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Wood ash versus expanded clay aggregate as internal curing water reservoirs in high performance concrete

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Abstract The performances of expanded clay aggregate and wood ash as internal curing water reservoirs were studied in the mortar phase of a hypothetical high performance concrete with a low water-to-binder ratio. The two materials substituted the 15 and 30% of the sand volume. Two different binders, Portland cement and high-volume fly ash blended cement, were used. The compressive strength and the volume stability of the mortars in sealed and air-drying conditions were studied. Furthermore, the desorption capacity of the internal curing water reservoirs and the internal humidity inside the mortars during the first days after casting were analysed. The results shown that the reduction in the self-desiccation shrinkage was higher when the expanded clay aggregate was used, even in air-drying curing conditions, due to its higher desorption capacity in low-relative-humidity environments in comparison to that of the wood ash. However, wood ash had a stronger beneficial effect on early age autogenous shrinkage without significantly increasing the drying shrinkage. The two alternative aggregates influenced the strength moderately. Considering the technical, economic, and environmental implications of using the two lightweight aggregates, wood ash is recommended.

Keywords Internal curing agent · Curing sensitivity · Residues · By-product · Circular economy

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1 Introduction

Lightweight concrete containing lightweight aggregates (LWAs) has been successfully used for decades to decrease the dead load of different infrastructures. With this, the dimensions of the structural members can be reduced, less reinforcement is required, and longer spans are allowed [1]. Furthermore, less cracking and better durability in some of these infrastructures were attributed to the effect of internal curing [2]. Internal curing consists of the provision of water to a cementitious material from some of its constituents, sustaining cement hydration and preventing self-desiccation [3]. Self-desiccation is the precursor of autogenous shrinkage [4], which is a considerable problem in high-performance concrete (HPC) with a low water-to-binder ratio [5, 6]. In

lightweight concrete, the LWA is the constituent that provides the extra water, that is, it works as an internal curing water reservoir (ICWR). This is possible owing to the high absorption and desorption capacities of LWA. However, the internal curing effect is not always clear in existing lightweight concrete structures, as the materials used were not specifically designed for this purpose [7]. The use of pre-wetted LWA for the internal curing of HPC was not suggested until the early '90 s [8].

Many studies have already concluded that different types of natural and artificial LWAs are suitable to be used as ICWRs in HPC. Among them, those based on zeolite [9, 10], pumice [11, 12], shale [13, 14] and clay [15, 16] are the most popular. Field experience has also been documented [17]. However, inconveniences in conventional LWAs regarding absorption and desorption properties, which are key for the internal curing process, have been reported. For instance, natural zeolite has been considered ineffective for mitigating paste self-desiccation owing to its fine porous structure [18]. In addition, the complete saturation of lightweight expanded clay aggregate is difficult to achieve in practice, and a vacuum pump may be needed. For instance, light expanded clay aggregate (LECA) can absorb water from paste in a fresh state and block the conveying lines of pump concrete [19].

These technical inconveniences, together with the increasing interest in the development of cleaner alternatives in the concrete sector, have encouraged the proposal of some industrial by-products to work as ICWRs [20]. The waste-based alternative ICWRs must show proper water absorption and desorption properties, similarly to conventional LWAs. Thus, any type of ash could be an adequate candidate for this purpose. For instance, the potential use of coal bottom ash as an ICWR has been suggested [21]. However, the use of other types of ash for this purpose has seldom been researched.

The production of different biomass ashes is increasing as the generation of energy by burning of plant-derived organic matter (mainly forestry and agricultural wastes) is increasing because of its renewable and CO_2 neutral nature [22, 23]. The most promising beneficial use of biomass ash is its addition to agricultural soils to reduce their pH (liming effect) and to provide nutrients [24]. However, despite this feasible option, most biomass ash is still disposed of in landfills [25]. This can cause serious respiratory problems in communities near dumps, as the biomass ash particles are light and can be spread by the wind [26]. Leaching concerns have also been addressed [27–30]. Therefore, a more beneficial use must be determined. In fact, life cycle assessments of different alternatives in the construction sector have been proposed [31]. Many studies have proposed the use of biomass ash as a supplementary cementitious material in concrete [32–34], which has been suggested to be the most beneficial possible use [24]. However, only a few studies have investigated the possibility of using coarser particles such as wood bottom ash as a substitute for conventional aggregates [35]. For instance, positive effects have been detected in non-structural materials such as adhesive mortars [36]. However, Lessard et al. [37] detected detrimental effects on the workability and strength of dry-cast concrete when substituting conventional aggregate with dry biomass bottom ash by weight. Beltrán et al. [38] also detected detrimental effects on strength, water permeability, chloride penetration resistance, and shrinkage under air-drying conditions when incorporating biomass bottom ash produced in olive harvesting, despite having substituted the conventional aggregate by volume and compensated the water absorption of the particles. Cabrera et al. [39] reviewed the findings regarding the use of biomass bottom ash as a binder or aggregate in different cement-based materials. Nevertheless, the effect of biomass bottom ash on the self-desiccation of concrete has not been studied, despite the high water absorption capacity of this by-product. Only a few studies have detected the internal curing effect when using powder-size biomass ash particles as ICWRs [40–42].

2 Research significance

This study aims to investigate the performance of wood bottom ash as an ICWR in concrete by comparing it with LECA, a conventional LWA. Their capacity for mitigating autogenous shrinkage, effects on drying shrinkage, and compressive strength have been reported. Furthermore, an efficiency factor that considers technical aspects and the cost and carbon dioxide emissions of each mix is proposed. Other experimental studies on wood bottom ash as ICWR have not been reported in literature.

3 Material characterisation and mix design

All the materials used in the present work had a maximum particle diameter size of 4 mm. Thus, the experimental program was carried out on mortar mixes that did not comprise coarse aggregates but rather the paste and fine aggregates of a hypothetical HPC.

The crushed conventional sand (*S*), with a fineness modulus of 2.78, was substituted with 15 and 30% volume proportions of light expanded clay Arlita aggregate (LECA) and wood ash (WA). The LECA is a commercially available product. It is brownish in colour, rounded in shape and with a fineness modulus of 5.06. The WA is produced during the combustion of pine bark and other residues from the manufacture of wood boards. The burning process takes from 15 min to 1 h, depending on the moisture of the feed residue, and the burning temperature reaches 1000 °C. It is black in colour, flaky in shape and with a fineness modulus of 2.74. The specific gravities of S, LECA and WA are 2.47, 0.71 and 1.14 g/cm^3, respectively. The water absorption capacities of S and WA after 24 h of immersion are 2.43 and 36% by weight (6 and 41% by volume), whereas the absorption of LECA recorded after water immersion for 24 h in a pressurised vacuum chamber is 53% by weight (38% by volume). This wetting procedure is chosen for the LECA for the particles to be closer to saturation, although it should be noted that this procedure is complicated for site applications. A test method based on NY 703–19 E [43] was chosen for the determination of the specific gravities and absorption capacities of S, LECA and WA. Following this procedure, the aggregate samples were dried with filter paper towels after their saturation with water. The absorption kinetics of the aggregates are shown in Fig. 1.

The desorption capacities of the LECA and the WA were studied based on ASTM C1498 [44]. The results are shown in Fig. 2, where it can be seen that the desorption capacity of the LECA is inferior to that of the WA at a high relative humidity (97%) whereas superior at a low relative humidity (60%). Actually, at 60% relative humidity, WA reaches a moisture equilibrium higher than 10% whereas LECA completely dries. The capacity of biomass ashes to retain some water absorbed in this range of ambient humidities has been reported by other studies where their moisture buffering values were studied [45]. The
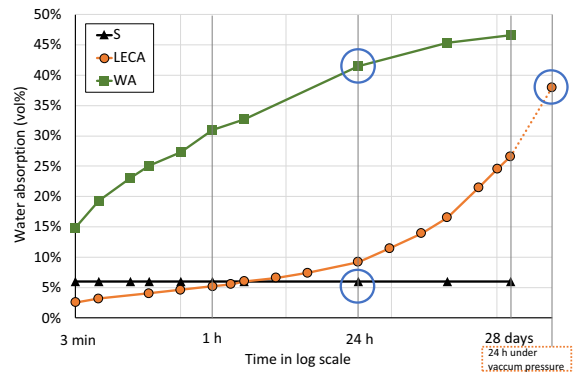

Fig. 1 Water absorption kinetics of S, LECA, and WA. The values chosen for calculating the ICW content are circled in blue
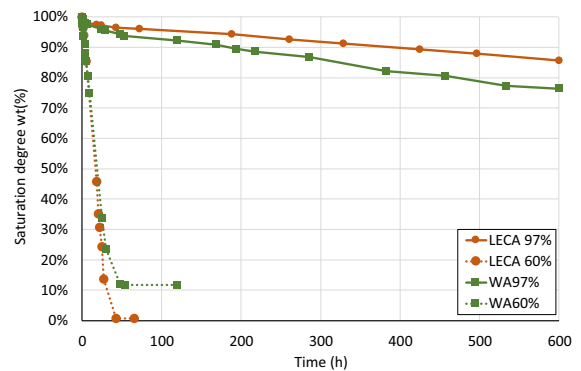

Fig. 2 Desorption of LECA and WA in environments with 97% and 60% relative humidity

different performance of the two aggregates at the two relative humidities are related with their pore structure and furtherly discussed in Sect. 5.2.

The three aggregates were pre-wetted with an amount of water equivalent to the described water absorption capacities 24 h before mixing and then protected from moisture loss. In the case of LECA, the particles were exposed to vacuum pressure, so they contained a similar amount of water as WA. This water is intended to internally cure the paste of the mortars; thus, it is referred to as internal curing water in the conventional sand (ICW-S) and internal curing water in the lightweight aggregates (ICW-LWA). The proportion of ICW-LWA in the mortars (fine aggregate substitution rate) was established based on Bentz et al. [46].

Two different binders were used: ordinary Portland cement (OPC) with a density of 3.12 g/cm^3 and blended cement (BC) composed of equal volume parts

of OPC and Class F fly ash (FA) with a density of 2.21 g/cm^3. Then, two series of mortars were designed. The series with OPC as binder is named as cement mortar (CM) and the series with the blended cement is named as blended cement mortar (BCM). A high range water reducing admixture (HRWRA) with a density of 1.05 ± 0.02 g/cm^3 and a solid residue of $20.3 \pm 1\%$ was dosed at 0.80% in terms of solid residue/OPC to enhance the fluidity of the mortar and attain a self-compacting behaviour. The mixing water (W) to binder ratio by volume remained constant for all the mixes. The mixing water did not include the ICW referred to in the previous paragraphs.

The combination of the two different binders with all the alternative aggregates and corresponding substitution ratios resulted in a total of 18 different mortar mixes (Table 1).

4 Testing methods

The internal humidity of the mortars was evaluated by measuring the humidity in a hole in cylindrical sealed specimens. The hole, also cylindrical, has diameter of 25 mm and a height of 60 mm and was formed in fresh state. A thermo-hygrometer was put into the hole and adjusted with a rubber plug. The test was carried out in 2 specimens per mix. Other researchers have measured the internal relative humidity in concrete following similar procedures [42, 47–49].

The compressive strength of the mortars was tested based on the UNE-EN 196–1 method [50] at seven different ages from 1 to 91 days after casting, whereas the strain was tested based on UNE 80,112 standard [51]. All the fabricated specimens were protected from moisture loss while being kept in moulds. Demoulding was carried out 18 h after casting so that the first records could be obtained as close as possible to the final setting time. After demoulding, the specimens were equally divided into two groups, which were cured in two different conditions: sealed (covered with aluminium foil) and in an air-drying 60% relative humidity environment. The temperature was kept constant in both curing environments at 22 ± 2 °C. The values of temperature (22 ± 2 °C) and low relative humidity (60%) were chosen in accordance with standards regarding the measurement of drying shrinkage [51, 52].

The compressive strength was tested on four specimens per mix and curing condition. The strain of the mortars was measured on three specimens per mix and curing condition, with dimensions of 25 mm × 25 mm × 285 mm and a gauge length of 250 mm. The changes in length at different ages were divided by the initial length (250 mm, as indicated in UNE 80,112 [51]); thus, the microstrain ($\mu\varepsilon$) was

Table 1 Mix proportions (kg/m^3)

	OPC	FA	S	ICW-S	LWA	ICW-LWA	W	HRWRA	Effective w/b Vol%	Effective w/b wt%	Total w/b Vol%	Total w/b wt%
CM-0	925	0	1112	27	0	0	239	15	0.85	0.27	0.94	0.30
CM-LECA15	925	0	945	23	48	25	239	15	0.85	0.27	1.01	0.32
CM-LECA30	925	0	778	19	96	51	239	15	0.85	0.27	1.07	0.34
CM-WA15	925	0	945	23	77	28	239	15	0.85	0.27	1.02	0.33
CM-WA30	925	0	778	19	154	56	239	15	0.85	0.27	1.1	0.35
BCM-0	463	327	1112	27	0	0	246	8	0.85	0.32	0.94	0.35
BCM-LECA15	463	327	945	23	48	25	246	8	0.85	0.32	1.02	0.38
BCM-LECA30	463	327	778	19	96	51	246	8	0.85	0.32	1.09	0.41
BCM-WA15	463	327	945	23	77	28	246	8	0.85	0.32	1.03	0.39
BCM-WA30	463	327	778	19	154	56	246	8	0.85	0.32	1.08	0.41

obtained. The strain in the sealed condition, that is, autogenous shrinkage, was recorded while a considerable self-desiccation occurred. This was 14 days in the case of CM, where self-desiccation was due to the hydration of Portland cement, and 56 days in the case of BCM, where pozzolanic reactions could cause long-term self-desiccation [53].

It should be noted that the experimental program of the present study was carried out in two different laboratories. The baseline mixes (CM-0 and BCM-0) were fabricated and tested in both laboratories (with the previously indicated number of specimens tested in each laboratory), using the obtained results to compare the possible scatter of the experimental data.

5 Results and discussion

5.1 Compressive strength

The use of WA decreased the strength of mortars owing to the weakness of the particles. However, the use of LECA had a negligible effect on compressive strength (Fig. 3). This suggests that LECA is quite strong despite its porosity owing to the characteristic hard shell of this type of aggregate [54]. In sealed conditions, the internal curing effect triggered by any of the two pre-wetted LWAs might partially compensate for the loss in strength by promoting cement hydration (Fig. 3a).

The tendencies of the CM mixes were similar when comparing both sealed and air-drying curing conditions. However, the ICW stored in the LECA was retained in air-drying curing conditions, which could contribute to the late strength development (Fig. 3b). In contrast, the water loss through evaporation in mortars with WA may be slightly higher, and thus the strength development in air-drying curing conditions stops at an earlier age (approximately 14 days). This phenomenon can be related with the results obtained in the desorption test. As the internal relative humidity inside the strength specimens (40×40 mm cross-section) is high, the WA desorbs water at a higher rate than LECA. Thus, the water initially stored in WA migrates to the surface of the specimens and evaporates at an early age. On the contrary, the water inside the LECA remains enclosed for a longer time, until the internal humidity in the specimens eventually decreases to a sufficiently low value. This different performance between the two aggregates is furtherly explained in Sect. 5.2.

The strength development in BCM is distinctive as the pozzolanic reaction of FA makes its contribution from the age of 14 days onwards (Fig. 4a). However, in air-drying curing conditions, this effect was drastically reduced in the baseline mix and in mortars with WA (Fig. 4b). Mortars with LECA were able to develop strength in low RH conditions until the age of 28 days, surpassing the long-term strength of the reference mix. This may be due to the capacity of LECA to retain the stored ICW even when the mortars are exposed to air-drying and only release it when pozzolanic reactions are developed at a high rate. It must be noted that the LECA completely dries when exposed to a 60% relative humidity environment (Fig. 2), but the humidity inside the compressive
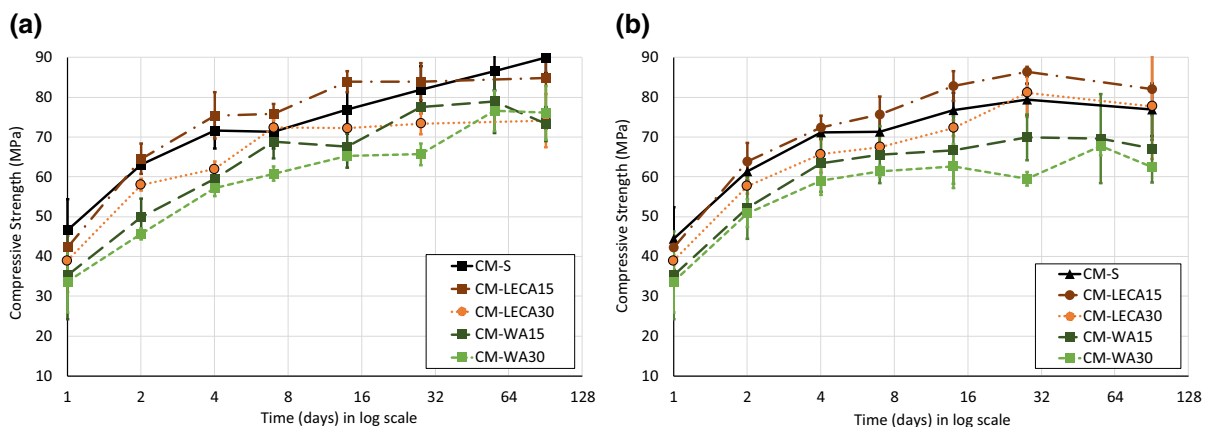

Fig. 3 Compressive strength of OPC mortars in **a** sealed curing and **b** air-drying curing conditions
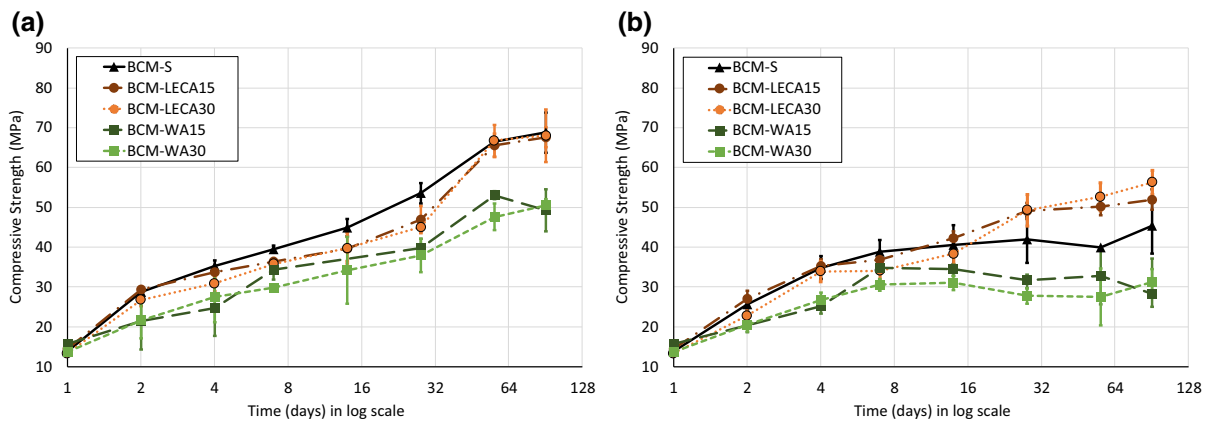
(a)

(b)

Fig. 4 Compressive strength of BC mortars in **a** sealed curing and **b** air-drying curing conditions

strength specimens exposed to this environment might be higher to that value for an extended period of time. Therefore, it is believed that the humidity threshold that need to be surpassed for the LECA to release its water at a high rate is not surpassed, or at least not at an early age, and this enhances the sustainment of hydration. When using WA, this sustainment of hydration is only observed in sealed specimens, as their pore structure might lead to an earlier, more progressive water desorption when the mortar is exposed to air-drying curing conditions.

In any of the binder compositions and curing conditions, the performance of all the LWAs was similar for the two different substitution rates. This phenomenon was especially noticeable in the BCM mixes, as their pastes were less strong and therefore their aggregates had a less predominant influence on the overall strength.

5.2 Internal relative humidity and autogenous strain

The internal relative humidities of the CM mixes are shown in Fig. 5. The relative position of the mixes with LECA and the mixes with WA indicates that the former has a higher desorption capacity in the self-desiccated paste. This correlates with the result obtained in the desorption test, where the WA tended to release the water at a slower rate in a low relative humidity environment.

The internal relative humidity of BCM mixes was studied following the same procedure as that applied for the CM mixes. Due to the low content in Portland
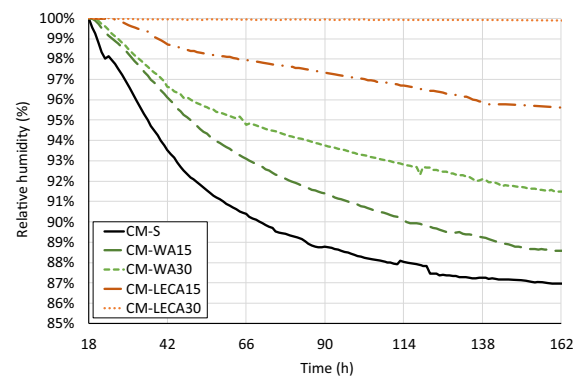

Fig. 5 Internal relative humidity inside the mortars

cement and the delay nature of pozzolanic reactions related with the presence of fly ash led these mixes to show no decrease in relative humidity (it was maintained at 99%) for the first 14 days after casting.

This desorption performance is the cause for the highest reduction in autogenous shrinkage to occur in CM when the highest ratio of LECA was used (Fig. 6a). The desorption of the ICW from this aggregate is low until the internal humidity significantly dropped, but quick and effective afterwards (see Figs. 2 and 5). The distinctive performance of the LECA could be due its structure, which consisted of an inner complex, tortuous, and partially interconnected highly porous network surrounded by a dense outer shell that could act as a barrier (bottleneck effect) [55]. This idea is supported by the difficulty in saturating the LECA and the relatively high water absorption capacity they showed when wetted under vacuum pressure (Fig. 1). The significant reduction of the
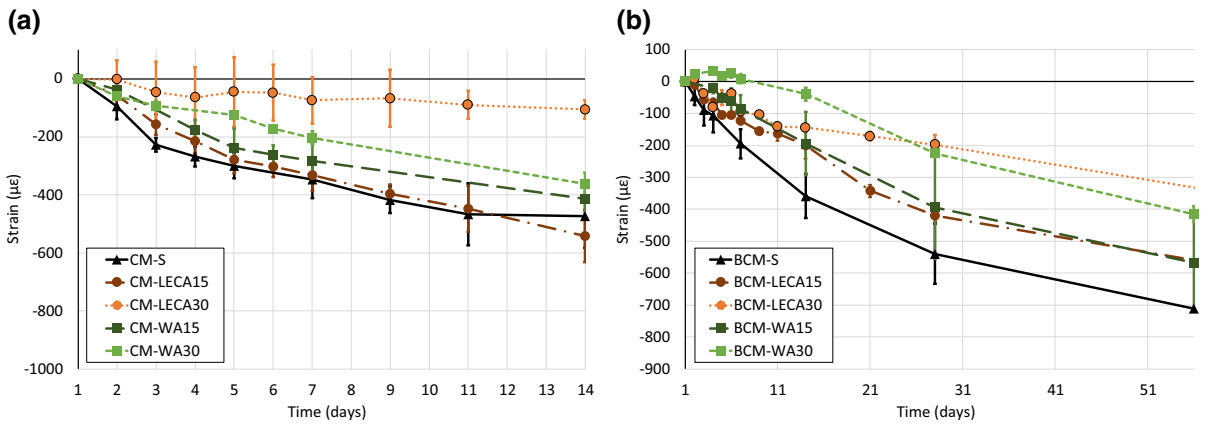
Fig. 6 Autogenous strain of **a** CM and **b** BCM

internal humidity in the CM is believed to occur during the first hours after casting, before the measurements started at the age of 18 h (Fig. 7a). However, BCM maintains high levels of humidity until the pozzolanic reactions increase their rate after one week [56] (Figs. 6b and 7b). Thus, the internal curing effect of LECA in BCM is much more visible in the long term

(Figs. 6b and 7c). The lowest content of LECA mitigates self-desiccation by a smaller magnitude than the highest content of this LWA, especially in CM, similar to the lowest WA content. Actually, the shrinkage of C-LECA15 is slightly higher than that of the reference mix at 14 days, what could be due to the poor compensating effect of the internal curing
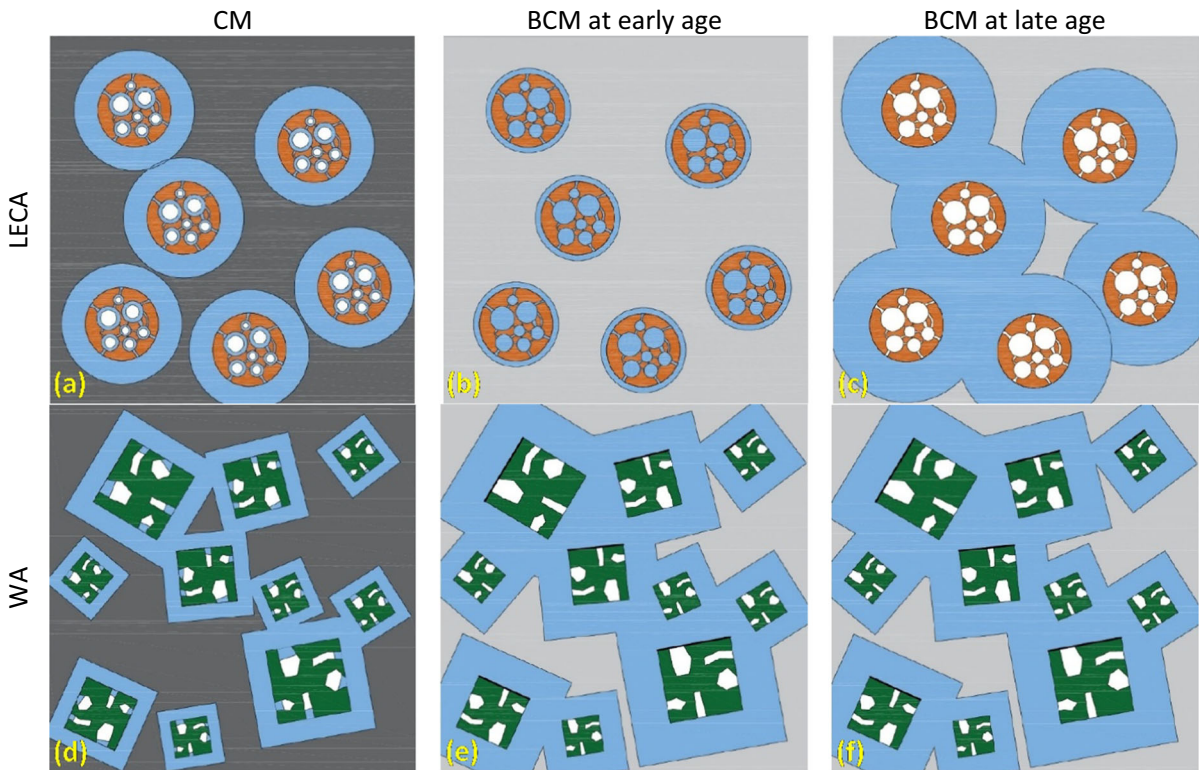

Fig. 7 Desorption of the internal curing water from the different LWA to the different pastes

together with a lower modulus of elasticity of the mortar when the LWA is incorporated. Nevertheless, the effect of the 15% substitution ratio was higher in the case of BCM. A wider pore structure in the blended paste may ease the enlargement of the sphere of influence of the LWA, leading to a higher volume of protected paste (Fig. 7c, e, f). Furthermore, the reduction in autogenous shrinkage when using WA seemed to be more proportional to the amount of ICW that was provided, probably caused by a more gradual desorption of the ICW. The openings of the pores of the WA may be wider than those in the LECA; therefore, there was no need for a strong self-desiccation to trigger the release of the ICW (Fig. 7e). This characteristic enabled the early swelling detected in BCM-WA30 (Fig. 6b).

5.3 Shrinkage in air-drying curing conditions

The distinctive performance of the highest substitution ratio of LECA was also found when the shrinkage was measured in air-drying conditions. It should be considered that in this situation, self-desiccation coexisted with drying. The quick and effective desorption of ICW mitigated self-desiccation and increased external drying. Therefore, similar shrinkage values were registered less in internally cured mixes when the highest content of LECA was used (Fig. 8a, b). In the case of BCM, a delay in the appearance of self-desiccation was found in sealed conditions because of the lower content of OPC and the late development of pozzolanic reactions. However, long-term self-desiccation due to pozzolanic reactions may not occur in the air-drying conditions.

An early humidity decrease in the thin shrinkage specimens caused by both self-desiccation and external drying could have triggered the premature desorption of the LECA-ICW. This ICW mitigated self-desiccation; therefore, lower values of shrinkage were registered during the first days after casting in the BCM. Some authors have also detected less early shrinkage in air-drying conditions when using a LECA-type LWA [57], whereas others proved the better performance of LECA regarding drying shrinkage in comparison with other LWAs [58]. However, the use of a 15% substitution ratio of LECA or any content of WA only has a slight effect on the shrinkage in air-drying conditions. In fact, the higher initial total water content of mixes with WA led to a modest long-term increase due to a higher evaporation rate (Fig. 8a, b).

It should be noted that the specimens used had a high surface-to-volume ratio, so the drying rate was much higher than that in a real construction element. This should be considered for a correct evaluation of the studied mixes, as the drying effect only affected the surface of an element and could be mitigated by external conventional curing [59].

6 Efficiency of LECA and WA

Other authors have already proposed efficiency factors to assess the performance of different internal curing water reservoirs and facilitate the comparison between them. For instance, Zhutovsky et al. [60] developed an efficiency factor as in Eq. (1):
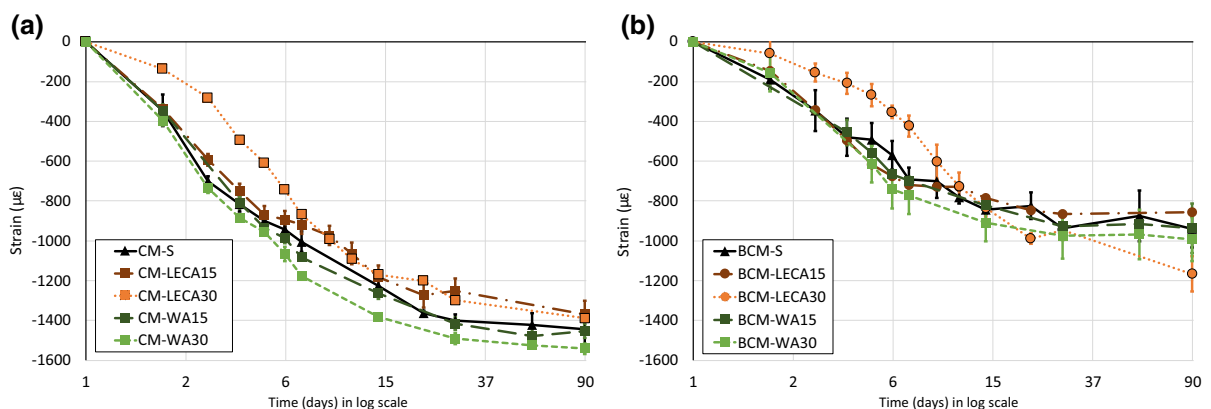

Fig. 8 Shrinkage in air-drying conditions for **a** CM and **b** BCM

$$\eta = \frac{W_{ic}}{S \cdot \phi \cdot W_{LWA}} \cdot SR \tag{1}$$

where η is the efficiency factor, W_{ic} is the internal curing water required to eliminate self-desiccation (g), S is the degree of saturation (%), ϕ is the water absorption capacity (wt%), W_{LWA} is the lightweight aggregate content (g), and SR is the autogenous shrinkage reduction (%).

This efficiency factor evaluates only the technical performance of the internal curing water reservoir, what is still useful when dealing with conventional lightweight aggregates. However, considering the economic and environmental costs is especially convenient when waste based materials are to be used. Thus, in this study, the technical performance of the proposed mixes was evaluated in combination with their economic cost and global warming potential (GWP) by the efficiency factor described in Eq. (2), based on other works [61, 62]. The only properties that were considered for the assessment of the technical performance are the compressive strength in sealed conditions at 90 days (f_c) and the final autogenous shrinkage (AS) (at 14 days for CM and 56 days for BCM). The compressive strength and shrinkage in air-drying conditions were excluded, as they were only representative of the concrete next to the surface in an improperly cured concrete element [63]. The coefficients 0.6 and 0.4 are chosen to reflect that a higher priority is given to shrinkage over strength when dealing with the internal curing of high performance concrete. In new concretes with a low water to binder ratio, the autogenous shrinkage is a critical problem that may affect their durability. This is considered as a major issue as it is directly related with the concrete sustainability, the efficient use of resources and the reduction of wastes.

$$\text{Efficiency factor} = \frac{0.4 \cdot \frac{f_c}{f_c \text{ref}} + 0.6 \cdot \frac{\text{AS ref}}{\text{AS}}}{\frac{\text{cost}}{\text{cost ref}} \cdot \frac{\text{GWP}}{\text{GWP ref}}} \tag{2}$$

"ref" denotes the value of the property (f_c, AS, cost or GWP) for the reference mix, i.e. CM-0.

The cost and GWP of each component are listed in Table 2. The GWP (cradle-to-door) was taken from an inventory [64]. The economic costs were taken from a database of prices for construction materials [65] and other sources [61, 62]. The economic costs and GWP

Table 2 Economic cost (€/kg) and GWP (kg CO_2/kg) of the materials used

Material	Cost (€/kg)	GWP (kg CO_2/kg)
OPC	0.115	0.950
FA	0.06	–
S	0.009	0.005
Water	0.001	0.001
LECA	0.087	0.393
WA	–	–
HRWRA	4.330	1.880

of the by-products used (FA and WA) were considered as zero.

The efficiency factors obtained using the CM and BCM mixes without internal curing as a reference are listed in Table 3.

All the BCM mixes showed higher efficiency factors than their CM counterparts because of their high volumes of FA, a by-product that is considered free of GWP. Furthermore, the highest LECA content reached the highest efficiency factors for both CM and BCM. This is due to its effective work as an ICWR, considerably reducing the autogenous shrinkage while maintaining its compressive strength. Nevertheless, the use of WA also increased the efficiency factor, always reaching higher values than mixes without internal curing.

In addition to the parameters included in the efficiency factor, other issues should be considered when analysing the convenience of using LECA or WA as ICWRs. For instance, in this study, LECA was saturated under vacuum pressure. This procedure significantly increased the absorption and avoided possible ongoing water absorption, which could lead to excessive densification of the interfacial transition zone. This phenomenon could hinder the subsequent water migration from the aggregate to the paste, that is, internal curing [66]. However, vacuum saturation is a more complicated wetting procedure than other methods, such as sprinkling, in which WA could reach comparable values of absorption. Therefore, the use of the latter is considered to be advantageous in this regard. Another issue that should be addressed is the optimisation of the WA production process. In this study, no specific controlled measures were taken for its production, such as the selection of burnt waste or

Table 3 Efficiency factors of the internally cured mixes

	Reference	LECA15	LECA30	WA15	WA30
CM (related to CM reference)	1.00	0.87	2.79	1.02	1.14
BCM (related to CM reference)	2.93	3.11	4.68	3.21	4.21
BCM (related to BCM reference)	1.00	1.02	1.46	1.05	1.36

burning temperatures. Recycling this by-product should be done so that the properties of the WA and the concrete that contain it can be predicted.

7 Conclusions

The effects of WA and LECA on the shrinkage and strength of mortars with different binders were studied. The following conclusions were drawn:

- The highest LECA content reduced the final autogenous shrinkage of both CM and BCM. The effect on BCM was delayed because the ICW only migrated from the LWA to the paste when the pozzolanic reactions occurred at a higher rate. However, this delay was not perceivable in air-drying curing conditions, where short-term shrinkage was reduced in both CM and BCM. The higher decrease in internal humidity in the thin specimens due to the coexistence of self-desiccation and external drying may have been the cause of this phenomenon. The effect of the internal curing water provided by the LECA on the compressive strength was especially remarkable in BCM in air-drying conditions, where mixes with this LWA continued to improve their performance after 28 days, unlike the reference mix.
- The WA seemed to release its ICW gradually, so it was able to reduce the autogenous shrinkage both in the short and long term, especially in mortars with FA. The internal curing via this LWA had no considerable influence on the development of the compressive strength, and it even slightly increased the shrinkage in air-drying curing conditions.

In addition to the technical characteristics of the two LWAs, it should strongly be highlighted that WA is a forestry by-product that needs new beneficial applications to be developed. LECA is an already established LWA that is commonly used in light-weight concrete, but its embodied energy is high. Therefore, despite the LECA showing better performance as ICWR, the use of WA is recommended. A good characterization including the water absorption and desorption kinetics is needed to describe the potential performance of any WA as an ICWR, as the characteristics of this by-product depend on the material source and the burning temperatures reached during the industrial process where they are produced. Nevertheless, further research regarding this by-product as ICWR is recommended as a future line framed in the objective of a circular economy.

Code availability   Not applicable.

Declarations

Conflict of 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.

References

1. Ramírez J, Olek J, Rolle E, Malone B (2010) Performance of bridge decks and girders with lightweight aggregate concrete. https://docs.lib.purdue.edu/cgi/viewcontent.cgi?article=1636&context=jtrp

2. Delatte N, Mack E, Clearly J (2007) Evaluation of high absorptive materials to improve internal curing of low permeability concrete. https://rosap.ntl.bts.gov/view/dot/37769 142:

3. ASTM (2015) ASTM C1761: Lightweight aggregate for lnternal curing of concrete

4. Persson B (1998) Experimental studies on shrinkage of high-performance concrete. Cem Concr Res 28:1023–1036. https://doi.org/10.1016/S0008-8846(98)00068-4

5. Baroghel-Bouny V, Mounanga P, Khelidj A et al (2006) Autogenous deformations of cement pastes: part II. W/C effects, micro-macro correlations, and threshold values. Cem Concr Res 36:123–136. https://doi.org/10.1016/j.cemconres.2004.10.020

6. Jiang Z, Sun Z, Wang P (2005) Autogenous relative humidity change and autogenous shrinkage of high-performance cement pastes. Cem Concr Res 35:1539–1545. https://doi.org/10.1016/j.cemconres.2004.06.028

7. Cavalline TL, Calamusa JT, Kitts AM, Tempest BQ (2017) Field-observed cracking of paired lightweight and normal-weight concrete bridge decks. Int J Concr Struct Mater 11:85–97. https://doi.org/10.1007/s40069-016-0176-1

8. Philleo R (1991) Concrete science and reality. In: Skalny JP, Mindess S (eds) Materials science of concrete II. American Ceramic Society, Westerville, pp 1–8

9. Tran YT, Lee J, Kumar P et al (2019) Natural zeolite and its application in concrete composite production. Compos Part B Eng 165:354–364. https://doi.org/10.1016/j.compositesb.2018.12.084

10. Zhang J, Wang Q, Zhang J (2017) Shrinkage of internal cured high strength engineered cementitious composite with pre-wetted sand-like zeolite. Constr Build Mater 134:664–672. https://doi.org/10.1016/j.conbuildmat.2016.12.182

11. Zhutovsky S, Kovler K (2012) Effect of internal curing on durability-related properties of high performance concrete. Cem Concr Res 42:20–26. https://doi.org/10.1016/j.cemconres.2011.07.012

12. Şahmaran M, Lachemi M, Hossain KMA, Li VC (2009) Internal curing of engineered cementitious composites for prevention of early age autogenous shrinkage cracking. Cem Concr Res 39:893–901. https://doi.org/10.1016/j.cemconres.2009.07.006

13. Browning JA, Darwin D, Reynolds D, Pendergrass B (2011) Lightweight aggregate as internal curing agent to limit concrete shrinkage. ACI Mater J. 108:638–644. https://doi.org/10.14359/51683467

14. Cusson D, Hoogeveen T (2008) Internal curing of high-performance concrete with pre-soaked fine lightweight aggregate for prevention of autogenous shrinkage cracking. Cem Concr Res 38:757–765. https://doi.org/10.1016/j.cemconres.2008.02.001

15. Bentur A, Igarashi SI, Kovler K (2001) Prevention of autogenous shrinkage in high-strength concrete by internal curing using wet lightweight aggregates. Cem Concr Res 31:1587–1591. https://doi.org/10.1016/S0008-8846(01)00608-1

16. Shen D, Feng Z, Zhu P et al (2020) Effect of pre-wetted lightweight aggregates on residual stress development and stress relaxation in restrained concrete ring specimens. Constr Build Mater. https://doi.org/10.1016/j.conbuildmat.2020.119151

17. Bentz DP, Weiss WJ (2011) Internal Curing: a 2010 state of the art review. Natl NISTIR 7765:82. https://doi.org/10.1016/j.jvcir.2009.09.004

18. Ghourchian S, Wyrzykowski M, Lura P et al (2013) An investigation on the use of zeolite aggregates for internal curing of concrete. Constr Build Mater 40:135–144. https://doi.org/10.1016/j.conbuildmat.2012.10.009

19. Haist M, Mechtcherine V, Beitzel H, Müller HS (2003) Retrofitting of building structures using pumpable self-compacting lightweight concrete. In: Wallevik O, Nielsson I (eds) International RILEM symposium on self-compacting concrete. RILEM Publicacions SARL, pp 776–785

20. Al Saffar DM, Al Saad AJK, Tayeh BA (2019) Effect of internal curing on behavior of high performance concrete: an overview. Case Stud Constr Mater 10:e00229. https://doi.org/10.1016/j.cscm.2019.e00229

21. Rodríguez-Álvaro R, Seara-Paz S, González-Fonteboa B, Martínez-Abella F (2020) Use of granular coal combustion products as aggregates in structural concrete: effects on properties and recommendations regarding mix design. Constr Build Mater. https://doi.org/10.1016/j.conbuildmat.2020.121690

22. Biomass Power Association (2021) What is biomass power? https://www.usabiomass.org/about/#1551199533969-12bb0ec8-2047

23. Calderón C, Avagianos I, Oliveira M, Jossart J-M (2020) Report bioenergy landscape

24. Gaudreault C, Lama I, Sain D (2020) Is the beneficial use of wood ash environmentally beneficial? A screening-level life cycle assessment and uncertainty analysis. J Ind Ecol. https://doi.org/10.1111/jiec.13019

25. Milovanović B, Štirmer N, Carević I, Baričević A (2019) Wood biomass ash as a raw material in concrete industry. Gradjevinar 71:505–514. https://doi.org/10.14256/JCE.2546.2018

26. Cheah CB, Ramli M (2011) The implementation of wood waste ash as a partial cement replacement material in the

production of structural grade concrete and mortar: an overview. Resour Conserv Recycl 55:669–685. https://doi.org/10.1016/j.resconrec.2011.02.002

27. Mellbo P, Sarenbo S, Stålnacke O, Claesson T (2008) Leaching of wood ash products aimed for spreading in forest floors: influence of method and L/S ratio. Waste Manag 28:2235–2244. https://doi.org/10.1016/j.wasman.2007.09.037

28. Supancic K, Obernberger I, Kienzl N, Arich A (2014) Conversion and leaching characteristics of biomass ashes during outdoor storage–results of laboratory tests. Biomass Bioenergy 61:211–226. https://doi.org/10.1016/j.biombioe.2013.12.014

29. Barbosa R, Lapa N, Dias D, Mendes B (2013) Concretes containing biomass ashes: mechanical, chemical, and eco-toxic performances. Constr Build Mater 48:457–463. https://doi.org/10.1016/j.conbuildmat.2013.07.031

30. Pöykiö R, Rönkkömäki H, Nurmesniemi H et al (2009) Chemical and physical properties of cyclone fly ash from the grate-fired boiler incinerating forest residues at a small municipal district heating plant (6 MW). J Hazard Mater 162:1059–1064. https://doi.org/10.1016/j.jhazmat.2008.05.140

31. da Costa TP, Quinteiro P, Tarelho LAC et al (2019) Environmental assessment of valorisation alternatives for woody biomass ash in construction materials. Resour Conserv Recycl 148:67–79. https://doi.org/10.1016/j.resconrec.2019.04.022

32. Pereira AM, Moraes JCB, Moraes MJB et al (2018) Valorisation of sugarcane bagasse ash (SCBA) with high quartz content as pozzolanic material in Portland cement mixtures. Mater Constr 68:1–10

33. Chowdhury S, Mishra M, Suganya O (2015) The incorporation of wood waste ash as a partial cement replacement material for making structural grade concrete: an overview. Ain Shams Eng J 6:429–437. https://doi.org/10.1016/j.asej.2014.11.005

34. Rojo-López G, Nunes S, González-Fonteboa B, Martínez-Abella F (2020) Quaternary blends of portland cement, metakaolin, biomass ash and granite powder for production of self-compacting concrete. J Clean Prod 266:1–14. https://doi.org/10.1016/j.jclepro.2020.121666

35. Tamanna K, Raman SN, Jamil M, Hamid R (2020) Utilization of wood waste ash in construction technology: a review. Constr Build Mater. https://doi.org/10.1016/j.conbuildmat.2019.117654

36. Modolo RCE, Silva T, Senff L et al (2015) Bottom ash from biomass combustion in BFB and its use in adhesive-mortars. Fuel Process Technol 129:192–202. https://doi.org/10.1016/j.fuproc.2014.09.015

37. Lessard JM, Omran A, Tagnit-Hamou A, Gagne R (2017) Feasibility of using biomass fly and bottom ashes in dry-cast concrete production. Constr Build Mater 132:565–577. https://doi.org/10.1016/j.conbuildmat.2016.12.009

38. Beltrán MG, Agrela F, Barbudo A et al (2014) Mechanical and durability properties of concretes manufactured with biomass bottom ash and recycled coarse aggregates. Constr Build Mater 72:231–238. https://doi.org/10.1016/j.conbuildmat.2014.09.019

39. Cabrera M, Díaz-López JL, Agrela F, Rosales J (2020) Eco-efficient cement-based materials using biomass bottom ash:

a review. Appl Sci 10:1–23. https://doi.org/10.3390/app10228026

40. Dixit A, Gupta S, Pang SD, Kua HW (2019) Waste valorisation using biochar for cement replacement and internal curing in ultra-high performance concrete. J Clean Prod. https://doi.org/10.1016/j.jclepro.2019.117876

41. Vieira AP, Toledo Filho RD, Tavares LM, Cordeiro GC (2020) Effect of particle size, porous structure and content of rice husk ash on the hydration process and compressive strength evolution of concrete. Constr Build Mater 236:1–9. https://doi.org/10.1016/j.conbuildmat.2019.117553

42. Van VTA, Rößler C, Bui DD, Ludwig HM (2014) Rice husk ash as both pozzolanic admixture and internal curing agent in ultra-high performance concrete. Cem Concr Compos 53:270–278. https://doi.org/10.1016/j.cemconcomp.2014.07.015

43. Bureau NYSD of TM (2008) NY 703–19 E Moisture content of lightweight fine aggregate. pp 1–4

44. ASTM (2016) ASTM C1498–Standard test method for hygroscopic sorption isotherms of building materials. 4

45. Giosuè C, Mobili A, Toscano G et al (2016) Effect of biomass waste materials as unconventional aggregates in multifunctional mortars for indoor application. Procedia Eng 161:655–659

46. Bentz DP, Lura P, Roberts JW (2005) Mixture proportioning for internal curing. Concr Int 27:35–40

47. Kim HK, Ha KA, Lee HK (2016) Internal-curing efficiency of cold-bonded coal bottom ash aggregate for high-strength mortar. Constr Build Mater 126:1–8. https://doi.org/10.1016/j.conbuildmat.2016.08.125

48. Shen D, Wang T, Chen Y et al (2015) Effect of internal curing with super absorbent polymers on the relative humidity of early-age concrete. Constr Build Mater 99:246–253. https://doi.org/10.1016/j.conbuildmat.2015.08.042

49. Wei Y, Xiang Y, Zhang Q (2014) Internal curing efficiency of prewetted LWFAs on concrete humidity and autogenous shrinkage development. J Mater Civ Eng 26:947–954. https://doi.org/10.1061/(asce)mt.1943-5533.0000883

50. AENOR (2005) UNE-EN 196–1 Methods of testing cement. Part 1: determination of strength

51. AENOR (2016) UNE 80112 Test methods of cements. Physical analysis. Determination of contraction in air and expansion in water

52. AENOR (2002) UNE-EN 12617–4 Products and systems for the protection and repair of concrete structures. Test methods. Part 4: determination of shrinkage and expansion.

53. De La Varga I, Castro J, Bentz D, Weiss J (2012) Application of internal curing for mixtures containing high volumes of fly ash. Cem Concr Compos 34:1001–1008. https://doi.org/10.1016/j.cemconcomp.2012.06.008

54. Ke Y, Beaucour AL, Ortola S et al (2009) Influence of volume fraction and characteristics of lightweight aggregates on the mechanical properties of concrete. Constr Build Mater 23:2821–2828. https://doi.org/10.1016/j.conbuildmat.2009.02.038

55. Bogas JA, Mauricio A, Pereira MFC (2012) Microstructural analysis of Iberian expanded clay aggregates. Microsc Microanal 18:1190–1208. https://doi.org/10.1017/S1431927612000487

56. Deschner F, Winnefeld F, Lothenbach B et al (2012) Hydration of Portland cement with high replacement by siliceous fly ash. Cem Concr Res 42:1389–1400. https://doi.org/10.1016/j.cemconres.2012.06.009

57. Shafigh P, Chai LJ, Bin MH, Nomeli MA (2018) A comparison study of the fresh and hardened properties of normal weight and lightweight aggregate concretes. J Build Eng 15:252–260. https://doi.org/10.1016/j.jobe.2017.11.025

58. Schumacher K, Saßmannshausen N, Pritzel C, Trettin R (2020) Lightweight aggregate concrete with an open structure and a porous matrix with an improved ratio of compressive strength to dry density. Constr Build Mater. https://doi.org/10.1016/j.conbuildmat.2020.120167

59. Liu J, Shi C, Ma X et al (2017) An overview on the effect of internal curing on shrinkage of high performance cement-based materials. Constr Build Mater 146:702–712. https://doi.org/10.1016/j.conbuildmat.2017.04.154

60. Zhutovsky S, Kovler K, Bentur A (2004) Influence of cement paste matrix properties on the autogenous curing of high-performance concrete. Cem Concr Compos 26:499–507. https://doi.org/10.1016/S0958-9465(03)00082-9

61. Zhong R, Wille K, Viegas R (2018) Material efficiency in the design of UHPC paste from a life cycle point of view. Constr Build Mater 160:505–513. https://doi.org/10.1016/j.conbuildmat.2017.11.049

62. Wille K, Boisvert-Cotulio C (2015) Material efficiency in the design of ultra-high performance concrete. Constr Build Mater 86:33–43. https://doi.org/10.1016/j.conbuildmat.2015.03.087

63. Rodríguez-Álvaro R, González-Fonteboa B, Seara-Paz S, Hossain KMA (2020) Internally cured high performance concrete with magnesium based expansive agent using coal bottom ash particles as water reservoirs. Constr Build Mater. https://doi.org/10.1016/j.conbuildmat.2020.118977

64. Hammond G, Jones C (2011) Embodied carbon. The inventory of carbon and energy (ICE)

65. Base de Datos da Construción de Galicia (2020). http://www.presupuesta.com/bdc/index.php?bdc=BDCG16G

66. Kovler, K Jensen OM (2007) Internal curing of concrete. RILEM TC 196-ICC: State of the Art Report. https://www.rilem.net/publication/publication/105