Shrinkage and creep in structural concrete with recycled brick aggregates

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Abstract

In structural applications, long-term deformations of concrete are particularly important. The aim of this study is to analyze the deformations produced by shrinkage and creep in concretes in which both the fine and coarse fractions have been replaced with recycled brick aggregates (RBA), and to assess their use in structural applications. The percentages of substitution of the natural aggregates by RBA were 20, 35, 50, 70 and 100%. The deformations were measured over 400 days. The results show a strong increase in the shrinkage values and slight variations in the creep, although with substitutions of RBA of up to 20%, the long-term deformations do not exceed the usual values.

Keywords: Recycled concrete, brick aggregates, structural applications, shrinkage, creep.

1. Introduction

The recycling of aggregates from construction and demolition waste (C&DW) has become a priority for the European Union [1, 2], due to the costs involved in the extraction and dumping of natural aggregates and the environmental impact linked to this activity.

According to studies carried out in Spain [3], the most common components of C&DW are ceramic materials (54%), and concrete (12%), which once classified and processed, generate two types of waste: recycled brick aggregates (RBA) and recycled concrete aggregates (RCA).

Studies carried out to date in this field show that RBA can be used to substitute natural aggregates in low and medium strength concretes, although the water-cement ratio must be controlled. However, there is some controversy as to the suitability of using RBA for structural purposes. Studies carried out by Debieb and Kenai [4] discourage the use of RBA aggregates in concretes for structural purposes. Likewise, Silva [5] discourages the use of masonry recycled aggregates, although in this study the waste used contained traces of lightweight concrete blocks, ceramic roofing and tiles. However, the works carried out by Khatib [6], Cachim et al. [7] and Alves et al. [8], provide favourable results for medium strength concretes (<45 MPa), with waste concentrations below to 30%. Moreover, previous results obtained by the authors of this paper [9], show that for concrete with percentages of substitution of RBA up to 35%, the mechanical properties are not affected.

For concrete used in structural elements, durability and long-term properties are of great importance, especially shrinkage and creep values, which are non-instantaneous, time-dependent, with common characteristics and similar strain curves. Such phenomena are partially reversible and usually studied simultaneously [10].

After a curing period, the loss of water by evaporation causes dry shrinkage to begin in the hardened concrete mixture. Autogenous shrinkage also occurs due to cement hydration and the changes in the volume of chemicals, which is around 5% of the maximum drying shrinkage [11]. For practical purposes dry shrinkage and autogenous shrinkage are not usually evaluated separately (except in the case of high-performance concretes). Thus, concrete shrinkage caused by evaporation and that of chemical origin are contemplated together [12].

Creep is a complex phenomenon that depends on several factors. It is primarily caused by the loss of water in the hardened concrete, when it endures a sustained stress over time [10]. Such a loss causes changes in volume causing deformations, which can be greater than instantaneous deformations [12], hence its great importance in concrete structures.

Although shrinkage and creep are caused by complex interrelations of numerous factors, most theoretical expressions used to predict their extent assume that the elasticity modulus of concrete can provide an approximate measure of these phenomena [10]. In practice, creep and shrinkage occur simultaneously. Because they can cause micro-cracks, both phenomena must be taken into account during the design phase [13]. Over time, various problems may occur: micro-cracks can become big cracks, water can enter, and corrosion may appear. In fact, one of the main reason why structures do not complete their projected service life is an inadequate design in terms of creep and shrinkage [11].

Creep has a direct influence on prestressed concrete structures, since it can lead to excessive deflection and also causes a progressive load transfer between the concrete and the reinforcements. For example, when the steel used in a structure yields, any increase in load must be supported by the concrete. Bazant [14] establishes an classification of five levels of importance for studying creep and shrinkage when designing concrete structures. According to this classification, level 1 corresponds to "Reinforced concrete beams, frames and slabs with spans under 65 ft (20 m) and heights of up to 100 ft (30 m), plain concrete footings, retaining walls". Level 5 refers to "Record span bridges, nuclear containments and vessels, large off-shore structures, large cooling towers, record-span thin roof shells, record-span slender arch bridges”.

There are few studies on shrinkage in concretes with recycled brick aggregates (RBA), unfortunately they show discordant results. Some authors such as Silva et al. [15], conclude that more research is necessary. Suzuki et al [16] find that for concrete with RBA, at least two effects occur: a) low restraining capacity to control shrinkage, because the aggregates have a low elasticity modulus; b) high water absorption capacity can facilitate concrete curing, control excessively fast drying, and improve autogenous shrinkage.

Bektas et al. [17] studied the use of RBA in high strength mortars (60 MPa), replacing the fine fraction in percentages of 10 and 20%, and keeping the water-cement (w/c) ratio constant; which reduces the workability (from 122 mm to 93 mm). For 10% of RBA, a slight increase in shrinkage (+12%) was observed at 56 days, while for 20%, a slight decrease (-12%) was observed when compared with conventional concrete. Nevertheless, it is mentioned that the shrinkage phenomenon requires further research.

Crushed clay brick was used by Mansur et al. [18] to replace 45% of the coarse fraction in concretes with strengths from 30 to 60 MPa, keeping the water-cement (w/c) ratio constant, and using additives to improve workability. This decreases from 116 mm to 95 mm for 60 MPa concrete. The modified concrete had similar drying shrinkage and creep to conventional concrete.

Debieb and Kenai [4] studied the substitution of the fine fraction, the coarse fraction, or both with RBA from crushed bricks in medium strength concretes (35 MPa). They increased the amount proportion of water to keep workability constant, with a w/c ratio ranging between 0.57 and 1.08 depending on the percentage of replacement with recycled aggregates. The results obtained show a continuous increase in shrinkage that reaches 65% for 100% substitution with coarse RBA. When only the fine fraction is substituted, the increase is 45% for the same percentage of RBA, and when the fine and coarse fractions are substituted, the increase in shrinkage reaches 72%. They conclude that it acceptable to replace 25% of the coarse fraction or 50% of the fine fraction with a shrinkage increases of 9% and 18% respectively.

Khatib [6] added RBA to medium strength concretes (50 MPa) with a constant w/c ratio. The results show a decrease of 37% in the slump when adding 100% of RBA, with respect to the value for control concrete. While the addition of fine recycled concrete aggregates (RCA), increases shrinkage by 37%, for low percentages of substitution (25%), for higher concentrations a significant decrease were obtained: for 100% substitution the values were only 10% higher than the control concrete.

Vieira et al. [19] worked with medium strength concretes (25 MPa), substituting fine natural aggregates with crushed brick aggregates (CBA) and sanitary ware aggregates (SWA). In the case of CBA the shrinkage of 90-day cured concrete increases by 35%, 52% and 101% for replacement percentages of 20, 50 and 100%, respectively. For SWA, the increment of the shrinkage, was lower: 10%, 12% and 17% for the same substitution percentages. Such differences are due to correlation between shrinkage and the elasticity modulus.

Poon and Chan [20] used crushed brick (from RBA) and ceramic tiles to replace the fine fraction in high resistance concretes (50 MPa), keeping the water and cement quantities constant. The specimens were dried in an oven at 105ºC for 3 days according to the BS 812-120 standard. The results show that a substitution of 20% provides similar shrinkage values to the control concrete. The resulting concrete is suitable for any purpose.

Summarizing, the replacement of fine or coarse fractions with 100% of recycled brick aggregates (RBA), causes shrinkage increments ranging from 45% to 100% depending on the dosage of water in the mixes. For example, concrete mixtures with a constant workability and high water-cement (w/c) ratio (due to the high absorption of RBA), have unfavorable results (Debieb and Kenai [4], Viera et al. [19]). The most favorable results are obtained with concrete mixtures with a constant w/c ratio (which leads to a reduction in workability).

Unfortunately, there is a lack of information concerning creep behaviour in concrete with RBA, although some contributions show good results. For example, the review on creep behaviour for recycled aggregates concrete by Silva et al. [5]; the work by Ahmad and Roy [21], which shows an increment of 32% in creep for 300-day concretes of different strengths (17, 24 and 27.5 MPa) where 100% of the coarse fraction was replaced by RBA; or the work by De Pauw et al. [22] where creep increased by 12-16% when aggregates were substituted by RMA.

There are few studies for concrete with RBA, where the RBA concentration is up to 100% and the w/c ratio is maintained constant. The main problem is the high water absorption by RBA, which makes it difficult to keep the workability constant. The results of these studies are shown in **table 1**, and in **figure 1**.

Table 1. Shrinkage of concrete with RBA with constant w/c ratio, by different authors.

Authors	**Type of RBA replacement**	**Shrinkage (µm/m)**			
		Control	**RBA (25%)**	**RBA (50%)**	**RBA (100%)**
Khatib	Fine	200	270	250	220
Poon and Chan	Fine	180	170	--	--
Bektas	Fine	820	720	--	--

Figure 1 shows that the average values of the slope for each curve is between +14µm/m and -20 µm/m, for every 10% increase in the RBA concentration. That is to say, the results provided by these authors indicate that if the w/c ratio is kept constant, the shrinkage variations are very small or non-existent. This statement should be taken as a hypothesis, since the number of available works is insufficient.

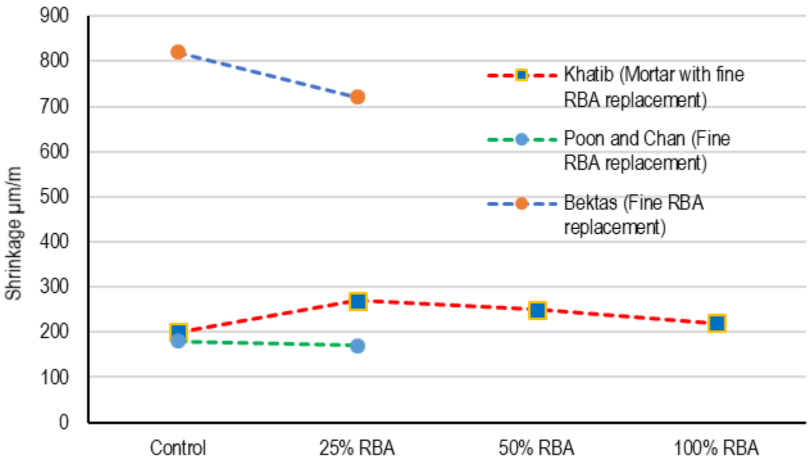

Figure 1. Shrinkage of concrete with RBA with constant w/c ratio

2. Aims and scope

This work is the continuation of two previous studies concerning the incorporation of RBA in concrete, for structural purposes [2, 9]. The work was carried out in the lab as well as in a precast concrete plant. The wastes were generated by a nearby ceramics factory, which manufactures bricks, floor blocks and ventilation ducts.

In the first work [9], the mechanical properties of concrete with RBA were studied, and in the second [2], prestressed concrete joists were elaborated and their mechanical properties were analyzed. The RBA used comes from waste ventilation ducts rejected during the manufacturing process. Such wastes have several advantages: they do not need to be classified, they are homogeneous materials, and they are free of undesirable residues or other harmful substances, such as mortar and plaster. Moreover, 3% to 7% of the production of ceramic manufacturing plants is rejected and is available for recycling [23].

The ultimate aim of this work is to determine the effects of RBA (coarse and fine fraction) substitutions, on the long-term deformations of the concrete used in prefabricated products.

3. Experimental study

3.1. Properties of aggregates

Ceramic bricks (**figure 2a**) were crushed into particles smaller than 8 mm. It should be mentioned that this RBA is the same as that used in the previous work by the authors [9].

The properties of the RBA are shown in the **table 2**, and the corresponding size distribution curves for all aggregates in **figure 2b**.

Table 2. Properties of aggregates.

Property	Standard	Washed sand 0/4 mm	Sand 0/4 mm	Natural gravel 4/10 mm	RBA
Density (kg/m^3)	EN 1097-6	2650	2650	2650	2000
Water absorption (%)	EN 1097-6	0.50	0.60	1.00	11.21
Sand equivalent	EN 933-8	90	78	--	88

a **b**

Figure 2. Ceramic waste (a) and sieve analysis of aggregates (b).

3.2. Dosage of concrete

The proportions of the concrete mixes followed those used by the authors in the previous work [9]. The control dosage was the used by the company for manufacturing prestressed joists. Both the fine and coarse fractions of natural aggregates were substituted with RBA, in weight percentages from 20% to 100%, keeping the quantity of cement constant (**table 3**). Due to the high absorption by RBA, in order to keep the workability, the water quantity was increased as the substitution of RBA was increased. The aggregates used were dry. The workability of the manufactured concrete, which was measured with a Vebe consistometer, was very dry. The effective w/c ratio was 0.32 but extra water was needed to the theoretical quantity, as the percentage of substitution was increased to maintain the workability. For this reason, the values of the total w/c ratio do not correspond directly with the effective w/c ratio.

Table 3. Concrete composition (kg/m^3)

Materials		**RBA (%)**					
		0	**20**	**35**	**50**	**70**	**100**
Cement CEM I 52.5 N		400	400	400	400	400	400
Natural gravel 4/10		810	648	527	405	243	0
Sand		1158	926	753	579	347	0
Washed sand AF-T 0/4 C-L		70	56	46	35	21	0
RBA,	Fine (88%)	0	271	474	677	947	1354
	Coarse (12%)	0	37	65	93	129	184
Water		142	176	202	228	263	314
w/c		0.35	0.44	0.5	0.57	0.65	0.78

The concrete manufacturing procedure was as follows: mix natural gravel (3 s), add dry RBA and mix (3 s); add sand and mix (3 s), add cement and mix (3 s), add 80% of water and mix (3 m), stop mixing for 2 min. Finally, add the remaining water and mix (3 m).

3.3. *Properties of concrete*

The mechanical properties of the concretes, were studied in the previous work [9]. In **table 4** the values of the mean compressive strength and the modulus of elasticity are shown.

Table 4. Results of the tests of concrete manufactured in the laboratory

	Percentage of RBA					
Property	0%	20%	35%	50%	70%	100%
Compressive strength (f_{cm}) (MPa)	59.8	55.6	52.8	54.1	46.8	43.4
Modulus of elasticity (E_c)(GPa)	42	36	31	28.5	22.5	16.5

3.4. *Shrinkage and creep tests*

Prismatic specimens of (100x100x400) mm were made in the laboratory, according to Standard EN 12390-1 [24], and the shrinkage tests were carried out following Standard UNE 83-318-94 [25]. The specimens were cured in a wet chamber. Shrinkage was evaluated at a temperature of 20ºC±1ºC and 50% humidity.

Daily measurements were taken using an extensometer and a 300 mm calibration bar. The shrinkage values for each percentage of substitution are shown in **figure 3**.

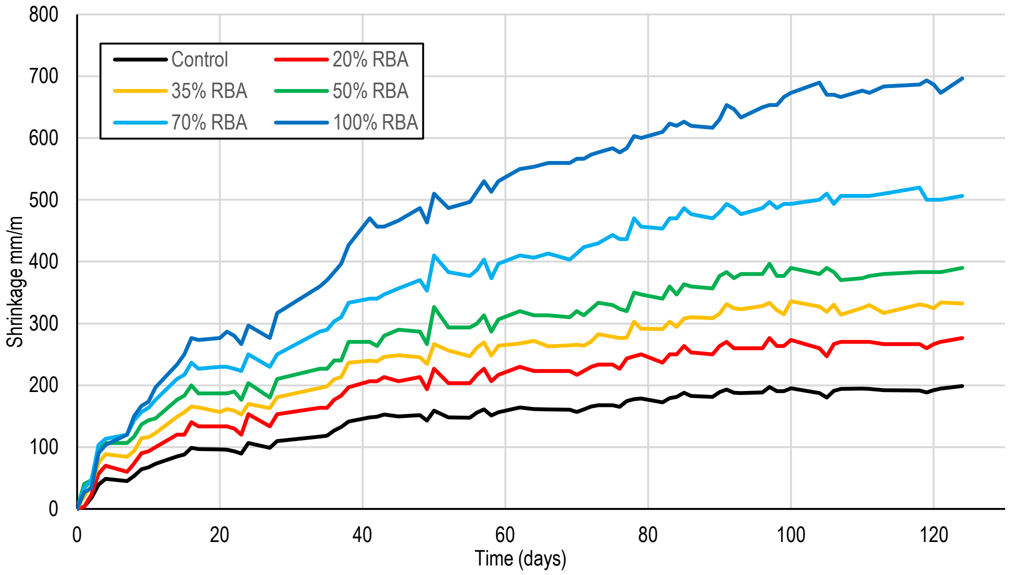

Figure 3. Shrinkage of concretes with RBA.

Cylindrical specimens Ø150x300 mm [24] were made following Standard EN 12390-2 [26], and the creep tests were performed in an air-conditioned chamber at 20±2ºC with a humidity of 65±10%. Rigid frames equipped with a hydraulic manual-action jack and a hydro-pneumatic accumulator were used to maintain the load over time (Figure 4). Deformations were measured using strain gauges, located in diametrically opposite generatrixes of each specimen and in the central third (**figure 4**).

The applied load was 35% of the compressive strength for each concrete (f_{cm}) as a function of the percentage of RBA. Two specimens were subjected to the creep test, which lasted 400 days, A third specimen was placed next to them, without load, to evaluate the shrinkage simultaneously.

Figure 4. Creep tests.

The shrinkage values during the creep test are shown in **figure 5**. They were calculated as the arithmetic mean of the values collected in the two gauges, placed in each test tube.

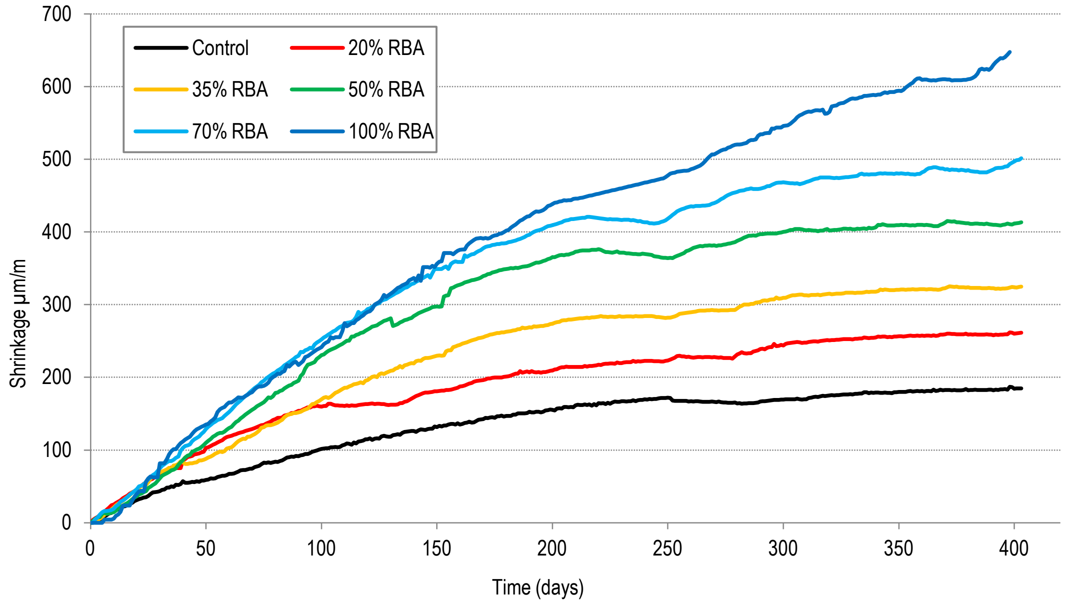

Figure 5- Strain by shrinkage of concrete during creep test.

Figure 6 shows the total strain values obtained for loaded specimens. These values include the elastic deformation due to the applied load. The strains were calculated as the arithmetic mean of the two specimens tested, which had the same percentages of RBA.

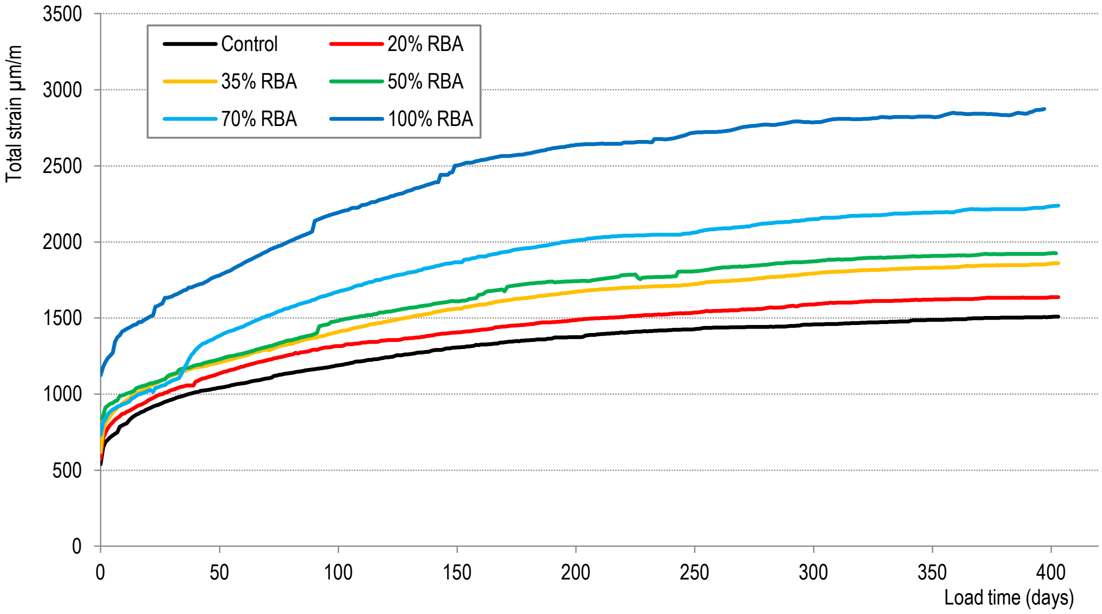

Figure 6. Total strain of concrete during creep test.

4. Analysis of results

4.1. Analysis of shrinkage

Figure 3 shows the evolution of shrinkage: it increases continuously over time. The shrinkage values increase when the percentage of RBA increases. For low percentages of RBA (up to 50%) the curves tend to stabilize at the end of the test period. However, for higher percentages (more than 50%), the shrinkage values continue increase over time. This is due to the high volume of water retained in the pores of the RBA.

The maximum shrinkage values for concrete with RBA are shown in **figure 7**. The behaviour of the shrinkage is practically linear with the percentage of RBA. These results depend on the percentage of RBA and the w/c ratio. The total w/c ratio was increased progressively, from 0.35 to 0.78, as the percentage of RBA increased. The objective was to compensate the high water absorption of the RBA aggregates and to maintain the workability of the mixtures.

The use of ceramic materials determines the elasticity modulus of concrete. In the authors' previous study, it was found that the elasticity modulus diminishes as the concentration of RBA increases [9]. A comparison of the results for shrinkage and the elasticity modulus concludes that shrinkage increases and the elasticity modulus decreases as the percentage of RBA increases. Thus, concrete has high shrinkage and a low elasticity modulus or viceversa. These results are similar to those reported in the literature [12].

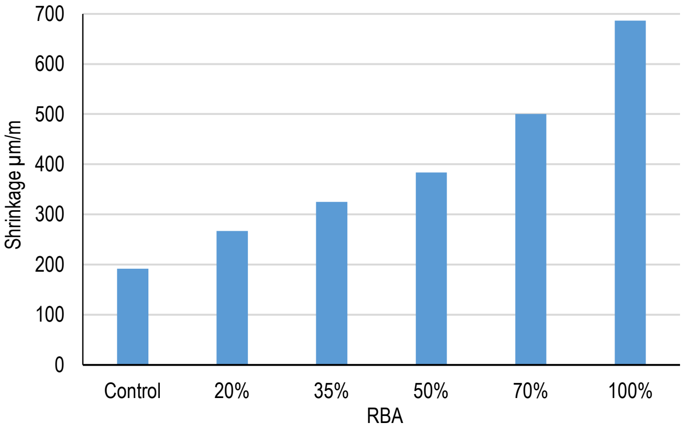

Figure 7. Shrinkage for concrete with RBA.

According to the literature, the relationship between the w/c ratio and shrinkage for conventional concrete is clear: if the ratio is high, the quantity of evaporable water in the mixture is high. With a high w/c ratio, the excess water is eliminated without shrinkage [12]. However, when high absorption aggregates such as RBA are used, the excess water added to maintain workability is absorbed by the RBA, so that the effective w/c ratio varies very little. The RBA aggregates retain water in their pores for a long time, releasing it slowly [27]. Thus, the shrinkage process is delayed.

The results of this study have been contrasted with previously published works with similar experimental conditions (i.e. slightly modifying the w/c ratio to maintain workability when the percentage of RBA increases). **Table 5** shows the characteristics of the control mixtures prepared by other authors.

Table 5. Comparison of control concrete mixtures by different authors.

	Control concrete characteristics					
Authors	**Aggregates (kg/m3)**	**Cement (kg/m3)**	**Water (l/m3)**	**w/c**	**Slump (cm)**	**Strength (MPa)**
Current work	2036	400	142	0.36	-	60
Debieb & Kenai	1849	350	213	0.61	6-8	30
Vieira et al.	1708	350	186	0.53	12	46

Table 6 and **figure 8** show the shrinkage results of these works. The shrinkage values for the control concrete are very different from the concrete mixtures with RBA substitutions.

Debieb and Kenai [4] used modified coarse aggregates which were soaked in water for 24 h and dried to obtain a saturated surface. These conditions increased the shrinkage by 72% when substituting 100% of fine and coarse fraction with RBA. Vieira et al. [19], observed an increase in shrinkage of 101% when substituting 100% of fine fraction. These differences depend on various factors. For example, the w/c ratio used in this work was 0.36, which was lower than those for the other studies (0.53 and 0.61), providing mixtures with different workabilities. The prestressed joists studied in this work were made with a dry concrete mix, while the other authors used mixtures with 6-12 cm slump (Abrams cone), for other uses. In summary, a high w/c ratio means a high quantity of evaporable water in the mixture, and consequently, high shrinkage [12].

Table 6. Shrinkage results of concretes with RBA by different authors.

Authors	**Type of RBA replacement**	**Shrinkage (µm/m)**		
		Control	**RBA (50%)**	**RBA (100%)**
Current work	Fine and coarse	192	383	686
Debieb & Kenai	Fine and coarse	550	800	950
Debieb & Kenai	Fine	550	700	800
Debieb & Kenai	Coarse	550	750	900
Vieira	Fine	400	600	800

According to **figure 8**, the relationship between the shrinkage values and the RBA concentrations is quite linear, thus the slope of the curves are very similar. The increase is almost constant, between 35 µm/m and 45 µm/m for every 10% of substitution with RBA. The highest values are obtained when substituting both the fine and the coarse fraction.

These values are clearly higher than those obtained by other authors when aggregates from concrete wastes (RCA) are used. Seara Paz et al [28], substituted the coarse fraction and obtained average shrinkage increases between 23 and 28 µ/m for each 10% replacement with recycled ceramic aggregates. Serna et al [29] obtain values between 19 and 28 µm/m for each 10% replacement depending on whether the fine fraction, the coarse fraction or both are substituted. These same authors, in a similar study [30] provide values between 12 and 20 µm/m for each 10% replacement of the coarse fraction, depending on the strength of the concrete. Bravo et al. [31] use mixed recycled aggregates of different origins and with very heterogeneous compositions. They obtain intermediate results between those corresponding to RCA and RBA with a wider range of values (between 20 and 35 µm/m for each 10% replacement).

In the manufacturing of lightweight concrete, the work of Wendling et al [32] provides an increase in shrinkage of 30µm/m for every 10% substitution of the coarse fraction with lightweight aggregates. This result is within the range obtained by the authors in the study presented in this paper.

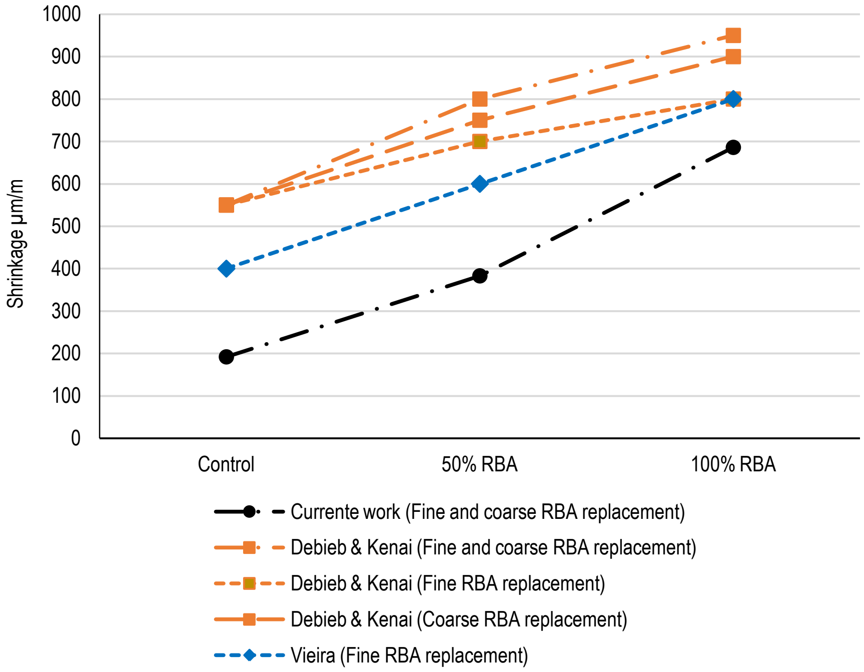

Figure 8. Shrinkage results of concretes with RBA aggregates.

It has been explained that two opposing effects occur when RBA are used. On the one hand there is an improvement in the concrete curing, as well as a decrease in the autogenous shrinkage, due to the continuous supply of water and the humidity retained in the RBA. On the other hand, the low elasticity modulus of these concretes reduces the capacity to control shrinkage. In this study, workability was maintained constant by increasing the w/c ratio. The previous results showed a drop in the elasticity modulus when increasing the percentage of RBA [8]. Clearly, more attention is necessary to improve the internal curing process. The current results show that shrinkage increases even for low percentages of RBA, which is consistent with results published by other authors [4, 19]. However, when the w/c ratio is maintained constant, as in other studies [6, 17, 20], the effect of internal curing may be more relevant.

Finally, **figure 9** shows a comparison of the results obtained in the tests and those estimated by Eurocode 2 (EC2) [33]. It can be observed that for the control concrete, the shrinkage is lower than estimated by EC2, as would be expected. For 20% of RBA the shrinkage is very slightly higher than predicted by EC2, but for 35% of RBA the shrinkage is higher (around 35%). For higher percentages of substitution, the resulting shrinkage is much higher than expected by the EC and has not been represented in the figure. Thus, if an adjustment to the EC2 forecast is to be achieved, the maximum acceptable rate of substitution with RBA would be 20%.

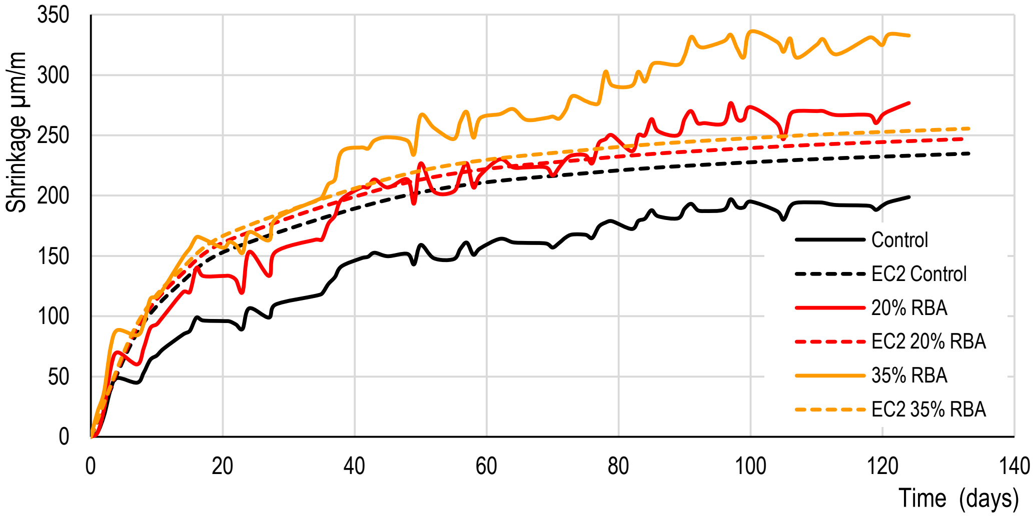

Figure 9. Comparison of shrinkage between tests and predictions from Eurocode 2

According to the results, manufacturing of prestressed joists is viable with up to 20% of RBA, because this percentage does not produce significant alterations in the properties. For a substitution of 35% of RBA, the concrete shrinkage increases by 70% with respect to the control concrete (from 192 µm/m to 324 µm/m). However, for low RBA concentration (20%), the increase obtained is 40%. It is important to mention that the Standard UNE-EN 15037-1 [34] corresponding to the manufacture of prestressed joists stipulates that the concrete used must be at least C30/37 [35]. The concrete exceeds this minimum and corresponds to category C45/55, with drying shrinkage of 0.36 mm/m±30% and 40% moisture [35].

4.2. Analysis of creep

The shrinkage values during the creep tests (see **figure 5**), show two well-defined behaviours: for low percentages of RBA (up to 50%) the curves tend to stabilize at the end of the test period. However, for higher percentages (70% and 100%), the shrinkage values continue to increase over time. This suggests that the shrinkage process is not yet stabilized at 400 days and could continue for a longer period. This is due to the high quantity of water retained in the pores of the RBA. **Table 7** shows the creep test data after 400 days of experimentation.

Table 7. Creep test data of concrete with RBA after 400 days

		Control	20%	35%	50%	70%	100%
Applied Load	Mpa	21.0	19.3	17.5	18.5	16.6	15.9
Initial strain	mm/m	540.1	573.3	617.7	672.4	733.5	1123.8
Ultimate shrinkage	mm/m (Increase %)	183.2	259.4 (41.6)	322.7 (76.1)	411.4 (124.6)	490.4 (167.7)	644.2 (251.6)
Ultimate total strain	mm/m (Increase %)	1507	1634 (8.4)	1853 (22.9)	1921 (27.4)	2227 (47.7)	2874 (90.7)
Ultimate creep strain	mm/m (Increase %)	784.2	801.3 (2.2)	912.3 (16.3)	836.7 (6.7)	1002.8 (27.9)	1106.3 (41.1)
Ultimate specific Creep	(mm/m)/Mpa	37.34	41.52	52.13	45.23	60.41	69.58

(Increase %)		(11.2)	(39.6)	(21.1)	(61.8)	(86.3)
Ultimate creep coefficient	1.45	1.40	1.48	1.24	1.37	0.98
(Increase %)		(-3.7)	(1.7)	(-14.3)	(-5.8)	(-32.2)

The shrinkage values during the creep test are shown in **figure 10**. They increase when the percentage of RBA increases. For each RBA concentration, a high shrinkage value has a low elasticity modulus value and vice versa.

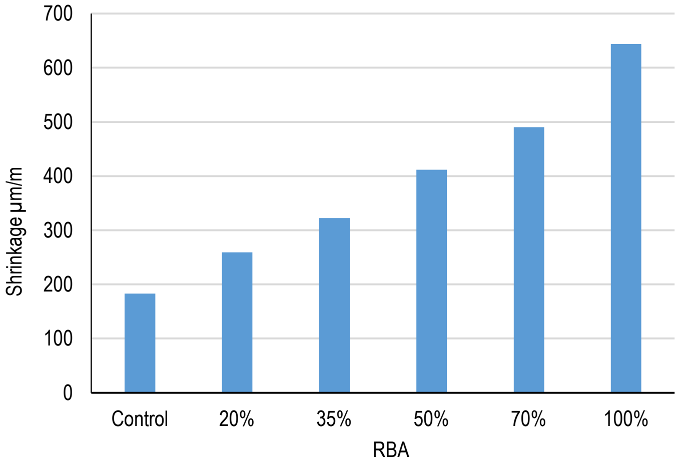

Figure 10. Shrinkage of concrete with RBA during creep test.

The results for the total strain, show values up to 2870 μm/m for concrete with 100% of RBA during the creep test (see **figure 6**). This value is the sum of elasticity strain, shrinkage and creep. Unfortunately, high values are not useful for structural applications. Thus, high RBA concentrations are not recommendable for these purposes.

Creep strain values are shown in **figure 11**. They were calculated by subtracting the values corresponding to shrinkage and instantaneous deformation from the total strain. This calculation procedure is not exact since the elasticity modulus of the concrete increases during the drying process. In addition, shrinkage and creep are not independent phenomena to which the principle of superposition can be applied [12]. However, these novel results contribute to the knowledge of the creep strain obtained for long-term behavior. In fact, in such calculus an error of little relevance is assumed.

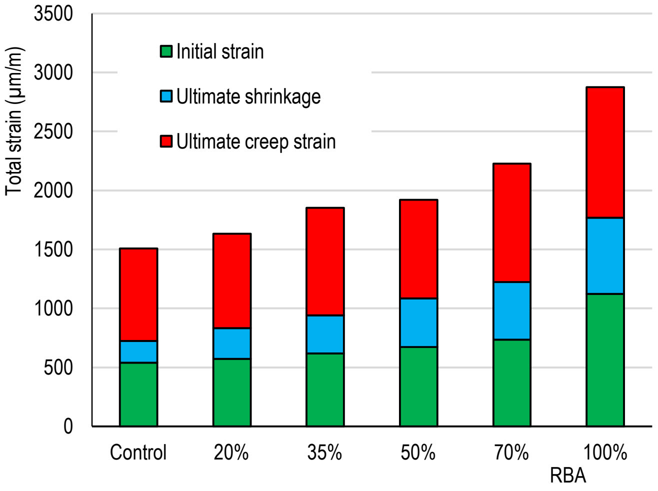

Figure 11. Components of the total deformation of concrete with RBA, during the creep test.

Following the same method, the specific creep over time was calculated by dividing the creep deformation by the applied load. The values are shown in **figure 12** and summarized in **table 7**. As shown, concretes with RBA have higher creep than the control concrete. Some differences are observed: a) a gradual increase of the values for concretes with 20% and 35% of RBA, b) for a percentage of 50% the value are lower than those for 35%, c) irregular behaviour for concrete with 100% of RBA. For concretes with 50, 70 and 100% there is a delay in the creep.

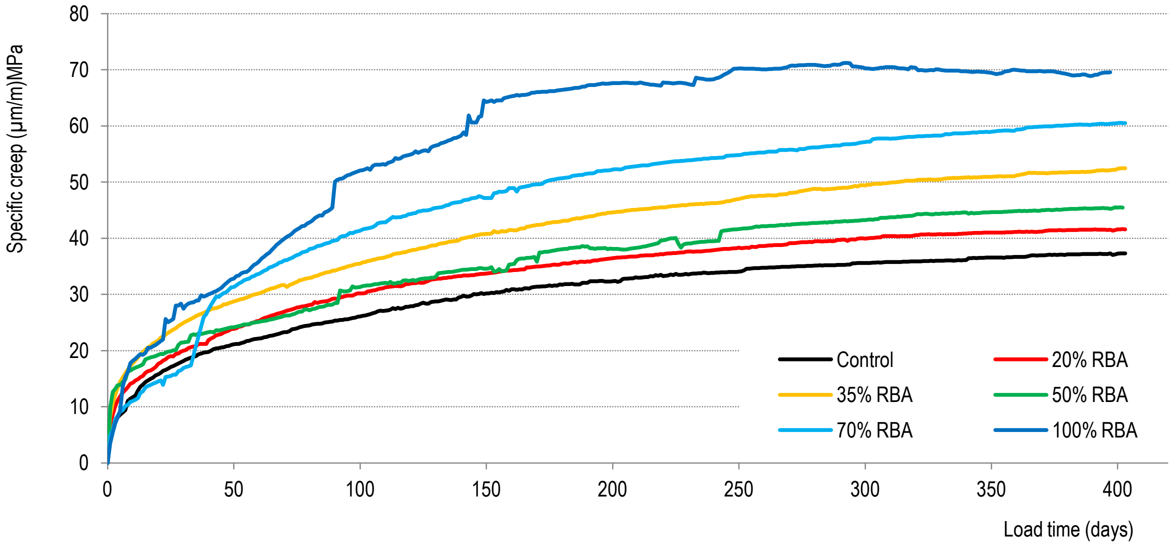

Figure 12. Specific creep for concrete with RBA

In order to compare the creep results with most influential parameter of concrete, namely shrinkage and the elasticity modulus [12], the maximum values for specific creep are shown in **figure 13**. The values increase for concretes with 20 and 35% of RBA, decrease for 50%, and increase for 70 and 100%, but with values higher than the control concrete. The highest increase (of 40%) was obtained for concrete with 35% of RBA. This behaviour is opposite to the elasticity values obtained in a previous work by the authors [9]. Thus, high percentages of RBA promote high specific creep but low elasticity modulus in concrete.

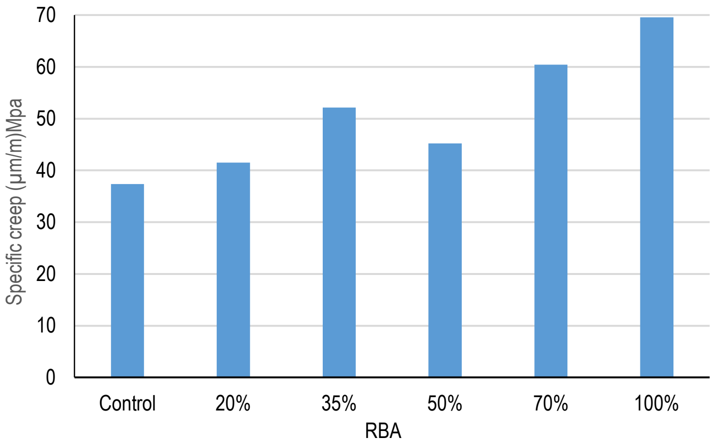

Figure 13. Specific creep for concrete with RBA.

The creep coefficient was calculated from the ratio between creep deformation and the elastic deformation under the same load (table 6). The values are shown in **figure 14**. For concretes with 20% and 35% of RBA, small variations in the values are obtained. For high RBA percentages the creep coefficient gradually decreases due to the high elastic deformation caused by the high percentages of RBA.

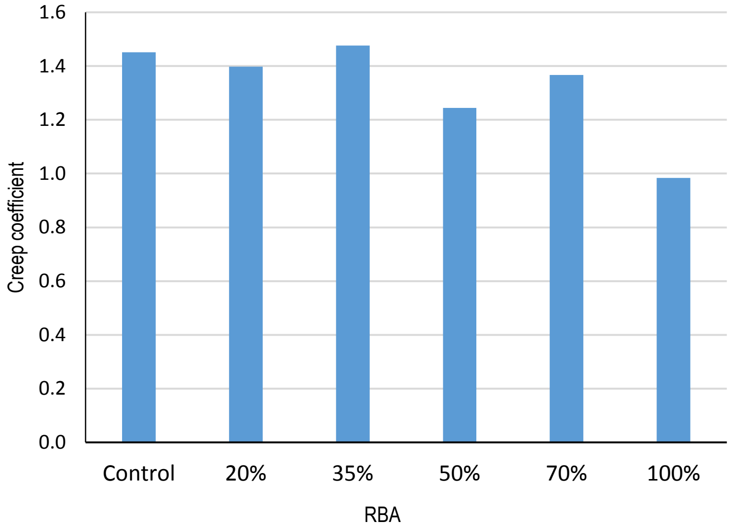

Figure 14. Creep coefficient for concrete with RBA.

The specific creep values do not vary as much as the shrinkage. They are below 40%, even for high concentrations of RBA. Moreover, Standard EN 1992-1 [35] indicates the creep coefficient as a way of assessing this phenomenon. In this study, the creep coefficient is almost constant for concretes with 20% and 35% RBA. Thus, taking into account both indicators, specific creep and creep coefficient, it does not seem to be a limiting factor in the manufacturing of prestressed joists.

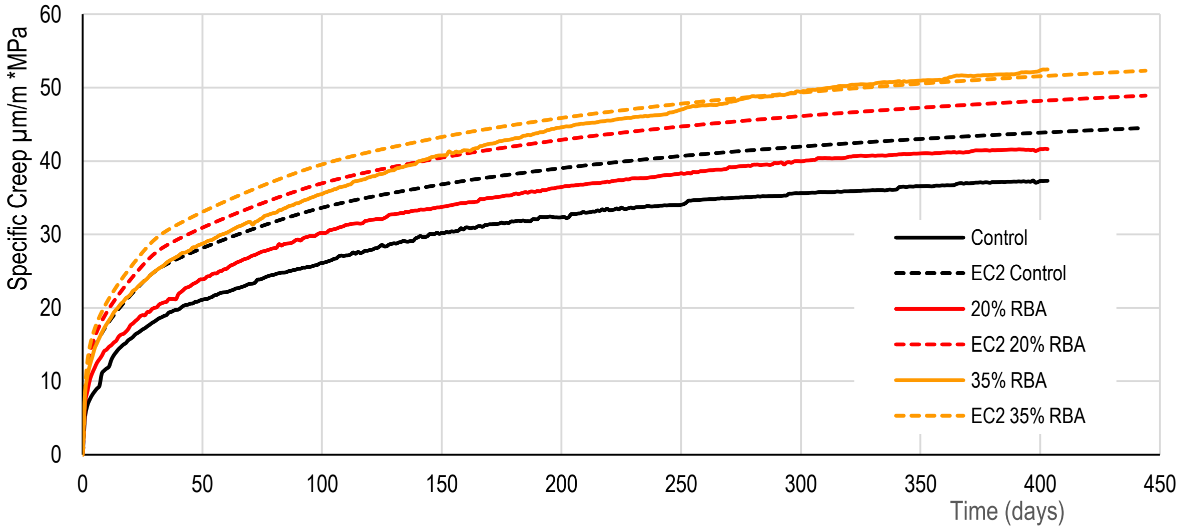

Figure 15. Comparison of specific creep between tests and predictions from Eurocode 2

Figure 15 compares the results for specific creep obtained in the tests and those expected according to Eurocode 2 [33]. The percentages considered are 20% and 35% because they provide the results closest to the control concrete. It can be observed that up to 20%

substitution the EC2 prediction is higher than the result obtained in the tests, while for 35% both values are equal. Thus, in order for creep to follow the EC2, 35% should be established as the maximum percentage of RBA.

Comparison of creep behavior in concretes with RBA with other studies in the literature is difficult, because few works have been published. Ahmad and Roy [21] obtained a 30% increase in the creep strain for 100% substitution with RBA. However, they substitute the coarse fraction, and modify the quantity of cement to maintain the resistance of the concrete. Even so, their results are very similar to those obtained in this work.

It is interesting to compare the results obtained in this work with the work of Lye et al. [36] who carries out an in-depth study of much of the published literature on this subject in relation to the substitution of the coarse fraction of natural aggregates with RCA. This study states that specific creep increases at a decreasing rate as the percentage of RCA increases, with an average of 32% for 100% substitution, although it may reach up to 60%. For a 20% replacement there is an average increase of 12%. For comparison purposes, lightweight concretes shows an increase in creep in relation to conventional concrete of around 60% when 100% of the coarse fraction is replaced [32] which is in the high zone of the mentioned interval. The results obtained in this work for 100% substitution of the fine and coarse fraction are clearly higher. Clearly this issue calls for further research as very few studies are available in which a direct comparison between these two types of aggregates is made

5. Conclusions

This work studies concrete made with recycled brick aggregates (RBA) to substitute both the fine and coarse fractions of the natural aggregates for the manufacturing of prestressed joists,. The conclusions based on the results of the long-term deformations, are summarized as follows:

- Shrinkage increases when the percentage of RBA increases, increasing up to two and a half times for 100% RBA. The reason for this increase is the continuous reduction of the modulus of elasticity produced when the percentage of this type of aggregate is increased.
- Shrinkage increases between 35 and 45 µm/m when the proportion of RBA increases by 10%. These results are in line with those obtained by other authors who show that, when only the fine fraction or only the coarse fraction is substituted, the shrinkage increase is in the lower part of this interval, whereas if both fractions are substituted, the shrinkage is in the upper part of the interval.
- Creep strain values are less pronounced than those for shrinkage. The values do not increase by more than 40%, even for high concentrations of RBA.
- According to the values for long-term deformations, concrete with 20% of RBA has similar behaviour to the control concrete. This RBA percentage is the most adequate for the production of precast prestressed concrete joists, according to the requirements of the current European standards.
- Concrete with 35% of RBA shows acceptable shrinkage values for structural purposes, but the decrease of the elasticity modulus may require further study.

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References

[1] European-Commission, COM(2011) 571 Roadmap to a Resource Efficient Europe. Communication from the Commission to the European Parliament., 2011.
[2] F.L. Gayarre, J.S. Gonzalez, M.A.S. Lopez, C.L.C. Perez, P.J.F. Arias, Mechanical properties of prestressed joists made using recycled ceramic aggregates, Construction and Building Materials 194 (2019) 132-142.
[3] M.D. Merino, P.I. Gracia, I.S.W. Azevedo, Sustainable construction: construction and demolition waste reconsidered, Waste Management & Research 28(2) (2010) 118-129.
[4] F. Debieb, S. Kenai, The use of coarse and fine crushed bricks as aggregate in concrete, Construction and Building Materials 22(5) (2008) 886-893.
[5] R.V. Silva, J. de Brito, R.K. Dhir, Comparative analysis of existing prediction models on the creep behaviour of recycled aggregate concrete, Engineering Structures 100 (2015) 31-42.
[6] J.M. Khatib, Properties of concrete incorporating fine recycled aggregate, Cement and Concrete Research 35(4) (2005) 763-769.
[7] P.B. Cachim, Mechanical properties of brick aggregate concrete, Construction and Building Materials 23(3) (2009) 1292-1297.
[8] A.V. Alves, T.F. Vieira, J. de Brito, J.R. Correia, Mechanical properties of structural concrete with fine recycled ceramic aggregates, Construction and Building Materials 64 (2014) 103-113.
[9] J.S. Gonzalez, F.L. Gayarre, C.L.C. Perez, P.S. Ros, M.A.S. Lopez, Influence of recycled brick aggregates on properties of structural concrete for manufacturing precast prestressed beams, Construction and Building Materials 149 (2017) 507-514.
[10] P.K. Mehta, P. Monteiro, Concrete. Microstructure, properties and materials, McGraw-Hil, New York, 2006.
[11] Z. Bazant, Mathematical modeling of creep and shrinkage of concrete, John Wiley & Sons Ltd, New York, 1988.
[12] A.M. Neville, Properties of concrete, 5th ed., Pearson, London, 2012.
[13] Z.P. Bazant, W.J. Raftshol, EFFECT OF CRACKING IN DRYING AND SHRINKAGE SPECIMENS, Cement and Concrete Research 12(2) (1982) 209-226.
[14] Z.P. Bazant, S. Baweja, P. Acker, I. Carol, J. Catarino, J.C. Chern, C. Heut, F.H. Wittmann, D. Carreira, CREEP AND SHRINKAGE PREDICTION MODEL FOR ANALYSIS AND DESIGN OF CONCRETE STRUCTURES - MODEL B-3, Materials and Structures 28(180) (1995) 357-365.
[15] R.V. Silva, J. de Brito, R.K. Dhir, Prediction of the shrinkage behavior of recycled aggregate concrete: A review, Construction and Building Materials 77 (2015) 327-339.
[16] M. Suzuki, M.S. Meddah, R. Sato, Use of porous ceramic waste aggregates for internal curing of high-performance concrete, Cement and Concrete Research 39(5) (2009) 373-381.
[17] F. Bektas, K. Wang, H. Ceylan, Effects of crushed clay brick aggregate on mortar durability, Construction and Building Materials 23(5) (2009) 1909-1914.
[18] M.A. Mansur, T.H. Wee, L.S. Cheran, Crushed bricks as coarse aggregate for concrete, Aci Materials Journal 96(4) (1999) 478-484.
[19] T. Vieira, A. Alves, J. de Brito, J.R. Correia, R.V. Silva, Durability-related performance of concrete containing fine recycled aggregates from crushed bricks and sanitary ware, Materials & Design 90 (2016) 767-776.

[20] C.S. Poon, D. Chan, The use of recycled aggregate in concrete in Hong Kong, Resources Conservation and Recycling 50(3) (2007) 293-305.
[21] S.I. Ahmad, S. Roy, Creep Behavior and Its Prediction for Normal Strength Concrete Made from Crushed Clay Bricks as Coarse Aggregate, Journal of Materials in Civil Engineering 24(3) (2012) 308-314.
[22] P. De Pauw, J. Vyncke, P. Thomas, J. Desmyter, Shrinkage and creep of concrete with recycled materials as coarse aggregates, International symposium on sustainable construction: use of recycled concrete aggregate, London, 1998.
[23] F. Pacheco-Torgal, S. Jalali, Reusing ceramic wastes in concrete, Construction and Building Materials 24(5) (2010) 832-838.
[24] EN 12390-1. Testing hardened concrete. Part 1: Shape, dimensions and other requirements for specimens and moulds., Brussels, 2001.
[25] UNE 83-318-94 Ensayos de hormigón. Determinación de los cambios de longitud, Madrid, 1994.
[26] EN 12390-2. Testing hardened concrete. Part 2: Making and curing specimens for strength tests., Brussels, 2001.
[27] T.C. Hansen, Recycling of demolished concrete and masonry, Taylor & Francis Ltd, London, 1992.
[28] S. Seara-Paz, B. Gonzalez-Fonteboa, F. Martinez-Abella, I. Gonzalez-Taboada, Time-dependent behaviour of structural concrete made with recycled coarse aggregates. Creep and shrinkage, Construction and Building Materials 122 (2016) 95-109.
[29] D. Pedro, J. de Brito, L. Evangelista, Structural concrete with simultaneous incorporation of fine and coarse recycled concrete aggregates: Mechanical, durability and long-term properties, Construction and Building Materials 154 (2017) 294-309.
[30] D. Pedro, J. de Brito, L. Evangelista, Influence of the use of recycled concrete aggregates from different sources on structural concrete, Construction and Building Materials 71 (2014) 141-151.
[31] M. Bravo, J. de Brito, J. Pontes, L. Evangelista, Shrinkage and creep performance of concrete with recycled aggregates from CDW plants, Magazine of Concrete Research 69(19) (2017) 974-995.
[32] A. Wendling, K. Sadhasivam, R.W. Floyd, Creep and shrinkage of lightweight self-consolidating concrete for prestressed members, Construction and Building Materials 167 (2018) 205-215.
[33] EN 1992-1-1, Eurocode 2: Design of concrete structures – Part 1-1: General rules and rules for buildings., CEN, Brussels, 2004.
[34] EN 15037-1 Precast concrete products. Beam-and-block floor systems. Part 1: Beams, Brussels, 2010.
[35] EN 1992-1-1 Eurocode 2: Design of concrete structures. Part 1-1:General rules and rules for buildings, 2016.
[36] C.Q. Lye, R.K. Dhir, G.S. Ghataora, H. Li, Creep strain of recycled aggregate concrete, Construction and Building Materials 102 (2016) 244-259.