to a 3rd generation aggregate.

Regarding the mechanical properties, it has been shown that the quality of the recycled aggregate influences the compressive strength, especially when it is desired to obtain strengths greater than 30 MPa. Sami and Tabsh [12] showed that when using high quality RA, the results obtained can be better than those obtained for control concrete. The results obtained by Pérez Benedicto when replacing 100% of the aggregate with waste from precast parts were in the same line [13]. Likewise, Sainz-Aja [14] demonstrated the viability of using recycled aggregate from out-of-service railway superstructure wastes for the manufacture of a more ecological SCC that also fulfils the mechanical requirements of slab tracks.

Another property that is usually affected by the incorporation of RA is the durability of concrete. In general, the incorporation of RA reduces the durability of concrete [15,16], although López-Gayarre [17] considers that the influence of RA is not significant since the durability is more dependent on the *w/c* ratio. Thomas [18] investigated the influence of the curing conditions of concrete with RA on its durability, observing a decrease in terms of permeability when the concrete is exposed to an aggressive environment.

The use of recycled aggregate causes a greater shrinkage in concrete compared to natural aggregate [19–21]. However, the greater or lesser variation in shrinkage can be influenced by other factors such as the dosage method, manufacturing procedure and curing conditions. For example, for a 100% substitution, Limbachiya [19] and Ravindraraja [20], found an increase of between 10–35%, while the results obtained by Domingo [21] showed increases greater than 70% with respect to the control concrete. The results obtained in different studies have shown that the incorporation of AR, can affect other physical processes related to the durability of concrete, such as resistance to frost [22–24] or resistance to erosion [19,25].

It can be seen that numerous studies have examined the use of concrete waste in the manufacture of new concrete, however, few studies relate to the use waste from the precast sector [6,13,26,27].

These studies are mainly focused on examining the influence of these wastes on the physical and mechanical properties of concrete [5,26]. Taking these data into account, the objective of this work was to analyse the influence that the use of RA from precast elements has on the durability of SCC under physical actions such as shrinkage, freeze-thaw cycles, thermal shock cycles and abrasion. This study can be considered innovative since, as mentioned above, the studies carried out to date have mainly focused on analysing the influence of these RAs on the mechanical properties of concrete. A SCC has been manufactured with a minimum compressive strength of 30 and 45 MPa for use in precast elements. The degrees of substitution analysed were 20%, 50%, 100% of the natural aggregate. The results of this research show that it is possible to use the recycled aggregate coming from precast pieces in order to the manufacture of self-compacting recycled concrete in the same precast industry.

2. Materials and Methods

2.1. Materials

CEM I- 52.5 R, according to the UNE-EN 197-1 Standard [28], was used. Cement was supplied by Grupo Cementos Portland Valderrivas (Mataporquera, Spain). Limestone filler (Artepref, Aranda de Duero, Spain) was used, complying with the ISO 9001 certificate. Two types of silica aggregates were used, with grain size fractions of 0/2 mm, for the finest aggregate, and 2/12.5 mm for the coarsest one. To achieve a workable SCC two superplasticizers were used: Sika ViscoCrete®-5920 HE (Sika, Madrid, Spain) and Sika ViscoCrete®-20 HE (Sika). These are two superplasticizers belonging to the group of polycarboxylates: Sika ViscoCrete®-5920 HE is a high-performance superplasticizer usually used in concrete with low water content and Sika ViscoCrete®-20 HE is a superplasticizer especially suitable for the preparation of concretes with great need for water reduction, with high initial strength and excellent fluidity.

Finally, recycled aggregate (RA) was used as an alternative to the coarsest aggregate, from crushed precast concrete waste with a size of 4/12.5 mm. This RA was obtained after crushing and grinding different unusable precast pieces [27], such as those shown in Figure 1. RA was used as an alternative to silica gravel.

Figure 1. Rejected recast products.

2.2. Mix Design

To carry out this study, two control mixtures were used to ensure a fresh, self-compacting concrete. Furthermore, control mixtures guaranteeing a minimum compressive strength of 30 MPa (HR-30) and 45 MPa (HR-45) were designed. The control mix proportions are intended to meet the standards of precast concrete plants and to cover the widest range of precast products. From the control SCC, the experimental program was done replacing 20%, 50% and 100% of the silica gravel with the same volume of RA. Table 1 shows the mix proportions for manufactured SCCs, in kg/m^3.

Table 1. Mix proportions of self-compacting concrete (SCC) (kg/m^3).

Material	HR-30-0% Control	HR-30-20%	HR-30-50%	HR-30-100%	HR-45 0% Control	HR-45-20%	HR-45-50%	HR-45-100%
RA 4/12.5	0	250	540	1040	0	250	540	1040
Sand 2/12.5	1150	920	540	0	1150	920	540	0
Sand 0/2	650	650	670	720	650	650	670	720
Limestone filler	320	320	320	320	280	280	280	280
CEM I-52.5 R	250	250	250	250	320	320	320	320
Water	112	112	112	112	112	112	112	112
Sika 20HE	0.50	0.50	0.65	0.85	0.50	0.50	0.65	0.85
Sika 5920	1.30	1.30	1.60	2.00	1.50	1.50	1.80	2.20
w/c_{eff}	**0.40**	**0.39**	**0.35**	**0.32**	**0.31**	**0.30**	**0.28**	**0.25**

Due to the high-water absorption coefficient of the RA, its incorporation as a substitute for aggregate 2/12.5 influences the effective water/cement ratio (w/c). In order to adequately compare the properties analysed in this study, the effective water/cement ratios $(w/c)_{\text{eff}}$ of each mix proportions used were calculated. The calculation of the effective water/cement ratios are obtained from Equation (1), where it has been estimated that the recycled aggregate reaches approximately 70% water saturation capacity [29]. Table 1 shows the $(w/c)_{\text{eff}}$ for each mixture:

$$\left\{\frac{w}{c}\right\}_{eff} = \frac{W - \frac{0.7}{100}\sum_i (P_i A_i)}{c} \tag{1}$$

where, $\left\{\frac{w}{c}\right\}_{eff}$ is effective water/cement ratio; W is the total amount of water incorporated in the mix; P_i is the weight of the components incorporated during mixing; A_i is the absorption of the components incorporated during mixing.

A total of eight mixes made up the experimental program. The HR-30-0% and HR-45-0% mixes correspond to the control SCC. The remaining six mixtures correspond to the SCC with RA (Table 2).

Table 2. Results of compressive strength and standard deviation **σ**.

SCC HR-30	[MPa]	σ [MPa]	SCC HR-45	[MPa]	σ [MPa]
HR-30-0%	49.09	12.00	HR-45-0%	63.36	5.28
HR-30-20%	49.98	7.50	HR-45-20%	64.13	4.47
HR-30-50%	55.34	10.35	HR-45-50%	66.82	7.04
HR-30-100%	56.75	3.27	HR-45-100%	72.81	8.22

In view of the results, there is a significant decrease in the $(w/c)_{\text{eff}}$ in recycled concretes, ranging from a ratio of 0.45 to 0.32, for HR-30 and from 0.35 to 0.25 in the HR-45.

2.3. Experimental Programme

The SCC is mixed in a vertical shaft concrete mixer, following the procedure described in ASTM C192 [30]. The mix procedure is as follows: first, the mixer is wetted, the coarse aggregates are added and half the water of the mixture is poured in. Next, the finest materials, cement and filler, and the other half of the water are introduced. A first mixing of 3 min is carried out and the mixture is left to rest for 3 min. Finally, a mixing of 2 more minutes is carried out. After this time, the mixing process is finished.

The specimens were manufactured according to the specifications of the UNE-EN 12350-1 standard [31]. The dimensions of the specimens are cubic specimens of 10 × 10 × 10 cm^3 and prismatic specimens of 7.5 × 7.5 × 27.5 cm^3. After demoulding, all the specimens were transferred to a humidity chamber where they were cured at a temperature of 20 ± 2 °C and a relative humidity of 95% for 28 days, following the recommendations of the UNE-EN 12390-2 standard [32].

2.4. Consistency of Fresh SCC

The consistency of the fresh SCC was determined according to the slump-flow test described in the UNE-EN 12350-8 [33] standard and using a cone similar to that described in the UNE-EN 12350-2 [34] standard for the slump-flow test. The fresh concrete is poured into the cone and once filled it is removed with an upward movement. Next, the time it takes for the concrete flow to reach a diameter of 500 mm is measured, this being the time t_{500}. Finally, the largest diameter of the extended self-compacting concrete and the perpendicular diameter to it are measured, the mean is the slump-flow. The same *w*/*c* has been used in all mix proportions. However, due to the higher absorption of the RA, the effective *w*/*c* ratio is reduced with the increase of the RA percentage. In order to maintain a similar fluidity, the amount of superplasticizer additive has been increased.

2.5. Physical Properties

2.5.1. Density of Hardened SCC

To determine the density of hardened SCC, the UNE-EN 12390-7 standard [35] was used. The relative density of SCC was determined after having the specimens curing in a humidity chamber for 28 days. The density of hardened SCC was determined in 3 cubic specimens of $10 \times 10 \times 10$ cm^3 for each mixing ratio and calculating the relationship between the weight of the dry specimen and its volume.

2.5.2. Shrinkage Cracking

For the shrinkage test and in compliance with the UNE 83,318 [36] standard, laterally drilled $7.5 \times 7.5 \times 27.5$ cm^3 prismatic moulds, to which metal parts have been attached internally, were used, fastened with a screw from the outside of the mould. The concrete specimens were compacted according to the method set forth in standard UNE 83,313 [37] and taking care not to touch the metal parts during the compaction of each of the specimens.

The first measurement was made 30 min after demoulding and after curing the specimens in water at 20 °C for 28 days. Subsequently, the specimens were cured under conditions of direct exposure to the weather. Figure 2. shows the curing conditions of concrete exposed outdoors. Three specimens were used for each mix and the lengths of the samples were measured at 2, 7, 14, 28, 98, 198 and 360 days.

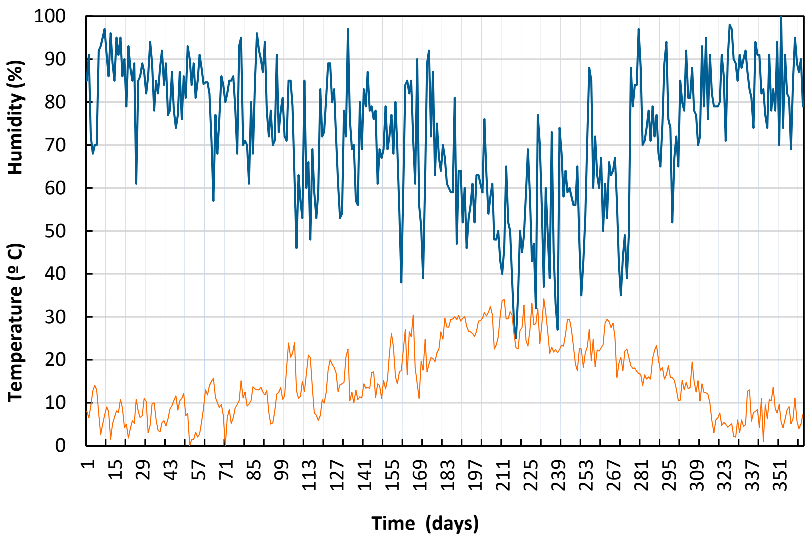

Figure 2. Graph of temperatures and humidity of the specimens during the shrinkage test.

2.5.3. Freeze-Thaw Resistance

The freeze-thaw tests were done in cubic specimens of 10 × 10 × 10 cm^3 and according to the UNE-EN 12390-9 [38] standard, which describes the procedure to subject the test specimens to freeze-thaw cycles. The specimens were subjected for a period of 16 h to a temperature of between −13 °C to −15 °C in a freezer chest. To control the temperature inside the specimens during the test, a thermal probe was drilled and was housed inside one specimen of each series. Taking the weight of the test specimens 24 h after immersion in water as a reference, the loss of mass at 7, 14, 28, 42 and 56 cycles was determined. Tests were performed on two specimens for each mix of SCC. Figure 3 show the freeze-thaw testing equipment with temperature of the sample and the water control.

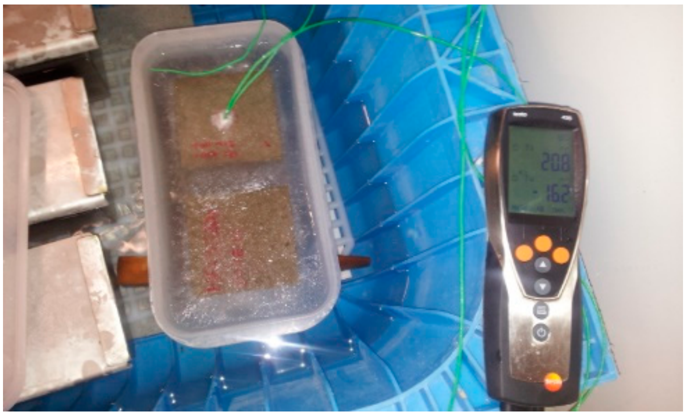

Figure 3. Freeze-thaw testing with temperature control.

2.5.4. Resistance to Ageing by Thermal Shock

Regarding ageing by thermal shock and in the absence of standards, it was determined by adapting the test of the UNE-EN 14,066 standard [39]. The specimens were subjected to cycles of 16 h in an oven at 70 °C and a period of 8 h immersed in water at a temperature of 20 °C for a total of 20 cycles. For each mixture, 3 cubic specimens of 10 × 10 × 10 cm^3 have been manufactured.

2.5.5. Abrasion Resistance

Regarding abrasion resistance, there is no UNE standard method to test concretes, so the procedure to evaluate the behavior slabs of natural stone that is described in the UNE-EN-1341 standard [40] was adapted. The measurement of the width of the footprint was carried out with a calliper on two of the faces of 2 cubic specimens of 10 × 10 × 10 cm^3, for the different SCC and replacement percentages.

2.6. Mechanical Properties

Regarding mechanical properties, the compressive strength of SCC was determined according to the specifications of UNE-EN 12390-3 [41]. The compressive strength tests were carried out to obtain reference data for the different mixtures with which to compare the results obtained after carrying out certain durability tests. Table 2 shows the average results obtained from 3 cubic specimens of 10 × 10 × 10 cm^3 for each mix proportions. Tests were performed at 28 days.

2.7. Statistical Analysis

The statistical analysis of the results obtained in this study was performed by calculating the standard deviations. The standard deviation was calculated according to Equation (2), taking into account the results obtained in each property and percentage of substitution. Typically, a total of three trials were performed for each percent RA:

$$y = \sqrt{\frac{\sum (x - \overline{x})^2}{(n - 1)}}, \quad (2)$$

where $\overline{x}$ is the average value and n is the sample size.

3. Results and Analysis

3.1. Characterization of Aggregates

The apparent density and water absorption of the natural aggregates are shown in Table 3, while the particle size curves are shown in Figure 3. The determination of the particle size distribution of the aggregates was carried out according with the UNE-EN 933-1 standard [42]. The results of the RA are also shown in Table 3 and Figure 4.

Table 3. Density and water absorption of the natural aggregates and RA.

Natural Aggregates	Sand 0/2	Gravel 2/12.5	RA	Standard
Apparent density (g/cm^3)	2.64	2.68	2.41	UNE-EN 1097-6 [43]
Water absorption (% wt.)	0.26	1.16	4.15	UNE-EN 1097-6 [43]

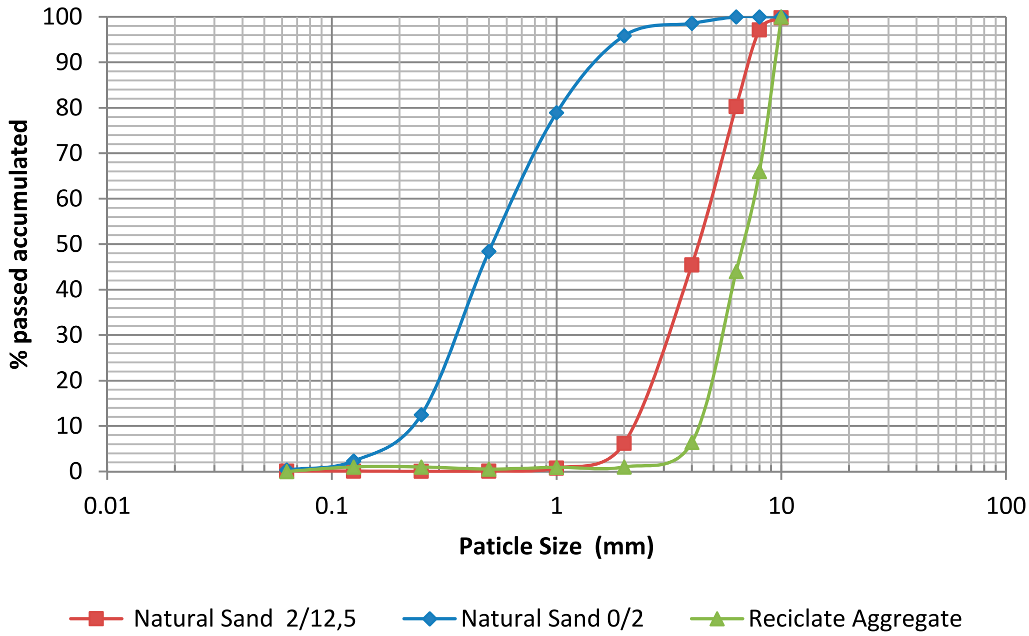

Figure 4. Grading curves of silica sands and RA.

3.2. Consistency of Fresh SCC

Table 4 shows the fresh concrete consistency results obtained for the different SCC. It can be seen that when replacing the natural aggregate 2/12.5 mm with RA there is a reduction in workability. This decrease occurs for all replacement percentages. Although the amount of additive was increased for the 50% and 100% substitutions, the values for the diameter of the extended SCC are still lower. This may be due to the higher water absorption by the RA, of 4.15%, with respect to the aggregate 2/12.5 mm, of 1.16%. This leads to a reduction in the effective w/c ratios and, therefore, in the workability of the SCC.

Table 4. Results of fresh concrete consistency.

SCC HR-30	Diameter (mm)	SCC HR-45	Diameter (mm)
HR-30-0%	680	HR-45-0%	750
HR-30-20%	600	HR-45-20%	710
HR-30-50%	580	HR-45-50%	600
HR-30-100%	550	HR-45-100%	650

3.3. Density of Hardened SCC

Figure 5 shows the values obtained for the different dosages as a function of the effective *w*/*c* ratio. Consistent with other studies [29,44] and according to Equation (3) it can be seen how the density decreases linearly as the *w*/*c* ratio increases:

$$y = Ax - B, \tag{3}$$

where, y is density; x is the effective water/cement ratio; A and B are parameters to be calculated.

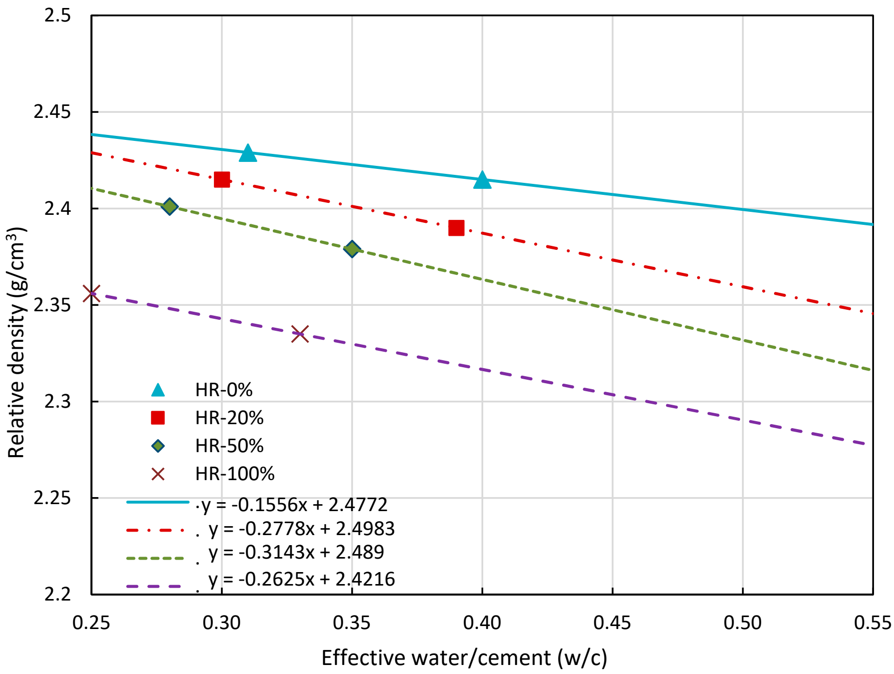

Figure 5. Results of relative density of hardened SCC as a function of the *w*/*c* ratio.

The results show a decrease in the SCC density as the percentage of RA in the mixture increases. Likewise, all degrees of substitution evolve in parallel. These results are in agreement with the results obtained by other authors, when using different types of precast concrete waste as substitutes for natural aggregate [17,26]. This is attributed to the higher particle density of natural aggregate compared to RA.

3.4. Shrinkage Cracking

3.4.1. Shrinkage as Function of Time

In this study, the influence of incorporation of RA on the shrinkage of the SCC has been analysed. Figures 6 and 7 show the evolution of the shrinkage as function of time for the two types of concrete, HR-30 and HR-45, obtaining a logarithmic fit as in Equation (4):

$$y = A\,\mathrm{Ln}(x) + B, \tag{4}$$

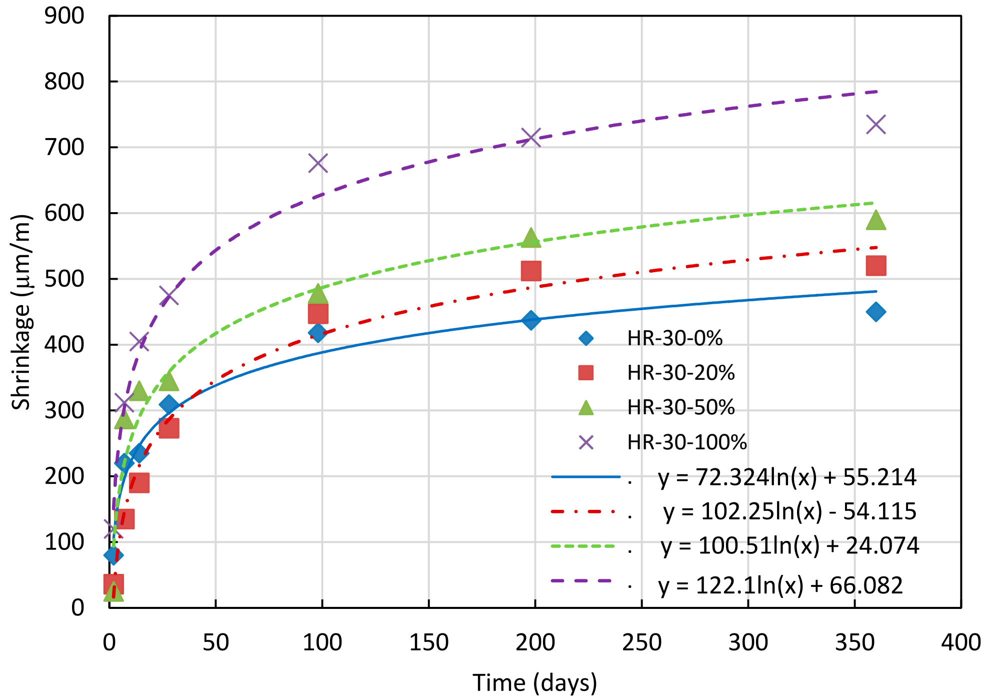

Figure 6. Evolution of the shrinkage vs. time of the HR-30 concrete.

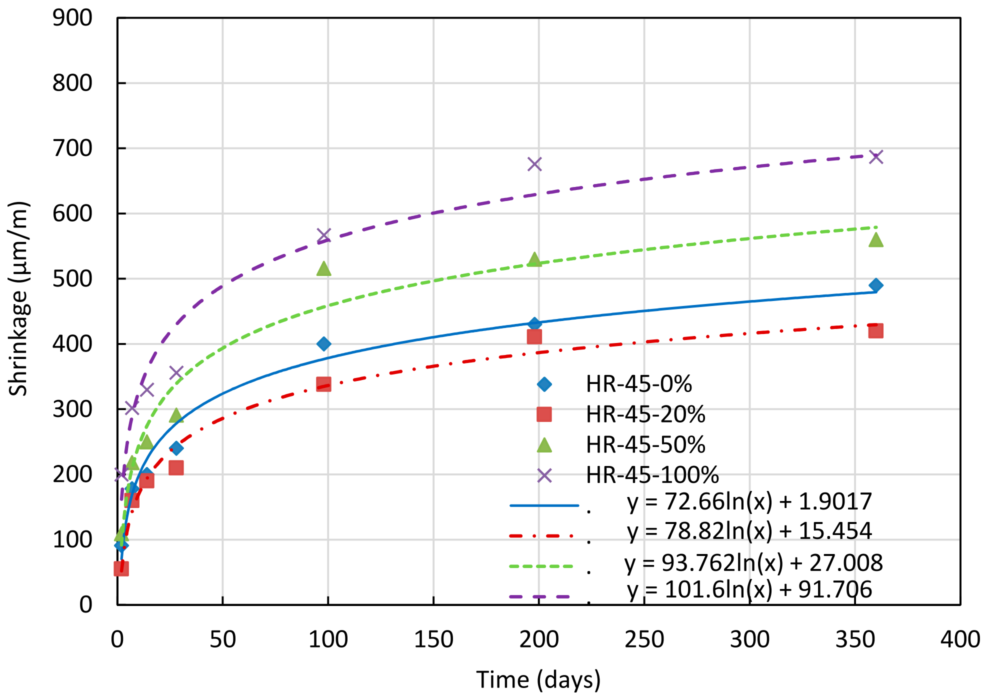

Figure 7. Evolution of the shrinkage vs. time of the HR-45 concrete.

In general, the shrinkage of recycled concrete is greater than the control concrete. However, the results do not show a clear trend for a ratio of 50% RA in the HR-45 concrete. HR-30% concrete with 100 days age show variations in shrinkage smaller than HR-20% and HR-50% concretes. Also, comparing with the control SCC, the HR-100% shows an increase of 37%. Both graphs also show that during the first 90 days the slopes of the logarithmic adjustment are quite steep, regardless of the percentage of RA. R. Loser [45] has shown that the greater shrinkage of self-compacting concretes, compared to conventional concretes, is due to the greater amount of paste.

These results are in line with those obtained in other studies, where a greater shrinkage of the concrete is observed when including different percentages of recycled aggregates as an alternative to natural aggregate [19–21]. This increase in shrinkage may be consequence of the greater absorption of water by the RA, which causes greater porosity of the concrete as the percentage of substitution increases and, therefore, an increase in shrinkage. Furthermore, Ravindrarajha et al. [20] suggest that recycled concrete made with high-quality aggregates, as in this study, presents greater shrinkage compared to those made with poorer quality aggregates.

3.4.2. Shrinkage as a Function of Effective Water/Cement Ratio

Figure 8 shows the relationship between the shrinkage of SCC, at 28 days, as a function of the effective *w*/*c* ratio. In the absence of specific literature linking these two parameters, the optimal effective fit was adapted to an increasing logarithmic curve with Equation (3).

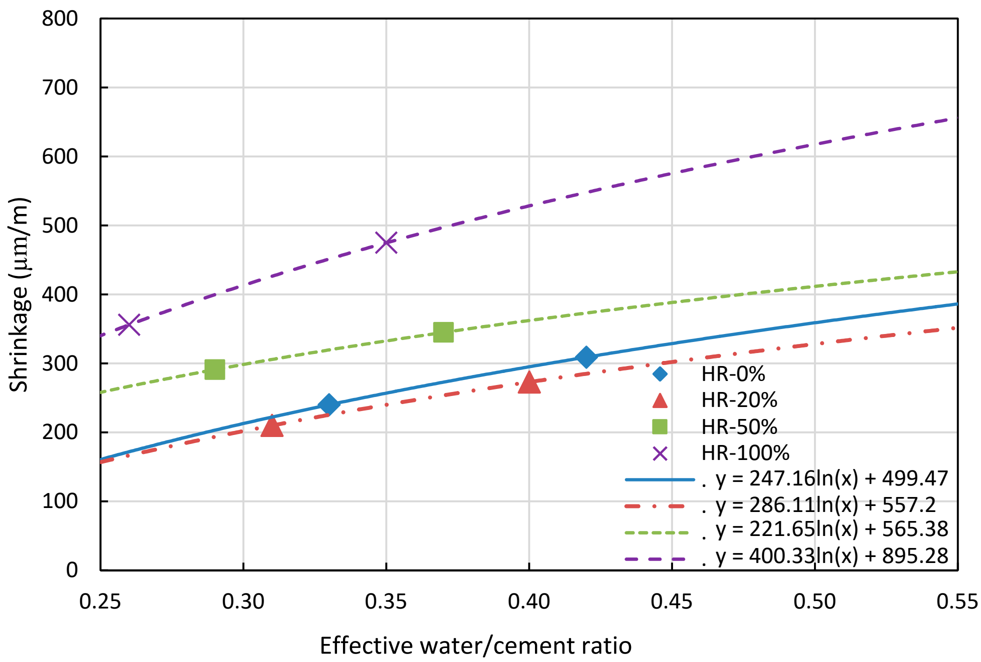

Figure 8. Shrinkage of SCC as a function of effective *w*/*c* ratio.

As in Figures 6 and 7, an increase in shrinkage with increasing RA percentage is observed. However, the variations are less for each degree of substitution. The control concrete curves and those of concrete with a ratio of 20% RA are similar. There is some variation for the ratio of 50% curve and the greatest difference occurs in the curve of 100%, the increase of which represents approximately 28% for the same effective *w*/*c* ratio.

3.4.3. Correlation between Compressive Strength and Shrinkage

According to the studies consulted [44], the relationship between compressive strength and shrinkage of concrete can be represented by a linear graph. In Figure 9 the relationship between compressive strength and SCC shrinkage with RA at 28 days can be seen. The results obtained show a decrease in shrinkage as the compressive strength increases for each type of SCC. For substitutions of up to 50%, it can be seen that the slope of the graphs hardly changes. However, for the ratio of 100% of RA, a more marked increase in shrinkage as the strength decreases is observed. These results show the influence of recycled aggregate in the paste at 28 days' ageing.

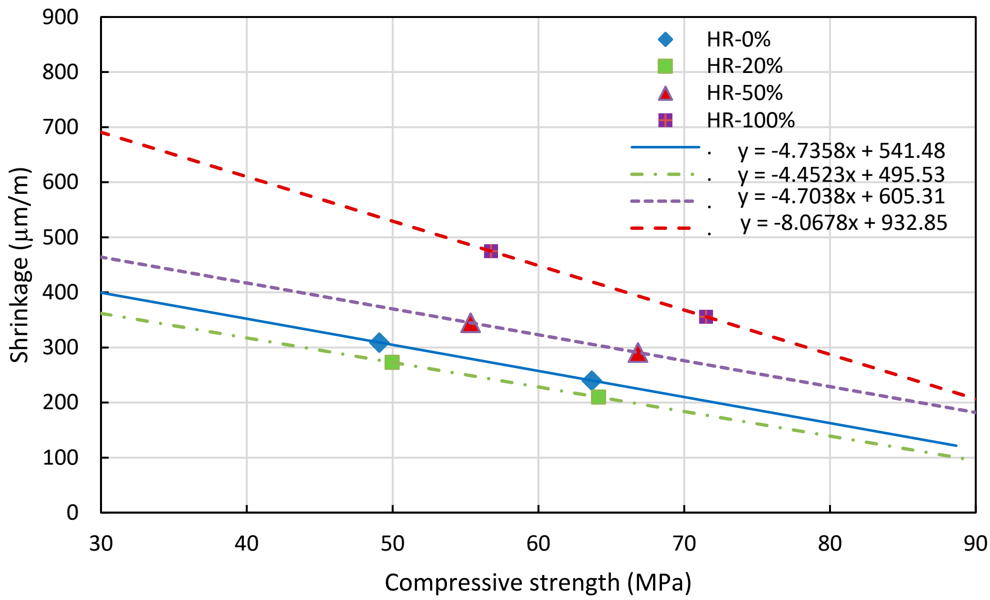

Figure 9. Correlation between shrinkage and compressive strength at 28 days' ageing.

3.5. Freeze-Thaw Cycle

Table 5 shows the weight loss results in the corresponding freeze-thaw cycles applied for the different SCCs. Weight loss at 7, 14, 28, 42, and 56 cycles was determined. The results show two different behaviors depending on the strength of the SCC, HR-30 and HR-45. For concretes with a higher *w/c* ratio (0.45), corresponding to HR-30, the weight loss as the cycles progress is significantly greater. For the dosage of lower ratio *w/c* (0.35), corresponding to the strength of HR-45, although weight loss is also seen, it is not greater than 10% of the initial weight. This greatest weight loss for the dosages with a higher *w/c* ratio of the concrete with RA is in line with the results obtained in other studies [46].

Table 5. Weight loss results in freeze-thaw tests.

Type SCC	7 Days	18 Days	28 Days	42 Days	56 Days
HR-30-0%	1.49	2.91	4.52	8.37	11.42
HR-30-20%	0.41	0.83	1.55	2.60	4.74
HR-30-50%	0.51	0.89	1.22	8.95	12.57
HR-30-100%	2.1	4.63	9.56	12.30	15.87
HR-45-0%	0.61	0.74	1.54	3.08	4.68
HR-45-20%	0.28	0.67	0.86	1.86	3.16
HR-45-50%	0.71	1.99	2.58	4.51	8.14
HR-45-100%	0.79	2.18	3.47	5.23	9.50

Figure 10 specifies the compressive strength results before and after freeze-thaw cycles as a function of the effective *w/c* ratio.

Decreases in strength for concretes with higher *w/c* ratios are observed, while for lower water/cement ratios, the tendency is toward increasing strength. For the higher *w/c* ratio (HR-30), strength losses were observed between 8% for the ratio of 20%, and 30% for the substitution of 100% RA with respect to the specimens taken as reference. However, for the dosages of HR-45, there is a slight increase in strength, between 5% and 7%, compared to the reference SCCs. In this regard, there are studies that reflect this better behavior [47,48]. Mulheron and Omahony [48] observed that the durability of concrete made with crushed concrete and clean recycled aggregate is better or similar to the durability of concrete with natural aggregates, when subjected to freeze-thaw cycles.

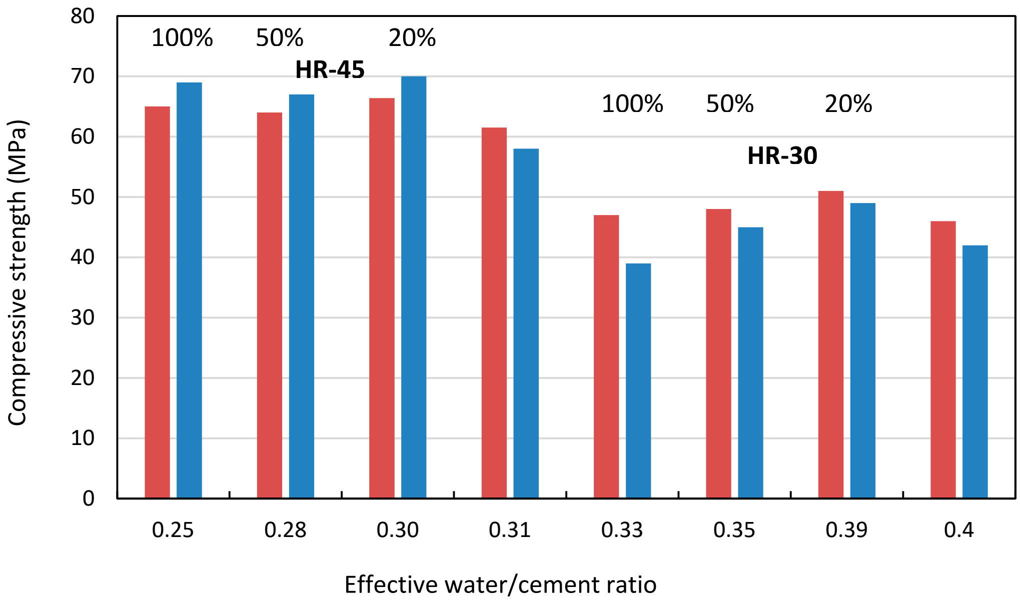

Figure 10. Compressive strength results (**blue**) of the specimens after the freeze-thaw test compared to reference (**red**) specimens, as a function of the effective *w*/*c* ratio.

The behavior under the freeze-thaw cycles was more favorable for the concrete with a lower *w*/*c* ratio, even achieving resistance values significantly higher than those of the control concrete and reference specimens. For the higher *w*/*c* ratio, in general, the results reflect a trend of poorer behavior as we increase the degree of substitution.

3.6. Abrasion Resistance

The average results of the footprint, in mm, of the abrasion test for the different types of SCC and percentages of RA can be seen in Table 6.

Table 6. Abrasion test results and standard deviation **σ**.

SCC HR-30	Footprint (mm)	σ [mm]	SCC HR-45	Footprint (mm)	σ [mm]
HR-30-0%	19.32	0.11	HR-45-0%	19.22	0.18
HR-30-20%	19.33	0.09	HR-45-20%	19.51	0.44
HR-30-50%	19.95	1.13	HR-45-50%	19.92	0.38
HR-30-100%	20.58	0.05	HR-45-100%	19.97	0.59

Knowing that the lower the footprint values, the greater the abrasion resistance, it can be said that the use of RAs produces a loss in abrasion resistance of the SCC. The results also show that the smaller the *w*/*c* ratio is, the smaller is the width of the footprint and, therefore, the stronger is the concrete. For the replacement of 100% of the HR-30 concrete, a significant increase in the depth of the footprint is observed with respect to the same percentage of HR-45 concrete, approximately between 3% and 5% compared to the reference concrete. These values are below those obtained by other authors [25,49]. It can be seen that the results converge for low *w*/*c* ratios, close to 0.25, indicating that the highest resistance to abrasion occurs for the highest quality paste. However, the footprint values obtained for the different replacement percentages are below the maximums required by Spanish regulations for outdoor environments [50,51].

3.7. Resistance to Ageing by Thermal Shock

Table 7 shows the variation in mass of the specimens, in grams, after having subjected them to 24 h cycles with a stage of immersion in water (8 h) and another stage of drying in a stove (16 h).

The results do not show notable modifications for the different SCCs, even a certain weight gain is observed, certainly produced by some water retained in its pores. Thus, it can be concluded that that deterioration does not occur in the samples due to alteration in the concrete surface layer.

Table 7. Accelerated ageing by thermal shock: Pn mass variation.

Type SCC	Pn (g) Starting	Pn (g) Ending	Δ Weight (%)
HR-30 0%	2433.0	2438.0	+0.21 ⬆
HR-30 20%	2325.0	2329.0	+0.17 ⬆
HR-30 50%	2399.5	2401.8	+0.10 ⬆
HR-30 100%	2323.9	2338.2	+0.61 ⬆
HR-45-0%	2427.0	2433.0	+0.25 ⬆
HR-45-20%	2390.0	2395.0	+0.21 ⬆
HR-45-50%	2404.6	2409.9	+0.22 ⬆
HR-45-100%	2372.3	2378.8	+0.27 ⬆

Figure 11 shows the results of the compressive strengths obtained as a function of their effective water/cement ratio, carried out before and after the thermal shock test. Although a slight increase in strength is observed, for control SCCs and 50% and 100% substitutions, there is no clear trend in the results.

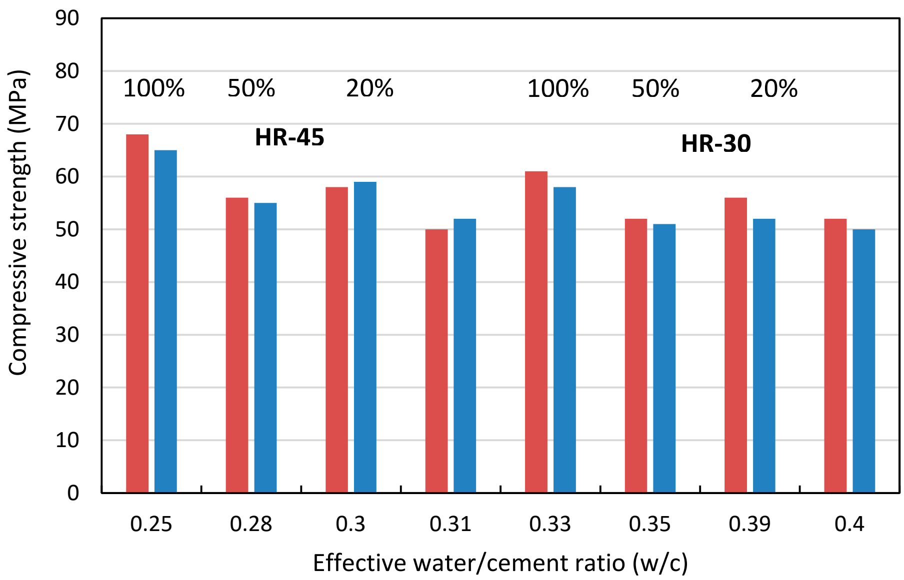

Figure 11. Comparison of compressive strength results after thermal shock cycles (**blue**) with the reference (**red**) specimens as a function of their effective *w*/*c* ratio.

4. Conclusions

Once the results obtained in this study had been analyzed, it could be concluded that:

- The results obtained, when analyzing the physical and chemical properties of RA, are within the limits of the current Spanish Specification EHE-08. Therefore, it can be said that the properties of RAs are adequate for the manufacture of a new concrete resulting in a good material with good strength, resistance, uniformity and little contamination.
- As expected, the densities of hardened SCCs are decreased as the percentage of RA present in the mixture increases.

- The incorporation of RAs produces an increase in the shrinkage of SCCs. The greatest variation occurs for a 100% substitution, while for 20% and 50%, the variations with respect to control concrete are smaller.
- The shrinkage values obtained show that during the first 90 days the variation is more pronounced regardless of the percentage of RA.
- The results obtained show a decrease in shrinkage as the compressive strength increases. For a ratio of 100% a more marked increase in shrinkage is observed, which shows the influence of the recycled aggregate on the concrete paste.
- The use of RAs has little influence on physical actions such as thermal shock or abrasion, since the values are similar to those of the control concrete. In addition, in the case of the abrasion test, the results are below the maximums required by Spanish regulations.
- The behavior of concrete under freeze-thaw cycles was more favorable for concrete with a lower *w/c* ratio, even achieving resistance values significantly higher than those of control concrete and reference specimens. For higher *w/c* ratios, in general, the results reflect a trend towards poorer behavior, as also occurs and as we increase the degree of substitution.

The results obtained in this study show a favorable response of recycled SCC to physical actions that affect durability. Ultimately, we can conclude that it is feasible to manufacture a concrete with high strength and performance with aggregates recycled from precast elements, obtaining satisfactory results even with a 100% replacement.

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