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Effect of the maturity of recycled aggregates on the mechanical properties and autogenous and drying shrinkage of high-performance concrete

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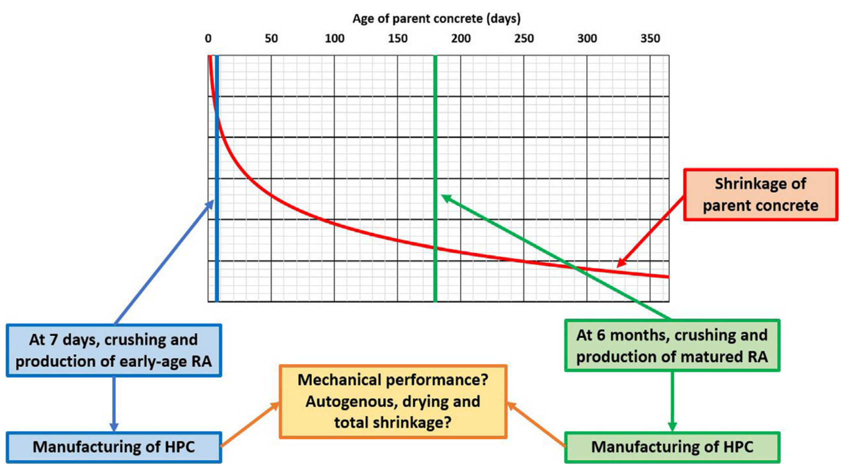
HIGHLIGHTS

- HPC produced with both coarse and fine matured or early-age recycled aggregates.
- Autogenous, drying and total shrinkage, and mechanical properties analysed.
- Lower strength and stiffness of early-age RA slightly worsened mechanical behaviour.
- Water storage of RA reduced autogenous shrinkage, but increased drying shrinkage.
- Shrinkage of early-age RA increased all shrinkage types of HPC.

GRAPHICAL ABSTRACT



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ABSTRACT

The high cement content of high-performance concrete (HPC) results in improved strength, but also in large shrinkage. The substitution of natural aggregates (NA) with recycled aggregates (RA) notably affects these properties in conventional concrete. This study intends to analyse the effect of the content of RA and their maturity (time elapsed between casting and crushing of the parent concrete from which RA are obtained) on these properties of HPC. To this end, five mixes were manufactured with 0%, 25%, and 100% of coarse and fine RA of different maturities, 7 days (early-age RA) and 6 months (matured RA). The mechanical properties and the autogenous, drying, and total shrinkage of all mixes were determined. Both the increase of RA content and the lower stiffness and strength of early-age RA relative to matured RA worsened the mechanical behaviour of HPC. Regarding shrinkage, the lower stiffness and higher water absorption of matured RA compared to NA decreased autogenous shrinkage by 20%, but increased drying and total shrinkage. The lower stiffness of early-age RA and their shrinkage amplified all types of shrinkage of HPC around 10–20%. Nevertheless, the hydration of their unhydrated cement particles during the mixing process reduced those increases from what was expected. Total shrinkage of early-age recycled aggregate HPC could be estimated from the shrinkage of both a HPC mix of identical composition but

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with matured RA and the parent concrete. Overall, it can be concluded that RA's maturity affects the mechanical performance and, especially, the shrinkage of HPC, so it should be considered when using this type of aggregate.

1. Introduction

It is widely known that the construction sector has a great environmental impact. On the one hand, the manufacture of both cement and bitumen for asphalt mixtures produces high CO_2 emissions [1]. Furthermore, this sector consumes huge amounts of natural aggregates (NA), which represent approximately 70–90% volume of traditional engineering materials, such as concrete or asphalt mixes [2]. In view of this situation, many alternatives have emerged to try to increase the sustainability of this sector, among which the use of wastes in the manufacture of these materials stands out [3]. In the specific case of concrete, in recent years, the use of different alternative binders as substitutes for cement [4], as well as the use of recycled aggregates (RA) from crushed rejected concrete elements [5], has been studied in detail. It has even been demonstrated that the performance of RA is suitable for the production of non-conventional concretes, such as self-compacting concrete, in which its high flowability in the fresh state precludes vibration during placement [6]; or high-performance concrete (HPC), characterized by both its high strength and optimal durability properties [7].

The high mechanical properties of HPC are obtained by increasing the cement content, a low water-to-cement (w/c) ratio, and a correct packing of the aggregates [8]. Moreover, the use of suitable quantities of mineral additions (for example, fly ash or silica fume) as a complement to ordinary Portland cement allows improving even more the hardened-state performance of this type of concrete [9]. The final aim of this design is to obtain a dense microstructure that maximizes both the strength and the durability of concrete [10]. Nevertheless, all these aspects cause the workability of HPC to be generally reduced, a problem that can be solved by adding superplasticisers [11]. Some mineral additions also allow balancing the fresh and hardened behaviour of this type of concrete [12].

Regarding the incorporation of RA in HPC, it is expected that it will hinder its mechanical properties, as in conventional concrete [13]. However, its high microstructural density reduces this decrease compared to that of conventional concrete. Thus, the use of 20–50% of only one RA fraction has led the compressive strength to decrease only by 3–7% [14,15]. The joint use of low amounts of both fractions has shown the same trend, with a decrease in compressive strength of around 5% for both coarse and fine RA content of 50% [7]. Furthermore, in different studies, the strength of coarse recycled aggregate HPC was higher than that of the reference mix (100% NA) for constant w/c ratio and volume of both coarse and fine aggregates [16]. This unexpected situation is usually attributed to the above-mentioned high microstructural density of HPC [17]. Therefore, if RA are added in low contents, the design of HPC allows effectively compensating the characteristics of this waste that are detrimental to concrete strength. These characteristics are the existence of contaminants or mortar particles in the fine fraction [18], or the appearance of weak interfacial transition zones (ITZ) when adding the coarse fraction [19]. The decreases produced by high RA contents are greater [20], although, if the rest of variables that affect strength remain constant, strength follows an approximately linear inverse proportion to the RA content [7]. Nevertheless, the research works that have evaluated the use of fine RA in HPC, both alone and combined with coarse RA, are quite scarce.

In addition to mechanical properties, the incorporation of RA affects some other properties of conventional concrete. On the one hand, the use of any RA fraction increases the porosity of concrete due to the presence of mortar adhered to the coarse particles, and the modification of the rheology of the cement paste caused by the smallest particles [21]. On the other, its higher water absorption and lower stiffness lead to an increase of the drying shrinkage, which is caused by the evaporation of the water absorbed by the aggregate and released in a delayed way [22]. The effect of RA on the drying shrinkage depends on multiple factors such as its origin [23], the strength of the parent concrete (PC) from which RA are obtained [24], the crushing process [25], or the treatments applied to improve RA properties such as carbonation [26]. All these aspects hinder an accurate estimation of the shrinkage of recycled aggregate concrete [22]. However, the use of RA also has positive effects, such as the decrease of autogenous shrinkage [27]. This shrinkage is explained by the reaction between water and cement during the hydration of cement that occurs after the mixing process. It is measured by isolating the concrete specimen from the outside environment to avoid water evaporation [28]. Thus, the higher deferred water release of RA compared to NA reduces the autogenous shrinkage by restoring the water consumed in the delayed hydration of cement [27].

The discussed effects of RA are especially relevant in HPC. Due to its dense microstructure, HPC is very sensitive to the changes in porosity that RA cause [29], which can lead to important modifications of its mechanical and durability behaviour [10]. In addition, this type of concrete presents a high drying shrinkage due to its large cement content and hydration heat [8], a phenomenon that is amplified when RA are added [17]. The effect of fine RA is greater due to its higher water absorption [16]. However, there are different ways to reduce the shrinkage increase caused by RA in HPC. For instance, it has been shown that the higher the quality (strength) of PC, the lower the increase of shrinkage caused by the incorporation of RA [17]. On the other hand, the use of shrinkage-reducing admixtures, a higher ambient humidity, or a decrease in temperature can also partially compensate that increase in shrinkage [30]. The autogenous shrinkage of HPC is also more pronounced than in conventional concrete due to its higher cement content [31], but it can be reduced, in addition to the aspects discussed above, by adding RA [32]. However, the effect of the origin of RA in this type of shrinkage is the opposite of the one observed for drying shrinkage. So, the decrease of autogenous shrinkage is higher the lower the quality of PC, which is explained by the greater water storage capacity of RA obtained from low-strength concrete [17]. Therefore, reducing the autogenous shrinkage by incorporating RA means increasing the drying shrinkage [33], which shows their strong interrelationship [30]. These aspects related to the autogenous shrinkage of HPC have been analysed only in the short-term (up to 72 h after mixing) [17]. The effect of RA on the long-term autogenous shrinkage of HPC is still unknown. Furthermore, there is an aspect whose effect on the shrinkage of HPC has not been evaluated so far: the maturity of RA. RA have a rheological nature [34], so they also tend to shrink, which can therefore amplify the overall shrinkage of concrete [35]. This effect can be highly noticeable in HPC because of all the aspects addressed, especially if very early-age RA are used.

Therefore, this article addresses the various shortcomings related to HPC manufactured with RA that have been listed in this introduction, thus analysing novel aspects in this field. Firstly, the effect of the simultaneous incorporation of the coarse and fine fractions of this waste on the mechanical behaviour of HPC is studied. Thus, the few existing research works related to the performance of HPC manufactured with fine RA are complemented. Secondly, the long-term autogenous, drying, and total shrinkage of HPC manufactured with RA are analysed, which allows validating the aspects observed in the short-term. Finally, the effect of the maturity of RA on both the mechanical properties and the shrinkage of HPC, which has not been studied so far, is addressed. In order to analyse all these aspects, five HPC mixes with RA contents of 0%, 25%, and 100% (simultaneous replacement of the coarse and fine fractions) were cast. These replacement ratios allowed evaluating the effect of adding both small and large amounts of RA. In addition, two different maturities (time between casting and crushing of PC), which condition the stiffness and shrinkage of RA were considered for RA, 7 days and 6 months. Thus, the effect of RA of very different maturity on the performance of HPC is analysed.

2. Materials and methods

2.1. Materials

2.1.1. Non-aggregate materials: cement, admixture, and water

In this research work, CEM I 42.5 R ordinary Portland cement was used for producing HPC. CEM I 52.5 R was used to manufacture the parent concrete (PC). According to EN 197-1 [36], these European standard cements had a specific gravity of around 3.1 Mg/m^3 and a clinker content of approximately 98%. Furthermore, commercial limestone filler (density around 2.8 Mg/m^3) was used in the manufacture of the PC.

A superplasticiser according to EN 934 [36] was added to provide high workability to HPC. It was supplied by SIKA S.A. and it was composed by a combination of modified polycarboxylates.

Finally, the water was obtained from the main water supply of Lisbon, Portugal, where this research work was performed. It did not contain any harmful compound for the fresh or hardened behaviour of concrete.

2.1.2. Natural aggregates (NA)

Four different NA were added to the mixes in which the RA content was not 100%. On one side, two crushed limestone gravels, size 12/22 mm and 4/12 mm, were used, which were labelled NA-B2 and NA-B1 respectively. On the other, two siliceous sands of different sizes were utilized: a coarse sand 1/4 mm (NA-CS), and a fine sand 0/1 mm (NA-FS). The gradation of all these aggregates is shown in Fig. 1, and their physical properties, which presented current values [34], are collected in Table 1.

2.1.3. Recycled aggregates (RA)

Firstly, the PC was manufactured with 100% NA according to the composition shown in Table 2. PC had a compressive strength of 39.70 ± 0.57 MPa at 7 days and 45.50 ± 0.42 MPa at 28 days. Moreover, its 28-day splitting tensile strength was 2.57 ± 0.29 MPa, and its modulus of elasticity, 37.30 ± 0.28 GPa (see experimental procedure, section 2.4). According to these properties, the PC was classified as C30/37 class according to Eurocode 2 [37]. Subsequently, RA were obtained by crushing the PC in a jaw crusher. Coarse (4/22 mm) and fine (0/4 mm) fractions were separated by subsequent sieving. In this way, the proportion of coarse and fine aggregate remained constant in all mixes, so it did not influence the results obtained [38]. The crushing and sieving cited were carried out at two different ages of PC, 7 days and 6 months, as explained in section 2.2.

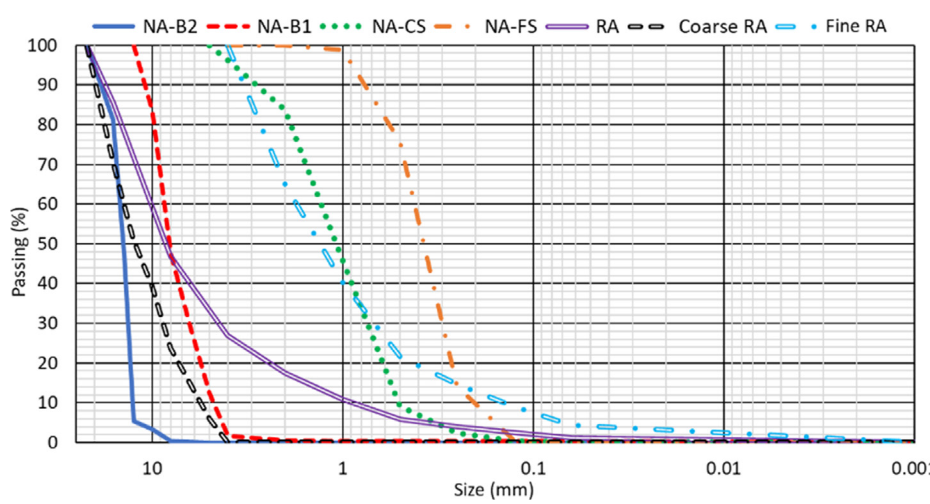

Fig. 1. Size distribution of the aggregates.

Table 1
Physical properties of the aggregates.

Property	Standard [36]	NA-B2	NA-B1	NA-CS	NA-FS	Coarse RA [1]	Fine RA [1]
Saturated-surface-dry density (Mg/m^3)	EN 1097–6	2.63	2.65	2.57	2.62	2.43	2.38
Oven-dried density (Mg/m^3)	EN 1097–6	2.59	2.62	2.55	2.61	2.42	2.35
Apparent density (Mg/m^3)	EN 1097–6	2.69	2.70	2.61	2.65	2.47	2.40
24-h water absorption (%)	EN 1097–6	1.39	1.11	0.81	0.62	4.89	6.77
10-min water absorption (%)	–	0.88	0.85	0.65	0.39	3.18	4.82

[1] Density and water absorption were the same for both matured and early-age RA as they were obtained from a PC with exactly the same composition.

Table 2
Mix design of PC (kg/m^3).

Cement CEM I 52.5 R	260
Limestone filler < 0.063 mm	82
Water	155
NA-B2	714
NA-B1	408
NA-CS	408
NA-FS	510
Water-to-binder ratio	0.45
Slump (cm)	4.9 ± 0.2

Table 3
Mix design (kg/m^3).

	RHPC	MAHPC25/EAHPC25	MAHPC100/EAHPC100
Cement	400	400	400
Water	150	160	195
NA-B2	690	520	0
NA-B1	390	295	0
NA-CS	380	285	0
NA-FS	470	355	0
Coarse RA	0	245	980
Fine RA	0	190	760
Superplasticiser	8	8	8

The physical properties of RA are also shown in Table 1, in which its lower density and higher water absorption compared to NA can be observed. Furthermore, RA exhibited a continuous gradation, adequate for concrete production (Fig. 1).

2.2. Mix design

Firstly, the composition of the reference mix, labelled "Reference HPC", RHPC, was defined. The aim was to have a high-workability HPC, S4 class as per EN 206 [36]. For this purpose, three different actions were performed:

- The proportions of aggregate and cement were established according to Eurocode 2 [37]. A current cement content (400 kg/m^3) in the production of HPC was considered. No mineral additions were included to avoid any interaction between the materials used [20]. Thus, only the effects of RA and their maturity were studied;
- The content of each NA was defined by a minimum square adjustment to the Faury curve with a maximum aggregate size of 22 mm. Thus, regarding the total aggregate volume, it was decided to add 35% NA-B2, 20% NA-B1, 20% NA-CS, and 25% NA-FS (55% coarse aggregate and 45% fine aggregate);
- Finally, an effective w/c ratio equal to 0.35 was defined, according to the water absorption in 10 min of NA (mixing time). This low w/c ratio, not enough to obtain a high workability, was compensated by adding a superplasticiser, and by the mixing process (see section 2.3).

After defining the reference mix, 25% and 100% of both coarse and fine NA were replaced with RA. The water content when adding RA was adjusted according to their water absorption in 10 min (Table 1), which was the mixing time (section 2.3). Nevertheless, as the aggregates were used in environmental conditions, this amount of water was slightly modified in an empirical way to compensate the natural moisture of RA. The aim in all mixes was to obtain a constant slump (180 ± 10 mm), which allowed disregarding the influence of water on the results obtained. Moreover, the PC was crushed at two different ages: after a 7-day air curing period (early-age RA, labelled EA), and after a 6-month air curing period (matured RA, labelled MA). These two ages were chosen to analyse the effect of the shrinkage of RA in detail. While at 6 months the shrinkage of concrete can be considered as having ended, it is still very high 7 days after its manufacturing. Thus, the effect of the maturity of RA on the shrinkage of HPC could be clearly evaluated. Four mixes were produced with RA: MAHPC25, MAHPC100, EAHPC25, and EAHPC100.

Through this mix design, it was possible to compare a commercial situation, using matured RA, and a situation that only occurs in research works, as is the use of early-age RA. This study shows the importance of considering in research the maturity of RA in order to provide a reliable and accurate approach to the behaviour of commercial concrete produced with RA.

The composition of all mixes performed is shown in Table 3, in which all the aspects addressed can be seen. Furthermore, the joint gradation of the mixes with 0%, 25% and 100% RA is shown in Fig. 2. These gradation curves are compared with both the Faury and Fuller curves, which are approximations to get an optimum aggregate packing when producing concrete. It can be observed that all mixes had a continuous gradation and that their adjustment to the Faury and Fuller curves was correct. Therefore, the aggregates presented an adequate packing in all mixes.

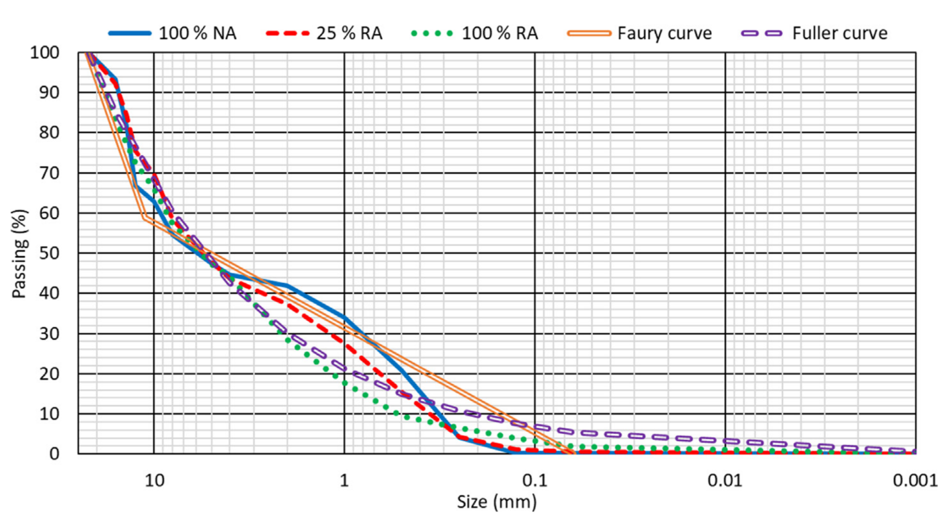

Fig. 2. Joint gradation of the mixes.

Table 4
Hardened-state tests.

Test	Standard [36]	Age (days)	Specimen type
Hardened density	EN 12390–7	7, 28	10x10x10-cm cubic specimens
Ultrasonic pulse velocity	EN 12505–4	7, 28	15x15x15-cm cubic specimens
Compressive strength	EN 12390–3	7, 28, 91 [1]	15x15x15-cm cubic specimens
Splitting tensile strength	EN 12390–6	28	15x30-cm cylindrical specimens
Modulus of elasticity	EN 12390–13	28	15x30-cm cylindrical specimens
Autogenous shrinkage	–	From 1 to 91	10x10x50-cm prismatic specimens
Total shrinkage	LNEC-E398 [40]	From 1 to 91	10x10x50-cm prismatic specimens

[1] The 91-day tests were performed only on the EA mixes to study the development of strength of early-age RA

2.3. Mixing process

Mixing processes by stages allow increasing the workability of concrete, as they maximize both the water absorption of the aggregates and the hydration of cement [39]. All the mixes studied in this research were produced using a two-stage mixing process to get a high slump: 180 ± 10 mm, S4 slump class as per EN 206 [36]:

- The first stage consisted of adding all the aggregates (NA and/or RA) and 70% of the mixing water in a vertical-axis mixing machine. All materials were mixed for 4 min;
- In the second stage, the mixer was stopped for 2 min, and the cement, the remaining water, and the superplasticiser were added. It was then mixed for another 4 min before the fresh tests were conducted.

The PC was also manufactured that way, but considering the limestone filler, added to complement cement (Table 2), as an aggregate. Therefore, it was added in the first stage to improve workability.

2.4. Experimental procedure

After mixing, two determinations of the slump, EN 12350–2 [36], were performed, one minute apart. The average slump obtained in all mixes had to be 180 ± 10 mm. Subsequently, the fresh density according to EN 12350–6 [36] was determined (two measurements) and the necessary specimens to conduct the hardened tests were produced. The specimens remained for around 22 h in the indoor environment of the laboratory (60 ± 5% humidity and 20 ± 2 °C temperature). Subsequently, mechanical-tests specimens were demoulded and kept in a moist room (95 ± 5% humidity and 20 ± 2 °C temperature) until testing time. The specimens in which the hardened density and shrinkage were measured were stored in a dry chamber (45 ± 5% humidity and 20 ± 2 °C temperature) until testing age or throughout the whole test respectively. The tests performed are collected in Table 4, in which the standards, the testing age, and the type of specimens used are also shown. All results in these tests, shrinkage ones included, were obtained as the arithmetic mean of two measurements.

There are no standards for the measurement of long-term autogenous shrinkage of concrete. Nevertheless, there are some considerations for its determination in the short-term (up to 2–3 days from the mixing end) [16], that can also be considered in the long-term. Therefore, the procedure for measuring the short-term autogenous shrinkage was extended to long-term autogenous shrinkage. Both autogenous and total shrinkage were measured in the same way, but the autogenous-shrinkage specimens were wrapped with aluminium foil tape to prevent water evaporation [30], as shown in Fig. 3.

From 22 h to 24 h after casting, the autogenous-shrinkage specimens were wrapped with aluminium foil tape. So, both autogenous and total shrinkage started to be measured 24 ± 0.5 h after the end of the mixing process. This moment is considered the "time zero" of autogenous shrinkage in high-performance pastes, *i.e.* the moment at which a solid "stable" skeleton is formed inside concrete [28] . Misusing this "time zero" can lead to measure plastic shrinkage (if started earlier) or not measure a large strain (if started later). Both shrinkages were measured every day during the first week, three times during the second week, twice during the third and fourth weeks, and once per week until the concrete reached an age of 91 days. This age of completion of the shrinkage tests was defined in accordance with other similar studies [23,38].

To perform the shrinkage measurements, a shrinkage equipment (Fig. 3) with a precision of ± 1 μm (±0.001 mm) was used. Furthermore, each shrinkage measurement on each specimen was performed 4 times, 2 in each direction, to ensure adequate accuracy and to obtain reliable results.

If both autogenous and total shrinkage are known and autogenous shrinkage is not disregarded, it is possible to calculate the drying shrinkage by subtracting the autogenous shrinkage from the total shrinkage. This procedure is collected in the formulation of Eurocode 2 [37], which is shown in equation 1. These three shrinkage types are analysed in section 3, in which shrinkage values are represented with a negative sign to reflect the shortening experienced by HPC. Finally, apart from shrinkage of the HPC mixes, shrinkage of the PC was also measured to perform a detailed analysis of the shrinkage of the HPC produced with early-age RA.

All the aspects addressed in section 2 are summarized in the flowchart of Fig. 4, in which all the tests and experimental plan carried out can be observed.

Fig. 3. Total-shrinkage specimen (up), autogenous-shrinkage specimen (in the middle), and shrinkage equipment (down).

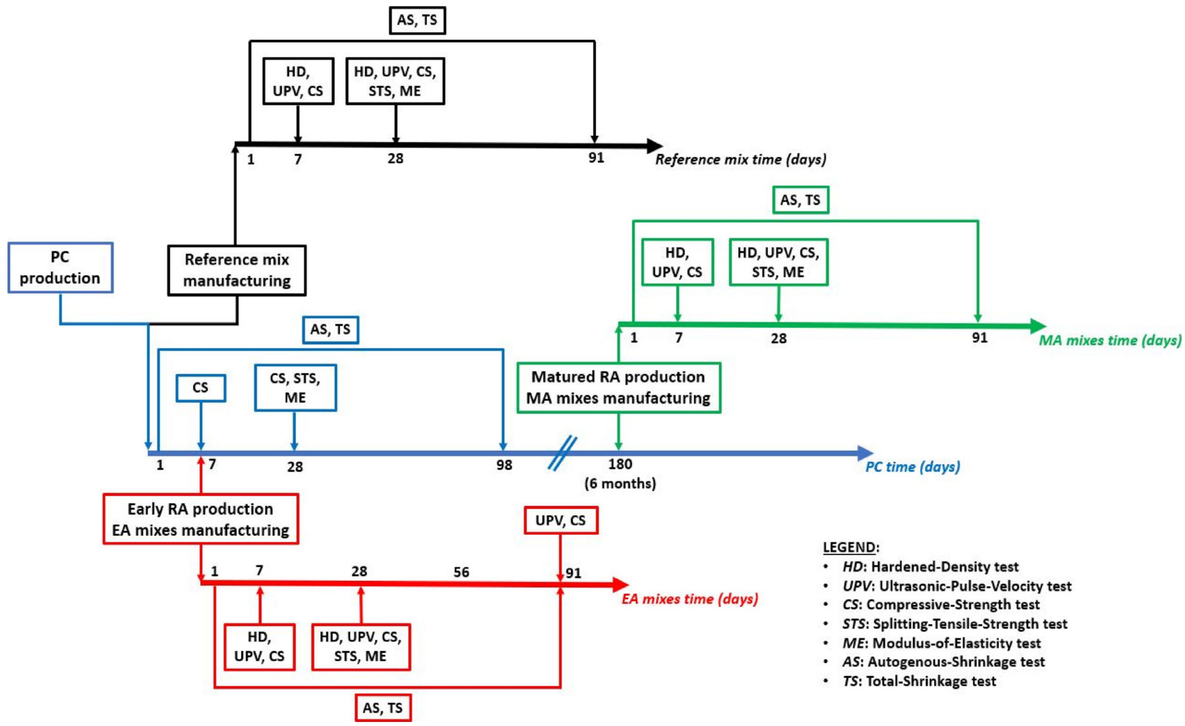

Fig. 4. Experimental procedure.

3. Results and discussion

3.1. Fresh properties

3.1.1. Workability

One of the design objectives of the mixes was to get a slump of 180 ± 10 mm in all the mixes. As shown in Table 5, all the mixes fulfilled this requirement and could be classified as S4 workability class as per EN 206 [36].

These slump values were obtained by increasing the effective w/c ratio of HPC when RA were incorporated. This compensated the higher water absorption of RA compared to NA (Table 1), especially of fine RA, which has a higher water absorption than the coarse fraction, due to its greater specific surface area [41]. On the other hand, this increase of water content also allowed compensating the loss of workability due to the irregular shape of RA. This irregular shape increases the friction between the different components of the concrete mix, and, therefore, reduces the slump [42]. Both phenomena, water absorption and friction, were increased with RA content, which led the w/c ratio to grow when adding higher quantities of RA, as in other similar studies [7].

Although the w/c ratio of the mixes with the same content of early-age and matured RA was not modified, the use of early-age RA slightly increased workability. Thus, the slump increased by 1.3% for the mixes with 25% RA, and 0.9% for the mixes with 100% RA. This small increase could be due to the lower strength of PC when it was crushed to produce early-age RA, which resulted in rounder shape of the RA particles that reduced friction between the different components of HPC.

3.1.2. Fresh density

As can be seen in Fig. 5, the fresh density of the mixes decreased linearly with RA content. This was due to the lower density of RA compared to NA [6], and the increase of water content necessary to keep the workability constant [20]. The increase of the air content caused by the use of RA also favoured this phenomenon [43]. The combination of these three aspects led the fresh density in the mixes with 100% RA to decrease by 7.4%.

Concrete exposed to air curing loses mass due to the evaporation of the water released by the aggregate [17]. Therefore, it was expected that the PC would have slightly lower density after 6 months of curing than after a 7-day curing period. This in turn would cause matured RA to be less dense than early-age RA under environmental conditions. This would theoretically result in a lower fresh density of recycled aggregate HPC. However, the fresh density of the mixes manufactured with both early-age and matured RA was the same. The reduction of concrete density caused by RA's maturity was minimal.

Fig. 6 shows the ratio between the theoretical density calculated from the composition of each mix and the fresh density of HPC. The fresh density was always lower than the theoretical density because the air content is not directly considered in the calculation of the theoretical density, but it has an important role on the value of fresh density obtained [7]. Furthermore, this ratio was lower the higher the amount of RA added, due to the increased air content caused by the use of RA [26]. Again, the maturity of RA did not influence this relationship.

Table 5
Slump and w/c ratio of the mixes.

Mix	Slump (cm)	w/c ratio	Effective w/c ratio
RHPC	18.55 ± 0.21	0.373	0.350
MAHPC25	18.10 ± 0.14	0.400	0.354
MAHPC100	17.30 ± 0.13	0.480	0.362
EAHPC25	18.33 ± 0.18	0.400	0.354
EAHPC100	17.45 ± 0.14	0.480	0.362

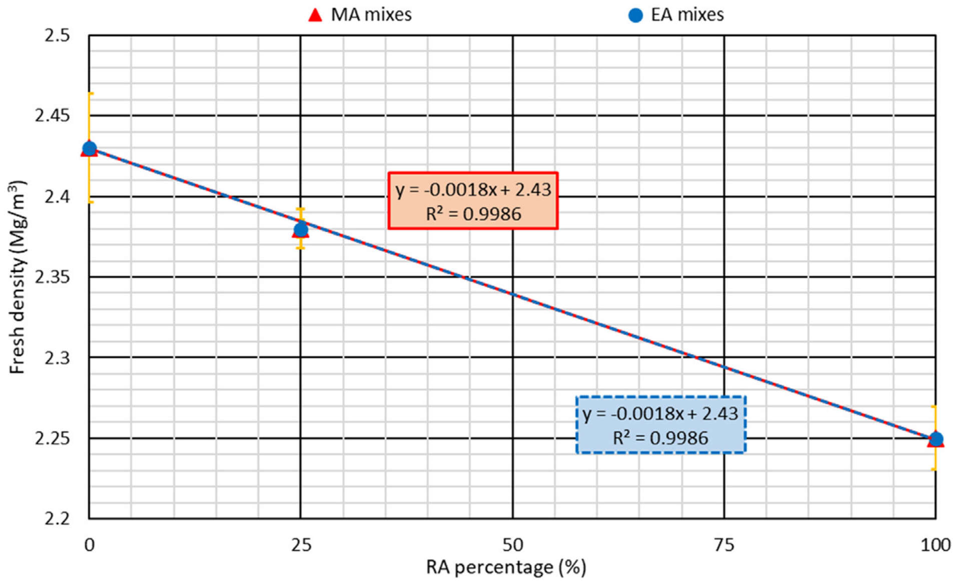

Fig. 5. Fresh density of the mixes.

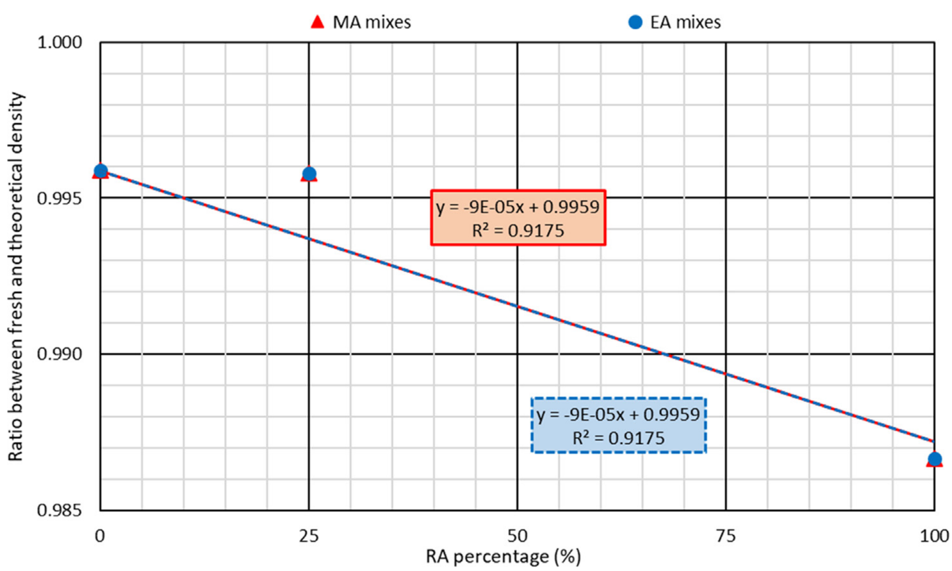

Fig. 6. Relationship between fresh and theoretical density of the mixes.

3.2. Mechanical properties

3.2.1. Hardened density

The hardened density of the mixes is shown in Fig. 7, in which a similar behaviour to that of the fresh density can be observed. On the one hand, at a specific age (7 or 28 days), the hardened density decreased linearly with the RA content. Again, the low density of RA [34], as well as the increase in water and air content that its incorporation caused [14], explain this evolution. On the other hand, the maturity of RA did not influence the hardened density, since the same values were obtained regardless of the maturity of RA used.

Concerning the evolution of the hardened density over time (Fig. 7), it slightly decreased from 7 to 28 days. According to the literature, this is due to the drying process (water evaporation) that concrete undergoes during dry curing [17], as performed in this study for this test. Thus, the loss of mass that concrete experienced at 28 days was greater than at 7 days, while the volume of the concrete specimens remained approximately constant. This led to a lower hardened density at later ages. Furthermore, the hardened density, regardless of the age of concrete, was lower than the fresh density due to the above-mentioned evaporation of water [19], as shown in Fig. 8. This figure also shows that the temporal decrease in density was greater in the mixes with high RA contents. The higher water absorption of RA compared to NA resulted in a higher deferred water release by the aggregates, which in turn increased water evaporation, mass loss, and density reduction [16].

3.2.2. Compressive strength

The most important property of concrete in the hardened state is compressive strength, which is shown for the mixes of this research in Fig. 9. In addition, Table 6 shows the effect of each factor (RA content and their maturity) on compressive strength.

According to Fig. 9, compressive strength decreased linearly with the use of RA, regardless of the age of concrete, similarly to

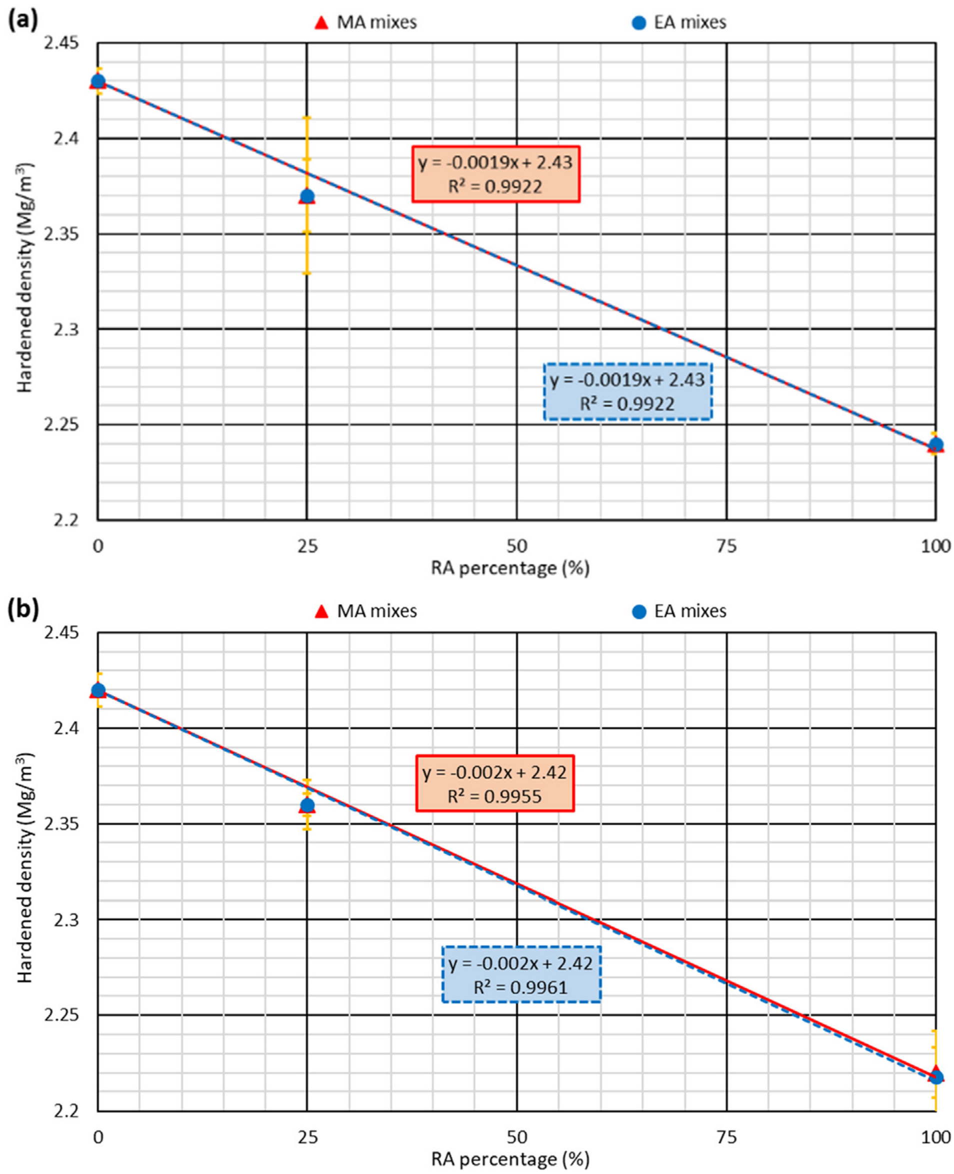

Fig. 7. Hardened density of the mixes: (a) at 7 days; (b) at 28 days.

other studies [38]. However, there are other valuable aspects to highlight in relation to the results obtained:

- The reduction of compressive strength caused by the incorporation of RA was lower for HPC than for conventional concrete when adding normal-quality RA (matured RA). In this study, the loss of strength at 28 days for 100% coarse and fine RA was around 20%, while for conventional concrete this decrease in compressive strength can reach 40% [44]. As stated in the introduction, this behaviour is associated with the mix design of HPC. Its high microstructural density minimizes the negative aspects of RA, such as the appearance of ITZ with poor adhesion [19] or the presence of mortar particles [18], compared to conventional concrete when subjected to compressive stresses;
- The quality (strength and stiffness) of PC from which RA are obtained has significant influence on the behaviour of recycled aggregate concrete [44]. Therefore, RA from higher-quality PC provide greater strength to the concrete produced with them [14]. As early-age RA were produced at an age at which PC exhibited lower strength and stiffness, the effect of RA's maturity on the compressive strength of HPC was similar to that of using PC of different quality [45,46]. Therefore, HPC produced with matured RA, of higher quality than early-age RA, had a higher compressive strength at both 7 and 28 days. 91-day compressive strength of early-age RA mixes was similar to 28-day compressive strength of mixes with matured aggregate. Comparing the compressive strength at both ages, the decrease at 7 days was higher than at 28 days because of the strength and stiffness development of RA themselves. The additional strength reduction caused by the maturity of RA was risen when increasing the RA content of the mixes;
- Finally, the compressive-strength development over time of the mixes was slower as the RA ratio increased. This was attributed to the higher water absorption of RA compared to NA, which leads to a greater release of water deferred in time [47]. This in turn improves the bond strength in the ITZ due to the formation of new calcium-silicate-hydrates [13]. Thus, while the MAHPC25 mix developed at 7 days 94.7% of its 28-day compressive strength, the MAHPC100 mix only developed 90.5%. The development of strength of the early-age RA

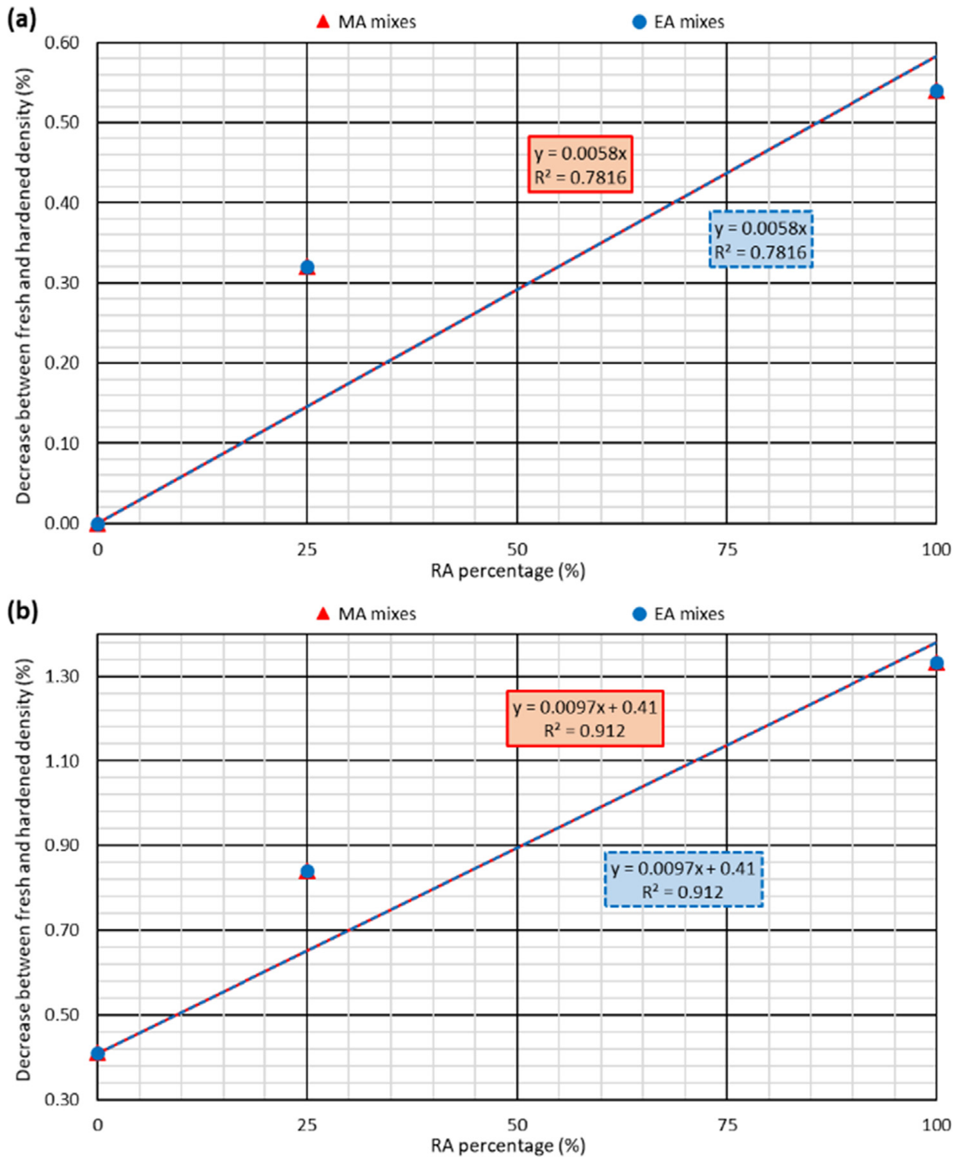

Fig. 8. Decrease between fresh and hardened density: (a) hardened density at 7 days; (b) hardened density at 28 days.

seemed to amplify this behaviour because early-age-RA mixes presented slightly lower percentages of compressive strength at 7 days. These aspects addressed can also be observed in the percentage decreases caused by the use of both early-age and matured RA (Table 6), which were smaller at 28 days than at 7 days.

3.2.3. Splitting tensile strength

The 28-day splitting tensile strength of the different mixes and the decrease caused by each factor (RA content, and RA's maturity) are shown in Fig. 10 and Table 7, respectively. According to the results, the use of RA decreased the splitting tensile strength. Thus, the reference mix showed a splitting tensile strength of 3.58 MPa, while it was 2.50–2.60 MPa in the 100%-RA mixes. This behaviour was caused by the higher porosity of the mixes as the waste content increased [43]. Furthermore, the bond strength between RA and the cementitious matrix was lower than when using NA [6]. This phenomenon is explained by the creation of weaker ITZ when the amount of RA increased [8]. The high dependence of the splitting tensile strength on the quality of the ITZ and the bond strength resulted in a more pronounced decrease than for compressive strength (Table 6 and Table 7). The use of low RA contents was more harmful than expected according to the linear adjustment obtained (Fig. 10), a phenomenon also observed in other studies [19,38].

The maturity of RA also affected the results obtained, which were a little worse when early-age RA were used (decrease around 3–4%). As in compressive strength, this behaviour is attributed to the lower quality of RA when a PC from an early age is used for its production. This notably affects the bond strength [13], an aspect that significantly conditions the splitting tensile strength of concrete [39]. Although this effect was more noticeable in mixes with 100% RA, no linearity was detected between the amount of early-age RA added and the decrease in splitting tensile strength due to RA's maturity.

3.2.4. Modulus of elasticity

The modulus of elasticity of the different mixes was measured at 28 days on 15x30-cm cylindrical specimens. The values obtained are shown in Fig. 11, where the elastic stiffness of the HPC decreased linearly as the RA content increased. The high accuracy of this relationship is explained by the robust behaviour of this

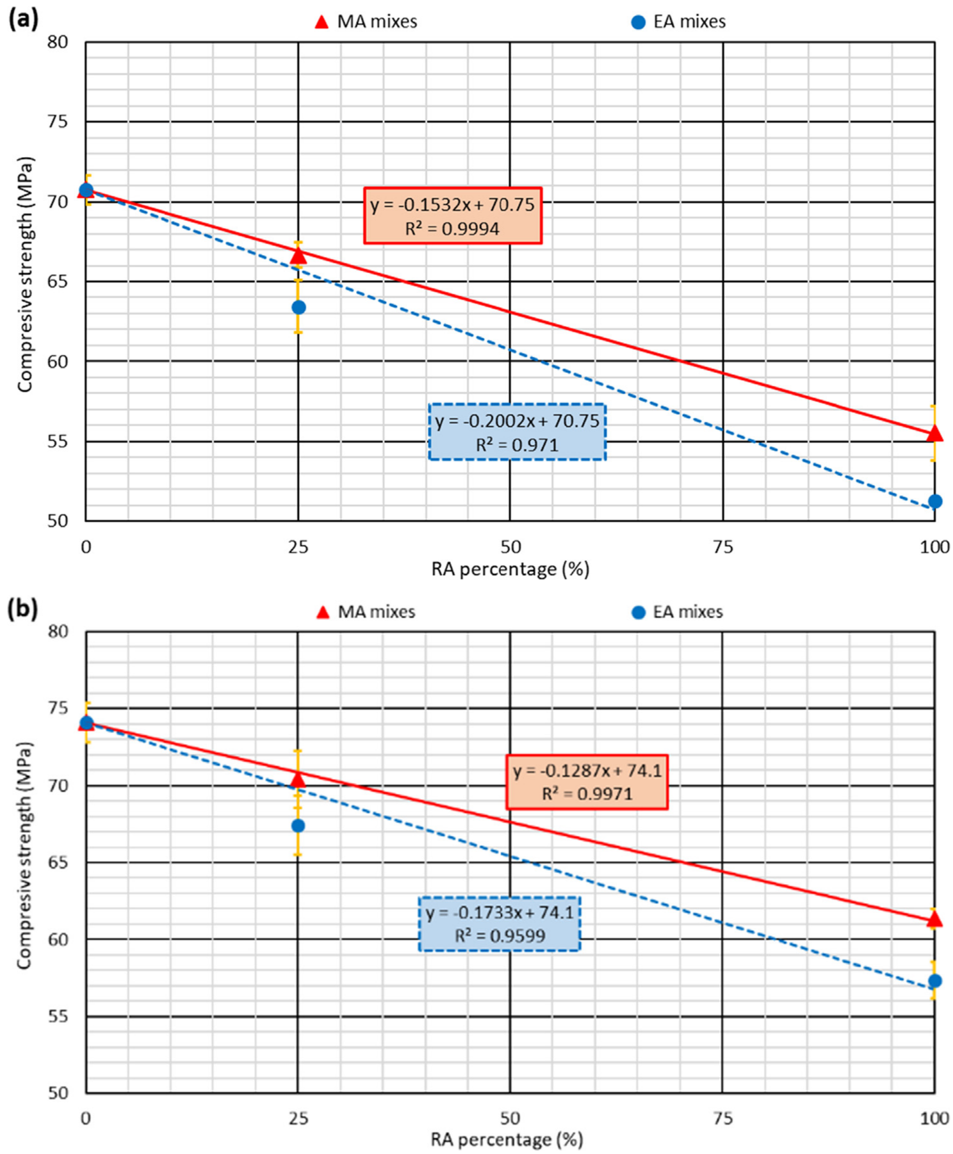

Fig. 9. Compressive strength of the mixes: (a) 7 days; (b) 28 days.

Table 6
Compressive strength (standard deviation in brackets) and effect of each factor.

	RHPC	MAHPC25	EAHPC25	MAHPC100	EAHPC100
Compressive strength at 7 days (MPa)	70.8 (0.9)	66.7 (0.8)	63.5 (1.6)	55.5 (1.7)	51.3 (0.2)
Compressive strength at 28 days (MPa)	74.1 (1.3)	70.4 (1.9)	67.5 (1.8)	61.4 (0.6)	57.4 (1.2)
Compressive strength at 91 days (MPa)	–	–	71.9 (1.6)	–	61.2 (1.8)
Δ RA content[1] (%) at 7 days	–	− 5.8	− 10.3	− 21.6	− 27.5
Δ RA content[1] (%) at 28 days	–	− 5.0	− 9.0	− 17.2	− 22.6
Δ RA's maturity[2] (%) at 7 days	–	–	− 4.8	–	− 7.6
Δ RA's maturity[2] (%) at 28 days	–	–	− 4.2	–	− 6.5
Δ 7–28 days[3] (%)	95.5	94.7	94.1	90.5	89.5

[1] Percentage decrease due to the use of RA (compared to RHPC's compressive strength).
[2] Percentage decrease when adding early-age RA (EA mixes compared to MA mixes with the same RA content).
[3] Percentage of compressive strength developed at 7 days regarding the 28-day compressive strength.

property of HPC against changes in its composition [31]. Therefore, the effect of using low ratios of RA in HPC is not so negative (Table 8), unlike the behaviour observed in the splitting tensile strength.

If the decrease of elastic stiffness of recycled aggregate HPC is analysed, the reduction in modulus of elasticity was around 32–35% for 100% RA (Table 8). These values are similar to other studies that addressed the simultaneous use of coarse and fine RA in the production of HPC [7,48]. The modulus of elasticity depends on the stiffness of both the aggregates and the cementitious matrix [13]. Since the stiffness of RA is lower than that of NA, recycled aggregate concrete generally has a lower modulus of elasticity

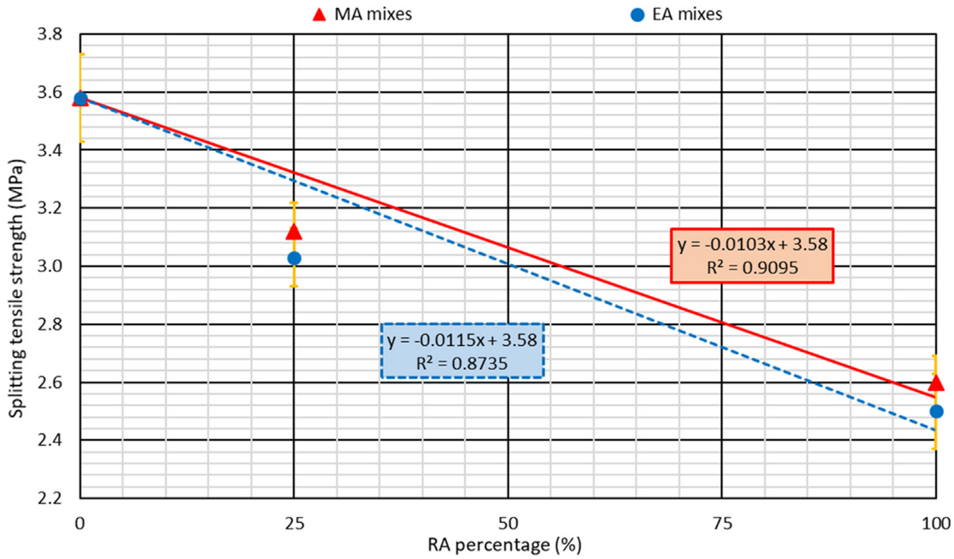

Fig. 10. Splitting tensile strength of the mixes at 28 days.

Table 7
Splitting tensile strength (standard deviation in brackets) and effect of each factor.

	RHPC	MAHPC25	EAHPC25	MAHPC100	EAHPC100
Splitting tensile strength (MPa)	3.58 (0.15)	3.12 (0.10)	3.03 (0.12)	2.60 (0.09)	2.50 (0.13)
Δ RA content[1] (%)	–	− 12.8	− 15.4	− 27.4	− 30.2
Δ RA's maturity[2] (%)	–	–	− 2.9	–	− 3.8

[1] Percentage decrease due to the use of RA (compared to RHPC's splitting tensile strength).
[2] Percentage decrease when adding early-age RA (EA mixes compared to MA mixes with the same RA content).

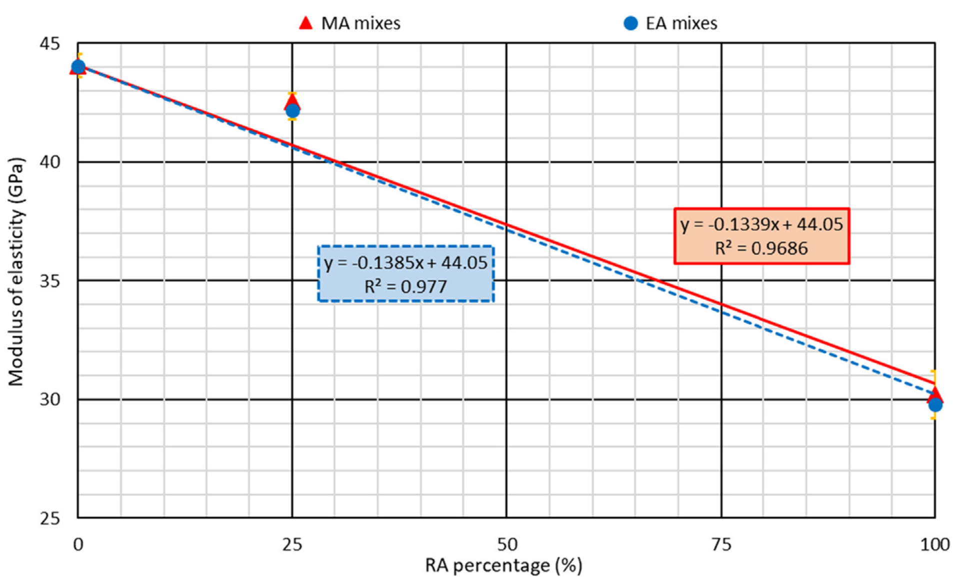

Fig. 11. Modulus of elasticity of the mixes at 28 days.

Table 8
Modulus of elasticity (standard deviation in brackets) and effect of each factor.

	RHPC	MAHPC25	EAHPC25	MAHPC100	EAHPC100
Modulus of elasticity (GPa)	44.1 (0.5)	42.6 (0.4)	42.2 (0.4)	30.2 (1.0)	29.8 (0.2)
Δ RA content[1] (%)	–	− 3.4	− 4.3	− 31.6	− 32.4
Δ RA's maturity[2] (%)	–	–	− 0.9	–	− 1.3

[1] Percentage decrease due to the use of RA (compared to RHPC's modulus of elasticity).
[2] Percentage decrease when adding early-age RA (EA mixes compared to MA mixes with the same RA content).

[8]. The slightly lower modulus of elasticity in the mixes produced with early-age RA is explained by the elastic stiffness of PC when they were produced. Nevertheless, compared to the decrease of compressive strength, the loss of modulus of elasticity due to the maturity of RA (around 1%) was almost negligible.

3.2.5. Ultrasonic pulse velocity (UPV)

UPV was determined on 15-cm cubes at 7 and 28 days, whose values are shown in Fig. 12. In addition, Table 9 shows the variation caused by each modification introduced in the composition of HPC (RA content, and RA's maturity). All UPV values obtained, between 4,200 and 5,400 m/s, corresponded to good quality concrete [49].

The compressive strength, modulus of elasticity, and UPV of concrete are interrelated [19]. Therefore, several of the aspects discussed in previous sections are also valid for the behaviour of mixes regarding UPV:

- UPV decreased with the increase of RA content. UPV is highly conditioned by the stiffness, density, and porosity of concrete [49]. Therefore, the decrease in density and stiffness, and the increase in porosity caused by the incorporation of this waste explains this behaviour [7]. Furthermore, as in the other properties, the decrease of UPV was linearly correlated with the RA incorporation ratio of the mix;
- UPV in the mixes produced with early-age RA was 2–3% lower than that of the mixes with matured RA at 7 days. As the density of the mixes was the same regardless of the maturity of the RA used (Fig. 7), this phenomenon was attributed to the lower stiffness of early-age RA [13]. The increase in the stiffness of RA over time led this reduction caused by the maturity of RA to be reduced from 7 to 28 days (Table 9). Nevertheless, this beneficial effect of the increase in RA's stiffness over time was almost negligible when using 100% RA.

However, there was a very important difference regarding the observed behaviour in compressive strength. The temporal increase (from 7 to 28 days) of UPV did not exhibit a clear trend, as the MAHPC25 mix increased UPV faster than the reference mix. This could be attributed to the deferred increase of the bond strength experienced by recycled aggregate concrete not being so

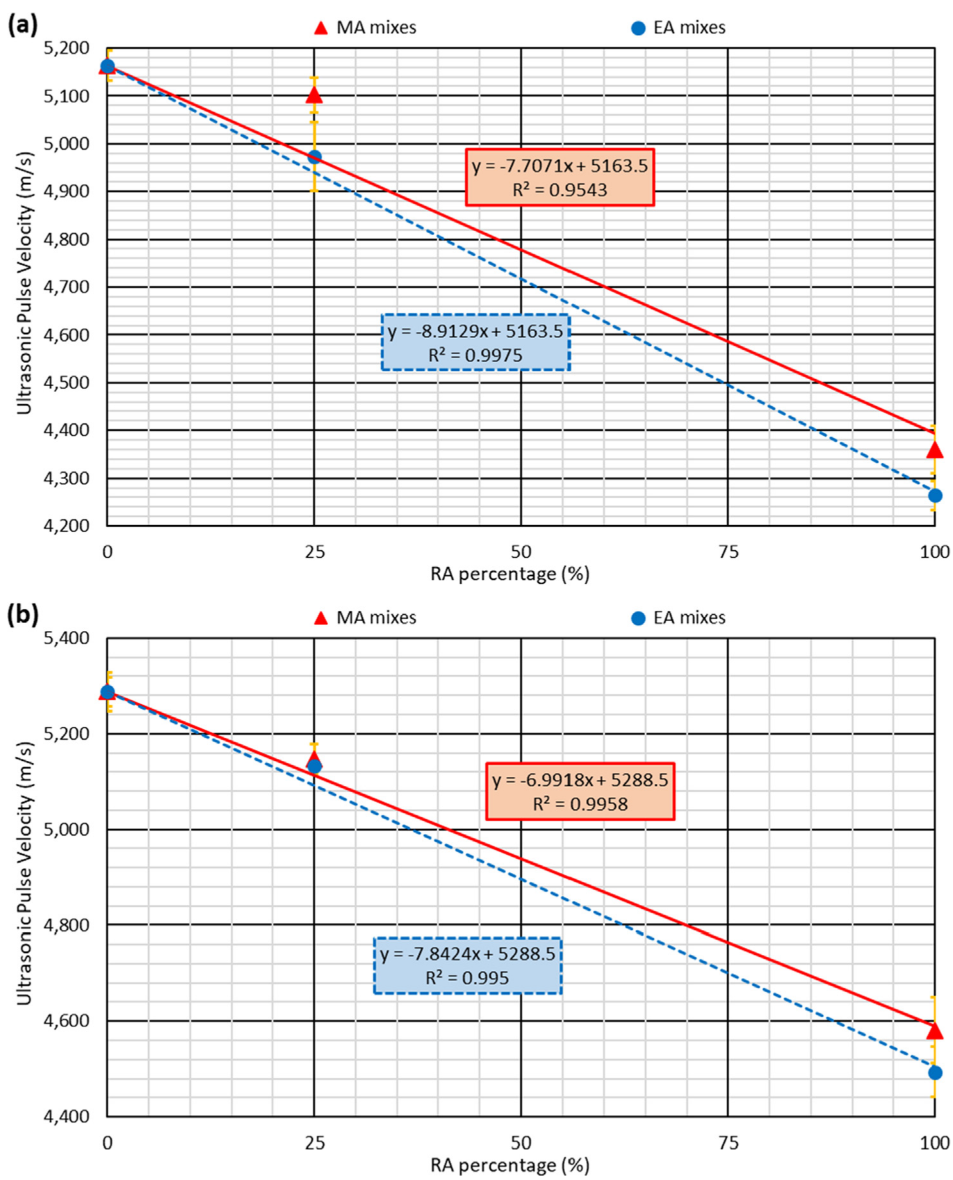

Fig. 12. UPV of the mixes: (a) 7 days; (b) 28 days.

Table 9
UPV (standard deviation in brackets) and effect of each factor.

	RHPC	MAHPC25	EAHPC25	MAHPC100	EAHPC100
UPV at 7 days (m/s)	5,163.5 (30.4)	5,102.0 (36.1)	4973.5 (71.2)	4360.0 (49.5)	4264.0 (29.9)
UPV at 28 days (m/s)	5288.5 (40.4)	5147.0 (31.1)	5133.5 (19.1)	4581.0 (69.3)	4494.0 (52.3)
Δ RA content[1] (%) at 7 days	–	– 1.2	– 3.7	– 15.6	– 17.4
Δ RA content[1] (%) at 28 days	–	– 2.7	–2.9	– 13.4	–15.2
Δ RA's maturity[2] (%) at 7 days	–	–	– 2.5	–	– 1.9
Δ RA's maturity[2] (%) at 28 days	–	–	– 0.3	–	– 1.8
Δ 7–28 days[3] (%)	97.6	99.1	96.9	95.2	95.1

[1] Percentage decrease due to the use of RA (compared to the UPV of RHPC).
[2] Percentage decrease when adding early-age RA (EA mixes compared to MA mixes with the same RA content).
[3] Percentage of UPV developed at 7 days regarding the UPV at 28 days.

relevant in this property as in compressive strength [6]. However, it could also be due to the variability of UPV, which can have quite large oscillations [49].

3.3. Shrinkage

3.3.1. Autogenous shrinkage

The autogenous shrinkage of the mixes during the first 91 days of curing, measured in wrapped specimens, is shown in Fig. 13.

The large cement content of HPC results in high shrinkage [8]. Accordingly, the developed mixes presented high values of autogenous shrinkage, between −0.15 and −0.19 mm/m at 91 days. As expected, these values were greater than those measured on conventional recycled aggregate concrete, in which maximum values between −0.10 and −0.12 mm/m were obtained [27]. Moreover, autogenous shrinkage did not stabilize within the first days, but experienced a continuous increase up to 91 days. This proved that the hydration of the cement occurred in a very delayed way, and not only during the first hours after mixing, as it had been considered so far in recycled aggregate HPC [31].

The water absorption of RA is much higher than that of NA, which in principle leads the autogenous shrinkage of recycled aggregate HPC to decrease in the short-term. RA release more water in a delayed way than NA, which enables a more efficient replacement of the water consumed during cement hydration after mixing, a phenomenon commonly called internal curing [17]. The effect of the matured RA in the long-term was exactly the same (Fig. 13). So, the use of 100% RA allowed reducing autogenous shrinkage by approximately 20% at 91 days. The effect of the addition of 25% RA was minimal, because the MAHPC25 mix exhibited approximately the same shrinkage as the RHPC mix. This behaviour is explained by the lower stiffness of the matured RA compared to NA, which leads to a lower opposition of RA to the contraction experienced by the cementitious matrix [42]. While the loss of stiffness is compensated by the internal curing effect when adding 100% RA, the beneficial effect caused by water absorption is smaller when adding low amounts of RA, and it is practically offset by the decrease of stiffness.

The autogenous shrinkage of the mixes with early-age RA was around 10% higher than that of the mixes in which matured RA were used. Two different aspects explain this behaviour. First, the lower stiffness of early-age RA due to the increase of stiffness of PC over time [13]. Second, the autogenous shrinkage of RA themselves due to the use of very young PC for their production. The shrinkage increase due to early-age RA, compared to the mixes made with the same content of matured RA, was greater in the mixes with higher RA content. The effect of the maturity of RA seemed to amplify approximately proportionally to the amount of RA added.

The approximately expected autogenous shrinkage of the mixes produced with early-age RA could be estimated as the sum of two shrinkages. On one side, the autogenous shrinkage of the mixes

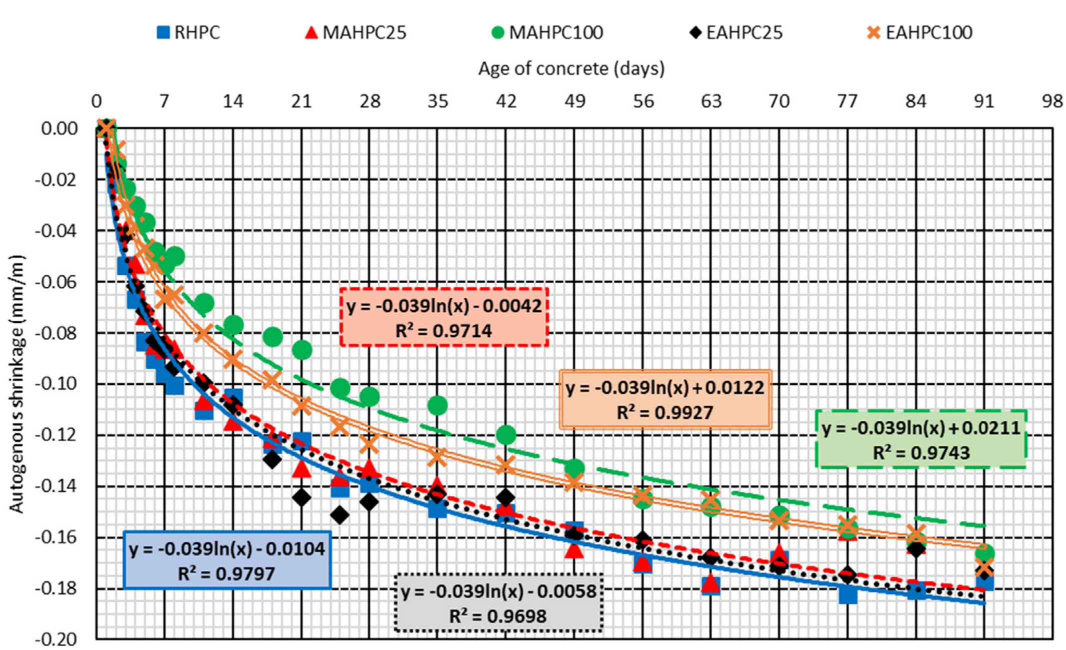

Fig. 13. Autogenous shrinkage of the mixes.

with the same amount of matured RA, which allows considering the effect of the higher water absorption and lower stiffness of matured RA than NA's. On the other, the autogenous shrinkage of PC multiplied by the percentage of RA added to recycled aggregate HPC. In this addend, only the shrinkage of PC from the age at which the RA is produced should be considered. This simplification is suitable as a simple approximation if it is considered that NA are infinitely rigid and evenly distributed in the concrete mix [24]. These expected autogenous shrinkage values are shown in Fig. 14, which were higher than the experimentally obtained autogenous shrinkage. In principle, the real autogenous shrinkage of the mixes with early-age RA should be greater than the expected one due to the increase of shrinkage caused by the lower stiffness of early-age RA, compared to their matured counterparts. However, the early-age RA is believed to have experienced a hydration of their unhydrated cement particles both during the manufacture of the HPC and during the development of the test. This process could have significantly decreased their autogenous shrinkage, since the shrinkage of concrete can be reduced by increasing the ambient humidity, or by keeping concrete moist [30]. This phenomenon was more noticeable in the EAHPC100 mix, which shows that this phenomenon was amplified by the increase of RA content.

3.3.2. Drying shrinkage

The drying shrinkage of the mixes, determined by subtracting the autogenous shrinkage from the total shrinkage, is shown in Fig. 15. As in autogenous shrinkage, drying shrinkage was higher than that of similar studies that analysed the behaviour of medium-strength concrete [24]. Again, this performance can be explained by the high cement content of HPC, which increases the hydration heat, in turn favouring water evaporation [33]. However, shrinkage due to these aspects was less than the one caused by the deferred hydration of cement when using 100% NA. The autogenous shrinkage of the reference mix, −0.19 mm/m, a mix whose behaviour is not affected by RA, was greater than the drying shrinkage, −0.09 mm/m.

The effect of adding RA in HPC was different from that obtained regarding autogenous shrinkage, since their addition increased drying shrinkage. This behaviour was due to the two aspects explained in detail in the previous section: the higher water absorption of RA and their lower stiffness compared to NA. The higher water absorption of RA makes them release more water later in time. This allows the absorption of capillary water by the cement to be compensated more efficiently, thus reducing autogenous shrinkage [27]. Nonetheless, it also increases the amount of water that can evaporate, which in turn boosts drying shrinkage [50]. Furthermore, the lower stiffness of RA reduces the internal opposition to the volumetric contraction of the cementitious matrix, which also favours this phenomenon [22]. The increase in shrinkage was approximately proportional to the RA content (60% in the MAHPC25 mix and 350% in the MAHPC100 mix). This behaviour was in line with that observed in the fresh-state and mechanical properties, and with the performance reported in other research woks [17].

The effect of adding early-age RA instead of matured RA was the same as in autogenous shrinkage: its use resulted in higher shrinkage. This increase was related to the lower stiffness of early-age RA due to the lower modulus of elasticity of PC at the age at which it was crushed [13], and with the drying shrinkage experienced by early-age RA because of their rheological nature. The shrinkage increased proportionally with the amount of early-age RA added regarding the drying shrinkage of the reference mix. Thus, the EAHPC25 mix exhibited a drying shrinkage 125% higher than that of the reference mix, while this increase for the EAHPC100 mix was 420%. Based on these results, it could be stated that there was a linear relationship between the drying shrinkage and the RA content of HPC regardless of RA's maturity.

The comparison between the expected drying shrinkage, calculated considering the hypothesis indicated in the previous section, and the experimental one is shown in Fig. 16. In this case, the experimental shrinkage was higher than the expected shrinkage. This increase may be due to the lower stiffness of early-age RA compared to matured RA. On the other hand, the hydration of the unhydrated cement particles of early-age RA could have had a positive effect by reducing the drying shrinkage of these aggregates, thus partly compensating the detrimental effect of the lower stiffness of early-age RA. Nevertheless, it was clearly less effective than in autogenous shrinkage. This performance could be like that observed in relation to the amount of water absorbed by RA during mixing. While the pre-soaking of RA seems to be very effective in

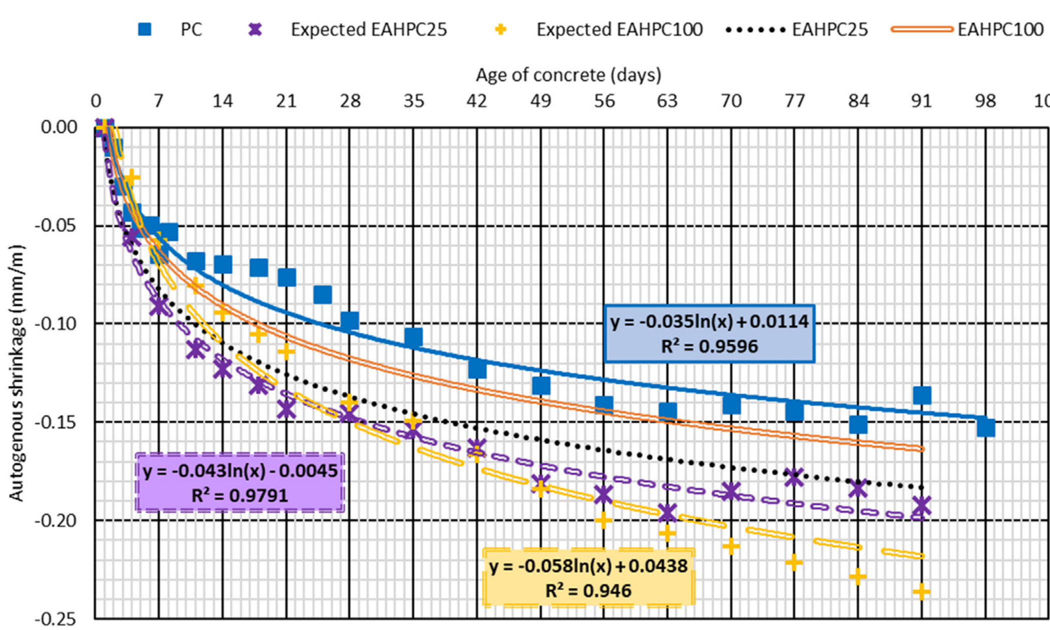

Fig. 14. Comparison between the expected and experimental autogenous shrinkage of the HPC mixes with early-age RA.

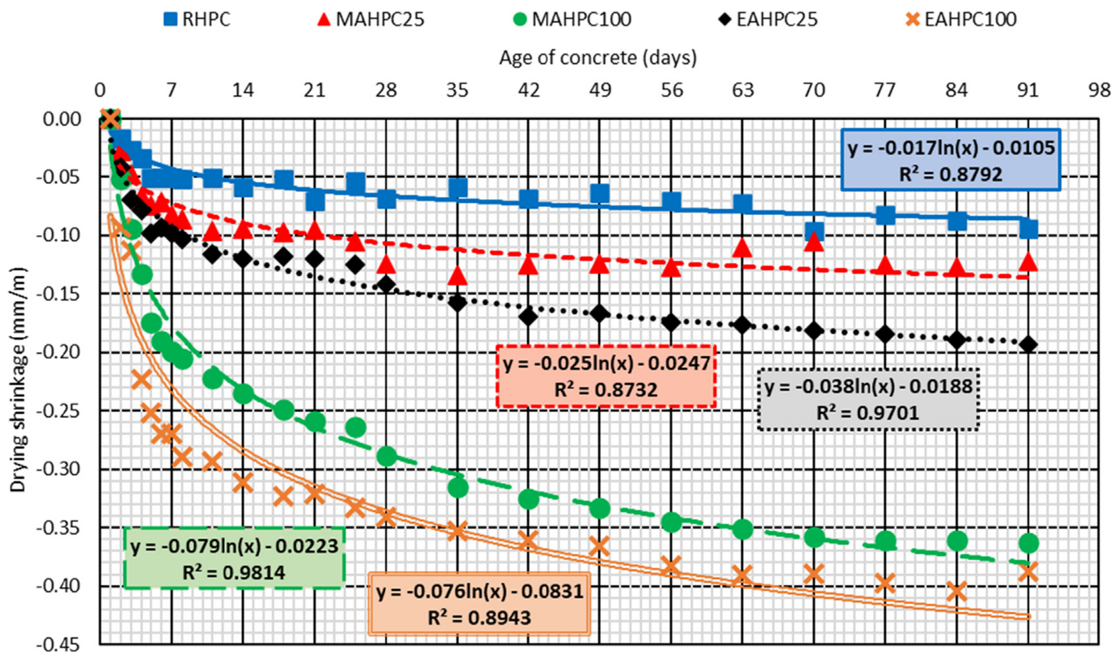

Fig. 15. Drying shrinkage of the mixes.

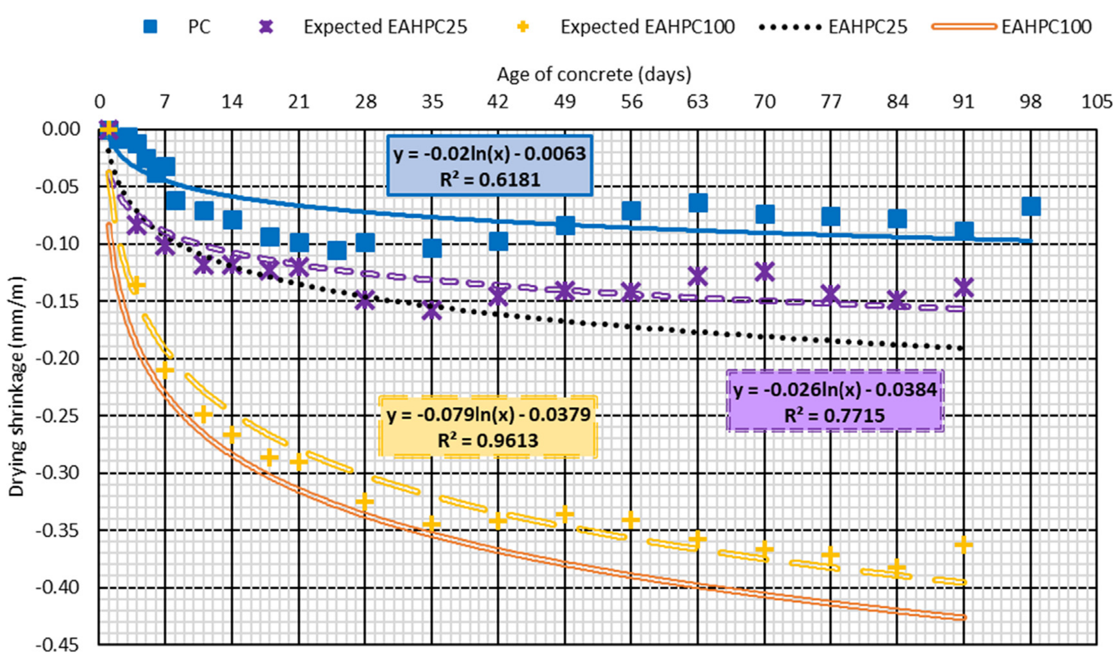

Fig. 16. Comparison between the expected and experimental drying shrinkage of the HPC mixes with early-age RA.

reducing shrinkage, the effectiveness of water compensation during mixing is lower due to the easier and faster evaporation of the water [51]. Since a water-compensation technique was used in this study and water evaporation is not avoided during the measurement of drying shrinkage, the contact time between early-age RA and the absorbed water was lower than in autogenous-shrinkage specimens. In autogenous shrinkage, the wrapping of the specimens allows considering RA as pre-soaked regarding the contact time between RA and water. This situation caused a lower reduction of the drying shrinkage of early-age RA compared to the reduction of autogenous shrinkage, as Fig. 16 show.

3.3.3. Total shrinkage

Fig. 17 shows the total shrinkage of the developed HPC mixes, which was higher than the values commonly obtained in conventional concrete [8]. This type of shrinkage is the one usually evaluated in existing research regarding recycled aggregate concrete [22], and is measured in specimens that are directly in contact with the ambient. Since total shrinkage is the sum of autogenous shrinkage and drying shrinkage, the effect of both early-age and matured RA on total shrinkage was the combination of their individual effects on both types of shrinkage, which were discussed in the previous sections.

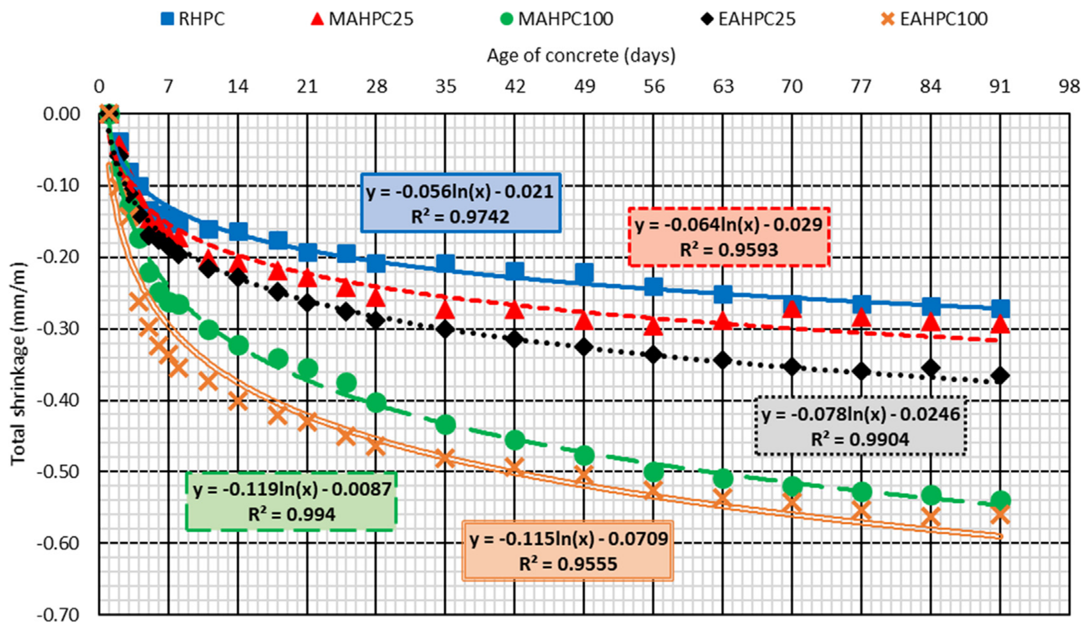

Fig. 17. Total shrinkage of the mixes.

The use of matured RA led to an increase of total shrinkage of HPC, due to its higher water absorption and lower stiffness than NA's [23]. Thus, the use of 25% RA increased total shrinkage by 20%, while 100% RA increased it by around 90%. These values were in line with the findings of other studies that evaluated the shrinkage of HPC manufactured with RA of similar quality [17]. These values also showed that the increase of total shrinkage was lower than that of drying shrinkage due to the decrease of autogenous shrinkage that RA caused. Furthermore, the increase of total shrinkage was approximately linear with the matured RA content of the mix, as in drying shrinkage.

Concerning the use of early-age RA, their effect on total shrinkage was also similar to that on drying shrinkage. Their lower stiffness, compared to matured RA, as well as their own shrinkage, increased total shrinkage of HPC. Once again, a direct proportionality between RA content and total shrinkage of HPC was detected regardless of whether early-age or matured RA were used. Other studies had demonstrated this relationship only when matured RA were used [24]. From the discussion in this paragraph and the previous one, it can be stated that total shrinkage was mainly conditioned by their drying shrinkage, since the same trends were observed in both. This behaviour was due to the greater magnitude of drying shrinkage compared to autogenous shrinkage. The maturity of RA did not affect this aspect.

The comparison between the expected total shrinkage, obtained as the sum of the total shrinkage of both the PC and the mixes with matured RA, and the experimental one is shown in Fig. 18. In this case, both shrinkages were practically the same, which validates the hypothesis of considering NA as an infinitely rigid material for the calculation of the shrinkage of HPC with early-age RA. As the experimental autogenous shrinkage was lower than the expected autogenous shrinkage, and exactly the opposite for drying shrinkage, the combination of both led to a minimal difference between the expected and experimental total shrinkage. This difference was 0.011 mm/m for 25% early-age RA, and 0.021 mm/m for 100% early-age RA at 91 days according to the trend lines in absolute value (Fig. 18). From a global point of view, the increase of shrinkage caused by the lower stiffness of the early-age RA compared to the matured RA was compensated by the decrease of their own shrinkage caused by the hydration of their unhydrated cement particles. Therefore, the total shrinkage of HPC with early-age RA can be reliably predicted as the sum of the total shrinkage of the same mix but made with matured RA, and the total shrinkage of the PC from which the early-age RA was produced, multiplied by the RA content of the mix. This conclusion is novel in the literature.

3.3.4. Statistical analysis of shrinkage results

The results obtained and explained in previous sections were validated by performing an Analysis Of Variance (ANOVA), shown in Table 10. In this case, a three-way ANOVA was conducted, since the factors that influenced the shrinkage of HPC were RA content, maturity of RA, and age of concrete. This implies the existence of three second-order interactions (factors two by two) and a third-order interaction, *i.e.* an overall interaction between all the factors.

The p-values lower than the significance level considered (5%) show the aspects that significantly influenced the shrinkage behaviour of HPC:

- On the one hand, all shrinkages increased over time (age of concrete). On the other, the increase of RA content amplified the variation of shrinkage caused by its use, while the use of early-age RA also increased it substantially. Therefore, all factors significantly affected the three types of shrinkage;
- Concerning the second-order interactions, the interaction between age of concrete and RA content was significant. This means that the relative variation of the shrinkage caused by each RA content, regarding the shrinkage of the reference mix, was different for each instant of time. In addition, the interaction between the content and maturity of RA was also significant. Therefore, the increase of shrinkage caused by using early-age RA instead of matured RA varied depending on its content. There was no significant interaction between RA's maturity and concrete age, so it can be stated that the relative increase caused by early-age RA was similar throughout the testing time;
- Finally, as expected, the third order interaction was also significant. Therefore, each combination of a different content and maturity of RA always resulted in a different shrinkage regardless of the moment in time when it was measured.

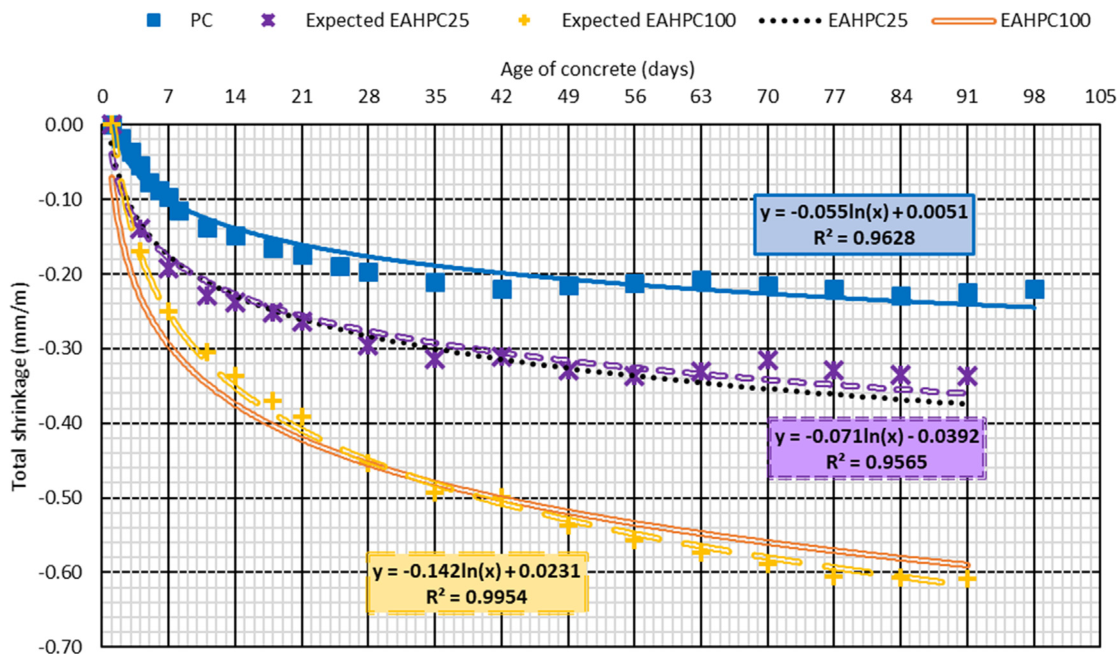

Fig. 18. Comparison between the expected and experimental total shrinkage of the HPC mixes with early-age RA.

Table 10
P-values for the three-way ANOVA for the different shrinkages.

Type of shrinkage	Autogenous	Drying	Total
Concrete age	0.0000	0.0000	0.0000
RA content	0.0000	0.0000	0.0000
RA's maturity	0.0000	0.0000	0.0000
Second-order interaction: Concrete age and RA content	0.0000	0.0000	0.0000
Second-order interaction: Concrete age and RA's maturity	0.0833	0.9701	0.9552
Second order interaction: RA content and RA's maturity	0.0000	0.0000	0.0000
Third-order interaction (global interaction)	0.0000	0.0000	0.0000

3.3.5. Analysis of the EC2

EN 1992: 2004, Eurocode 2 [37] collects a formulation that allows calculating the three types of shrinkage (mm/m) addressed in this study: autogenous shrinkage (ε_{ca}), drying shrinkage (ε_{cd}), and total shrinkage (ε_{cs}). The corresponding equations are listed below, in which t is the age of concrete in days; f_{ck} the characteristic compressive strength of concrete on cylindrical specimens at 28 days in MPa, which was calculated by subtracting 8 MPa from the 28-day average compressive strength; h_0 the average thickness of the concrete section in mm, which is calculated as the quotient of twice its area divided by its perimeter; k_h a coefficient that depends on the average thickness of the section (equal to 1 for the 10x10x50-cm specimens used); and $\varepsilon_{cd,0}$ the drying shrinkage at infinite time, which depends on the strength class of concrete.

$$\varepsilon_{cs}(t) = \varepsilon_{ca}(t) + \varepsilon_{cd}(t) \tag{1}$$

$$\varepsilon_{ca}(t) = -\left[1 - exp\left(-0.2 \times t^{0.5}\right)\right] \times \left[2.5 \times \left(f_{ck} - 10\right) \times 10^{-3}\right] \tag{2}$$

$$\varepsilon_{cd}(t) = -\frac{t-1}{(t-1) + 0.04 \times \sqrt{h_0^3}} \times k_h \times \varepsilon_{cd,0} \tag{3}$$

A maximization analysis of the R^2 coefficient showed that the logarithmic models were the ones that best fitted the different shrinkages evaluated (Fig. 13, Fig. 15, and Fig. 17). On the other hand, the expressions of EC2 [37] would also be suitable if the coefficients and constants of these formulas were adapted to each mix (R^2 coefficients around 85–95% depending on the shrinkage type and mix). However, the development of a different formula for each mix is useless because the standardisation of the model is not possible.

The design of concrete elements is greatly based on statistical adjustment and the use of partial correction coefficients [52]. In order to adapt the EC2 model [37] so that its standardised use for this type of mixes was possible, a model in which the formulas indicated could be used to predict the shrinkage of recycled aggregate HPC (ε^{raHPC}) using this methodology was developed. Thus, the different shrinkages of the mixes could be obtained by Equation 4, Equation 5, and Equation 6.

$$\varepsilon_{cs}^{raHPC}(t) = \varepsilon_{ca}^{raHPC}(t) + \varepsilon_{cd}^{raHPC}(t)$$

$$\varepsilon_{ca}^{raHPC}(t) = \varepsilon_{ca}(t) \times C_{ca}^{HPC} \times C_{ca}^{pRA} \times C_{ca}^{mRA}$$

$$\varepsilon_{cd}^{raHPC}(t) = \varepsilon_{cd}(t) \times C_{cd}^{HPC} \times C_{cd}^{pRA} \times C_{cd}^{mRA}$$

In these equations, the different types of shrinkage calculated according to EC2 [37] are multiplied by various partial correction coefficients to obtain the values for recycled aggregate HPC. These coefficients were different for each type of shrinkage due to the different phenomena on which each of them depends. In addition,

Table 11
Coefficients of the model developed.

Type of shrinkage	C^{HPC}	C^{pRA}			C^{mRA}		
		0% RA	25% RA	100% RA	Matured RA	Early-age RA	
						25% RA	100% RA
Autogenous	2.073	1	1.045	0.284·ln(t)	1	1.006	1.089
Drying	0.164	1	1.731	1.284·ln(t)	1	1.235	0.961

they had a progressive nature, since a different coefficient was proposed for each modification introduced in the composition of the mix. The values of these coefficients are shown in Table 11:

- C^{HPC} - The formulas in EC2 [37] are designed for conventional concrete. This coefficient enables them to be adapted to HPC. A low value was obtained for drying shrinkage because EC2 considers in this calculation both the plastic and drying shrinkage, and the plastic shrinkage was not evaluated in this research work;
- C^{pRA} - This coefficient allows reflecting the effect of RA, and had a different value for each RA content since the content of this waste had a significant effect on the shrinkage of the mixes (see ANOVA, Table 10). In addition, the ANOVA also showed

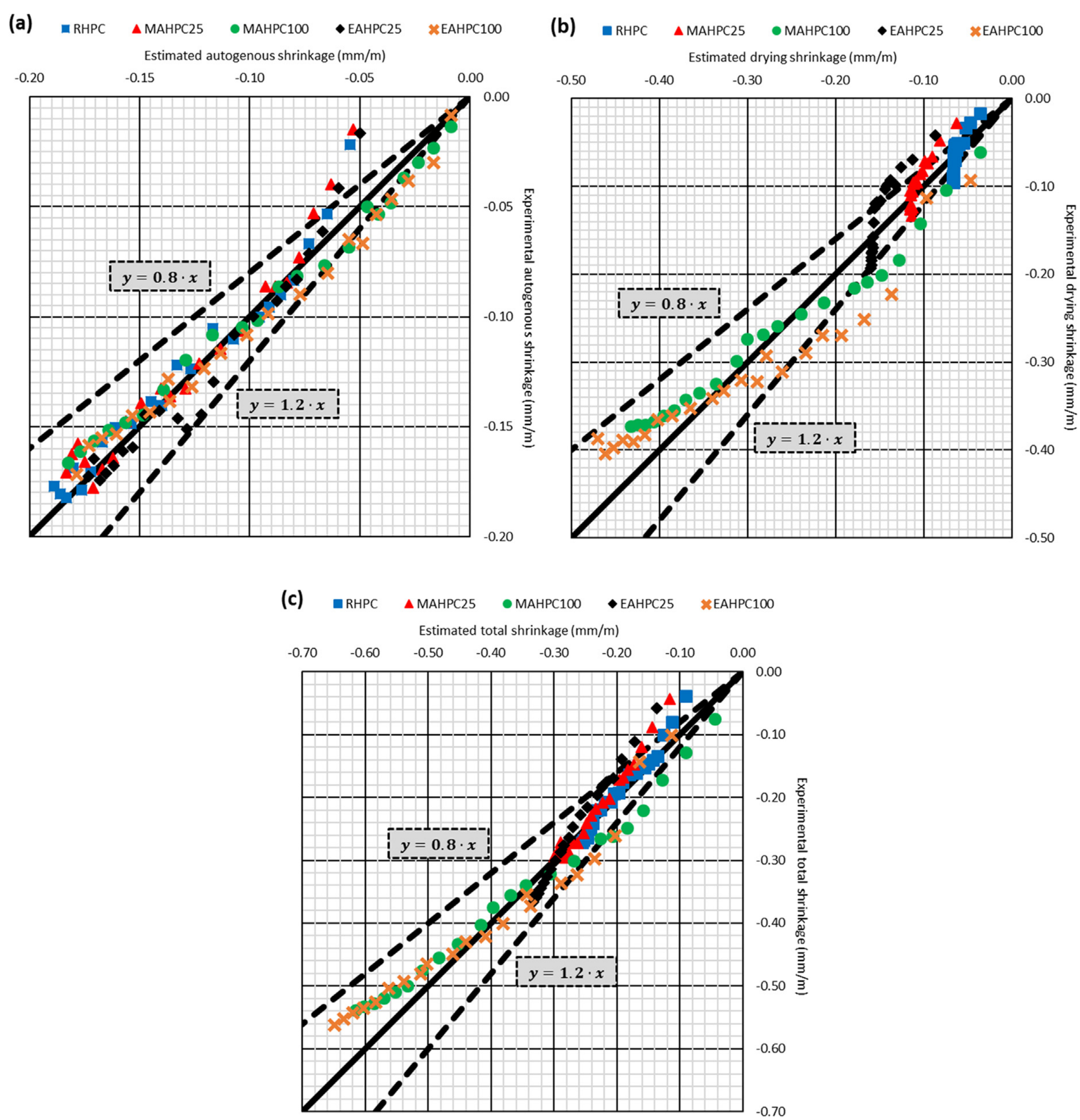

Fig. 19. Comparison between experimental and predicted shrinkage according to the model developed: (a) autogenous shrinkage; (b) drying shrinkage; (c) total shrinkage.

the significance of the interaction between RA content and time. For a RA content of 25%, a correct adjustment was obtained ignoring this aspect. However, for a RA content of 100% the variable time had to be introduced as a logarithmic function to improve the precision of the model;
- C^{mRA} - This coefficient depends on the maturity of RA. A different coefficient was proposed for each RA's maturity and content, since both the maturity of RA and its interaction with RA content were significant (see ANOVA, Table 10).

This model had an overall R^2 coefficient of 91%, and enabled the precise estimation of most of the shrinkage values at different ages, with a maximum deviation of 20%, as shown in Fig. 19. The greatest goodness-of-fit errors occurred at early ages, although this issue is not critical because usually, in the design of concrete elements, it is relevant to know shrinkage in the long-term.

The lack of data in the available bibliography prevents the validation of this model according to other research works. Nevertheless, it shows that, although complex models can be developed to estimate the shrinkage of recycled aggregate concrete [24,27], it is enough to adapt the models available to conventional concrete, as that of EC2 [37]. Furthermore, this model could be adapted to other aspects of RA that affect shrinkage, such as its quality or possible pre-treatments (*e.g.* carbonation) [22] by adding other partial correction coefficients.

4. Conclusions

The rheological nature of recycled aggregates (RA) causes their maturity to affect the behaviour of the concrete manufactured with them. Therefore, in this article, the influence of the maturity of RA on both the mechanical behaviour and the autogenous, drying, and total shrinkage of high-performance concrete (HPC) has been studied. Thus, five mixes were produced with 0%, 25%, and 100% of both matured (6-month air curing period) and early-age (7-day air curing period) RA, resulting from crushing of the same parent concrete (PC). The following conclusions can be drawn from the analysis performed:

- The maturity of the RA did not affect the fresh or hardened density of HPC. The slight density decrease of RA caused by water evaporation during air curing was negligible compared to the density of the entire concrete mix;
- The development of strength and stiffness of concrete over time made early-age RA weaker and more deformable than matured RA, which slightly worsened the mechanical behaviour of HPC. Nevertheless, this worsening was only notable in compressive strength and ultrasonic pulse velocity;
- Autogenous shrinkage decreased by 20% when adding 100% RA due to their higher water absorption compared to natural aggregates (NA). Both the lower stiffness of the early-age RA and their shrinkage reduced the beneficial effect of RA. However, the hydration of their unhydrated cement particles during mixing reduced the negative effect of using early-age RA;
- Drying shrinkage increased 10–20% with the addition of RA due to their lower stiffness than NA's, and their higher deferred release of water over time, which promoted water evaporation. The lower stiffness of early-age RA, as well as their shrinkage, also increased drying shrinkage;
- Total shrinkage increased when using RA, since the increase of drying shrinkage was greater than the decrease of autogenous shrinkage caused by using this waste. Early-age RA also increased total shrinkage, although the hydration of their unhydrated cement particles reduced their own shrinkage and offset the loss of stiffness of HPC when adding them. Thus, the total shrinkage of the early-age-RA mixes could be estimated as the sum of the total shrinkage of HPC with the same content of matured RA and the total shrinkage of PC multiplied by the percentage of RA added to HPC;
- All the shrinkage types of HPC developed could be accurately estimated based on the formulation of EC2 and by applying partial correction coefficients. These coefficients depended on the type of concrete (HPC), the RA content, and their maturity.

The main contribution of this article has been to demonstrate that the maturity of RA plays an important role in the mechanical and, especially, the shrinkage behaviour of HPC. Therefore, the maturity of RA is an aspect that should be considered when using them.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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