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Design of lightweight concrete with olive biomass bottom ash for use in buildings

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ABSTRACT

The ash generated during the combustion of biomass in electricity generation plants is a waste that has increased considerably in recent years, and whose management constitutes an environmental problem. In this regard, the recovery of biomass bottom ash as a partial replacement of natural materials for use in different civil engineering applications, as well as for the manufacture of construction materials, has been the subject of numerous studies that have shown its technical feasibility. However, for its application in the development of new sustainable materials, with thermal insulation properties, it is necessary to expand our existing knowledge of it. In this study, the use of bottom ash from original and processed biomass bottom ash in the manufacture of lightweight concrete, as a replacement for sand (15%–25%) and expanded clay (25%–35%), has been evaluated. In addition, after subjecting the ash to a grinding process, it was also incorporated into the concrete by replacing cement. The physical, mechanical, thermal and durability properties were evaluated according to regulations and the results showed that the thermal treatment applied to biomass bottom ash improved the mechanical performance of lightweight concrete. Likewise, thermal conductivity was reduced by up to 43%, which allows these concretes to be used as insulating materials in buildings. Therefore, this study shows the possibility of recovering biomass bottom ash in the manufacture of lightweight concrete for use in construction.

1. Introduction

Currently, concern and respect for the environment, together with the progressive depletion of natural resources, has driven initiatives towards sustainable development, such as the recycling of industrial by-products and the implementation of a circular economy. The main reasons for moving towards a circular economy are the increasing demand for raw materials and the scarcity of resources [1]. Several crucial raw materials are finite and, as the world's population grows, demand is also increasing. The use of industrial waste within the concrete industry is an effective alternative towards sustainable development. Concrete, the building material par excellence, is a benchmark with a high degree of economic impact in the building and civil engineering market. The possibilities for improving concrete in terms of the consumption of natural resources are still promising, with wide margins for innovation and development in the components of concrete (cement, additives and aggregates), in accordance with the new paradigms of environmental, economic and social sustainability.

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In recent years, an increasing number of researchers and academics have become interested in the sustainable development of concrete, such as the durability of concrete made from industrial by-products [2,3], complementary cementitious materials [4] and concrete recycling [5]; therefore, concrete made from industrial by-products (recycled concrete) has started to receive increasing attention as a feasible use in linear infrastructure works. Studies show that the use of concrete made from industrial waste not only meets the performance requirements of conventional concrete, but also solves the problem of landfill shortage, which is consistent with the essence of sustainable development, i.e., environmental protection and resource reduction [6–8]. In this regard, the use of bottom ash produced in coal-fired power plants in the manufacture of lightweight concrete has been studied in several research papers; Nisnevich [9], Nisnevich et al. [10] and Nisnevich et al. [11] improved the strength and reduced the porosity by incorporating furnace bottom ash and fly ash; Zhang and Poon [12] replaced sand with furnace bottom ash and the thermal conductivity could be lowered to around 70% to the control lightweight concrete; Lee et al. [13] developed an empirical equation for mechanical properties of lightweight concrete with bottom ash.

In the last decade, driven by concerns about CO₂ emissions into the atmosphere, the generation of electricity from biomass combustion has been consolidated as a way of obtaining energy in a more efficient way, while reducing pollution. The increase in biomass combustion also produces waste, as is the case of the ash from this process; the most common management of ash from biomass combustion is landfilling, which has significant economic and environmental drawbacks [14]. In accordance with the principles established by the European Union in sustainability policies, studies on biomass ash from heat and power generation have increased. There are numerous studies on the characterisation of biomass ash, focusing on its physical and chemical properties and environmental behaviour through the study of leachates [15–17]. Due to the heterogeneity of biomass bottom ash (BBA), there are not many studies using it as a potential building material. Carrasco et al. [18] produced compacted building blocks made from Portland cement and BBA, replacing cement with BBA in the range of 10%–90%. Medina et al. [19] manufactured new cement formulations replacing clinker with BBA. Rosales et al. [20] used different BBA processing methods (crushed, calcined, without light particles, crushed and calcined) to produce mortars and study their mechanical and durability properties. Cabrera et al. [21] reported on the stabilisation of expansive soils by removing lime and incorporating BBA, showing significant improvements in the mechanical behaviour of the mixtures studied.

Some authors have studied the manufacture of concrete with BBA due to its potential use as a substitute for materials such as natural sand or cement. Beltrán et al. [22] analysed the mechanical and durability properties of non-structural concretes made with BBA, the results showed results of up to 35 MPa with 6% substitution of natural sand by BBA. Fontes et al. [23] studied the physical and mechanical properties of conventional concrete made with 5% and 10% substitutions of sand by BBA, observing that the low pozzolanicity of BBA influenced the loss of strength.

Cabrera et al. [24] evaluated the properties of BBA with different treatments and the influence of their use on fresh and hardened properties (mechanical and durability) in the manufacture of self-compacting concrete. The study concluded with the recommendation to use self-compacting concretes with a maximum substitution of 30% of natural sand by BBA and up to 60% of filler by crushed BBA. The use of BBA in lightweight concretes has been little studied. Rosales et al. [25] reported the possibility of manufacturing lightweight concretes using recycled aggregates mixed with BBA, in which all mixtures presented compressive strength values within the limits established by the Spanish regulations [26] for lightweight structural concretes. In this context, the use of BBA is conditioned by its physical and chemical properties, mainly by its heterogeneity [27]. With all the above and with the widespread global concern for sustainable development, maximum interest has been given to the study of new building materials, including prefabricated ones, with thermal and acoustic insulation technology being an important method of energy saving, cleaner production, lower economic costs [28], if low-density concretes made with BBA are incorporated. All these new technologies and forms of construction are emerging rapidly.

Therefore, the main objective of the present work is to collaborate in the generation of knowledge on the performance related to thermal insulation for buildings without forgetting the mechanical and durability properties of lightweight concretes using BBA with three different treatments (oven-dried at 60 °C, heated at 300 °C and crushed) and lightweight aggregates. The results obtained show the viability of the use of concretes made with BBA for use as insulators in building works. The durability of concrete is a fundamental issue, since it allows us to understand the behaviour of concrete throughout the useful life of a structure. The affectation of the concrete's durability behaviour can be caused by agents external to the environment or by internal agents of the concrete, triggering one of the degradation phenomena that deserves the most attention, which is reinforcement corrosion [29]. The two main phenomena that initiate this pathology, by destroying the passive coating of the reinforcing bars, are carbonation and the penetration of chloride ion, and in this work these durability properties have been analysed, to study their influence on the quality of the lightweight concrete with manufactured BBA.

2. Materials

2.1. Description of materials

2.1.1. Cement

Ordinary Portland Cement (C) (Cementos Portland Valderrivas S.A, Alcalá de Guadaíra, Sevilla, Spain) type I with medium-high resistance 42.5 MPa at 28 days with high initial resistance R and sulphate resistant SR was used, CEM I 42.5-R SR (UNE-EN 197-1). This type of cement is recommended for making normal-high performance concrete, very suitable for the industrial manufacture of prefabricated structural elements that require maximum resistance. The composition is shown in Table 1.

Table 1
Chemical properties of cement (CEM I 42.5-R SR).

Content (%)								
SiO ₂	Al ₂ O ₃	FeO ₃	CaO	MgO	SO ₃	K ₂ O	Na ₂ O	Loss of ignition (LOI)
19.31	1.4	4.45	66.01	1.26	3.3	0.35	0.08	1.42

2.1.2. Natural aggregates

As fine aggregate a Natural Sand (NS) 0/4 mm size was used. As coarse aggregate a Natural Coarse Gravel (NCG) 8/16 mm size and a Natural Medium Gravel (NMG) 4/8 mm size were used. These aggregates come from a dolomitic quarry located in Padul, Granada. The main properties and standard used are listed in Table 2, and their granulometries are shown in Fig. 1.

2.1.3. Expanded clay

Expanded clay (EC) is a light aggregate of ceramic origin that is obtained from ground clay that expands when fired at 1200 °C in rotary kilns. This processing gives it a very porous internal structure, as well as high resistance, which is why it is usually used in the manufacture of lightweight concrete (LWC). EC properties are presented in Table 2, and its granulometry is shown in Fig. 1.

2.1.4. BBA

BBA is composed of coarse unburned particles produced in the primary combustion chamber at a temperature of 405 °C during the biomass energy production process [15,20]. The BBA comes from the biomass power plant called Biomasas de Puente Genil S.L. from the company Sacyr Industrial located in Puente Genil, Córdoba, Spain. The combustion boiler is a fixed bed combustion with a grilled supply system by spout, so the material is released at the beginning of the oscillating grill and part of the finest material is burned in suspension [16]. The biomass used as fuel supply for the generation of electricity is made up of 60% wood from almond and olive pruning, and 40% olive cake. According to Hinojosa et al. [16], BBA properties depend on the origin of the biomass as well as the technology of the combustion process. Although the biomass may present some variability, all the material comes from areas close to the combustion plant, so the variability is less. The properties of BBA from the same combustion plant are somewhat homogeneous.

Three types of processing were carried out on the BBA to be used in this study. BBA were processed in the laboratory to obtain different materials to manufacture LWC: i) BBA dried (BBA-D): BBA was dried at 60° Celsius in an oven for 24 h; ii) BBA heated (BBA-H): BBA was burned at 300° Celsius in an oven for 5 h; and iii) BBA crushed (BBA-CR): BBA was crushed in an abrasion equipment used for sands, composed of 4 rotating cylinders and an abrasive load of steel balls; to obtain a fine granulometry material 0.5 kg of mater-

Table 2
Physical properties of natural aggregates and BBA.

Properties	Test method	NS	NCG	NMG	EC	BBA-D	BBA-H	BBA-CR
Granulometry/Size (mm)	UNE-EN 933-1	0/4	8/16	4/8	3/8	0/10	0/10	–
Fines content (%)	UNE-EN 933-1	9.8	–	–	–	2.33	–	–
Sand equivalent (%)	UNE-EN 933-8	51	–	–	–	43	–	–
Apparent density of particles (ρ _a) (kg/dm ³)	UNE-EN 1097-6	2.83	2.76	2.76	0.63	2.34	2.38	–
Density of dry particles (ρ _{rd}) (kg/dm ³)	UNE-EN 1097-6	2.74	–	–	–	1.895	–	–
Density of saturated particles (ρ _{ssd}) (kg/dm ³)	UNE-EN 1097-6	2.77	–	–	0.96	2.085	2.14	–
Water absorption (%)	UNE-EN 1097-6	1.2	–	–	15	10.1	9.8	–
Friability ratio (%)	UNE 146404	24	–	–	–	19	–	–
Density of set (kg/dm ³)	UNE-EN 1097-3	–	–	–	0.36	–	–	–
Real density of filler (kg/dm ³)	UNE-EN 1097-7	–	–	–	–	–	–	2.543
Specific surface area (m ² /g)		–	–	–	–	–	–	0.816

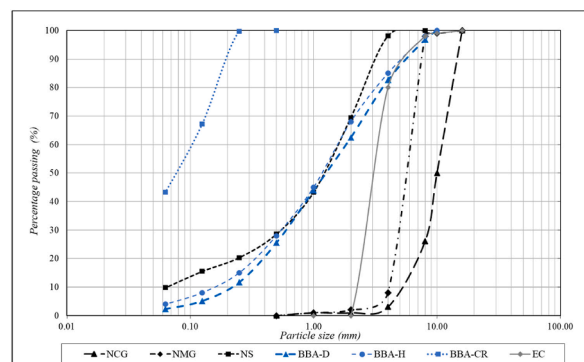


Fig. 1. Particle size distribution curve.

ial with 2.5 kg of abrasive load was subjected to 6000 revolutions. These materials were used in the manufacture of LWC: BBA-D and BBA-H as a replacement for NS and EC, and BBA-CR as a replacement for cement.

The physical properties of BBA-D, BBA-H and BBA-CR are listed in Table 2. As can be seen, the fines content of BBA-D (2.33%) is lower than NS (9.8%). However, the low bulk density value (2.34 kg/dm^3) as well as high water absorption capacity (10.1%) are due to the high porosity of BBA [15,30]. The friability coefficient determines the degree of fragmentation of the fine aggregate, being 19% for BBA and 24% for NS.

As shown in Fig. 1, BBAs present a continuous particle size distribution, allowing an adequate coupling of the LWC component particles. The laser granulometry test carried out by wet method was able to determine the specific surface area and the particle size distribution of BBA-CR (Fig. 2). The equipment used was Mastersizer 2000LF by Malvern Instruments.

The chemical composition according to EN 196-2, as well as the chemical properties of BBA according to EN 1744-1 are listed in Table 3. The chemical composition determined by XRF establishes that BBA is mainly composed of SiO_2 , CaO and K_2O , and in percentages less than 10% by Al_2O_3 , Fe_2O_3 , MgO and other components.

Due to the high potassium content of BBA, an alkali silica reaction (ASR) study was carried out. The combination of BBA with cement in the manufacture of concrete can lead to expansive actions caused by hydroxide ions with the alkalis (sodium and potassium). The alkali-silica reaction occurs when some forms of silica and hydroxide ions contained in the aggregates react with the alkalis present in the interstitial solution of the concrete. This reaction forms a gel which, when absorbing water, expands and deteriorates the concrete [31,32]. To determine the potential reactivity of alkali-silica and alkali-silicate BBAs, the UNE 146512:2018 standard was applied. Fig. 3 shows the results obtained.

In the case of BBA, the alkali-silica reaction is mainly due to the potassium content present [33]. The BBA values were located in the non-reactive aggregates, which demonstrates the non-reactivity of this type of material. Values similar to those obtained in previous studies [16] in which it was found that although BBA have a high potassium content, they are not considered reactive aggregates in the ASR evaluation.

The analysis of BBA leachates was carried out according to the European standard UNE-EN 12457-4. The leachate concentration of elements was determined with an L/S ratio of 10 l/kg in order to classify BBA as inert, non-hazardous or hazardous waste according to the European Council Decision 2003/33/EC [34]. Table 4 shows the values obtained for the analysed components, and they are compared with the established regulatory limits (in bold). As can be seen, Cu is the only element that exceeds the limit for inert waste. Therefore, BBA is classified as non-hazardous waste. Previous studies show that BBA can exceed the limits of some harmful trace elements such as Cu, As, Cr, Pb and V, mainly due to the use of phytosanitary products in agriculture [35].

According to X-ray diffraction (Fig. 4), preliminary analysis shows crystalline phases of calcite (CaCO_3) and quartz (SiO_2) as main elements; BBA is composed of portlandite (Ca(OH)_2), lausonite ($\text{CaAl}_2\text{Si}_2\text{O}_7(\text{OH})_2\text{H}_2\text{O}$), wadeite ($\text{K}_2\text{O}_9\text{Si}_4$) and kalsilite (AlKO_4Si).

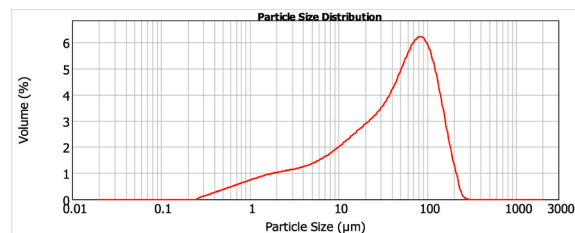


Fig. 2. Particle size distribution curve of BBA-CR by laser granulometry.

Table 3

Chemical composition and chemical properties of BBA.

Chemical composition (XFR)	Content (%)	Chemical properties	Content (%)
<i>Standard</i>	<i>EN 196-2</i>	<i>Standard</i>	<i>EN 1744-1</i>
SiO_2	26.51	Water-soluble sulphate ($\%\text{SO}_3$)	0.19
CaO	23.94	Acid-soluble sulphate ($\%\text{SO}_3$)	0.19
K_2O	14.68	Water-soluble chlorides	0.25
Al_2O_3	7.90	Organic matter content	3.31
Fe_2O_3	4.12		
MgO	3.27		
P_2O_5	2.67		
SO_3	1.15		
Na_2O	0.78		
TiO_2	0.53		
MnO	0.07		
LOI	13.50		

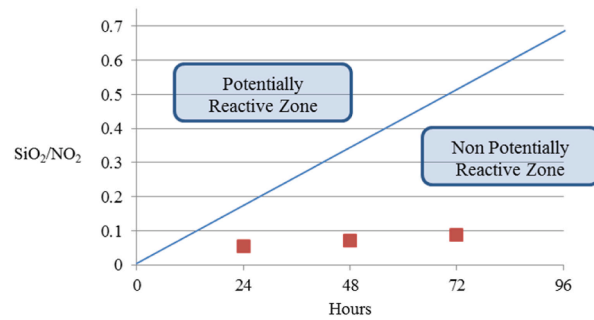


Fig. 3. Graphical representation of results of potential alkali-carbonate reactivity of BBA.

Table 4

Concentration of components on leachate at L/S = 10 l/kg and classification according to Decision 2003/33/EC [34].

Components (mg/kg dry substance) determined at L/S = 10 l/kg												
	Cr	Ni	Cu	Zn	As	Se	Mo	Cd	Sb	Ba	Hg	Pb
BBA	0.1388	0.2246	3.7702	0.3584	0	0	0.3219	0	0	0.3107	0.0007	0.0110
Classification	Leaching limit values											
Inert	0.5	0.4	2	4	0.5	0.1	0.5	0.04	0.06	20	0.01	0.5
Non-hazardous	10	0.1	50	50	2	0.5	10	1	0.7	100	0.2	10
Hazardous	70	40	100	200	25	7	30	5	5	300	2	50

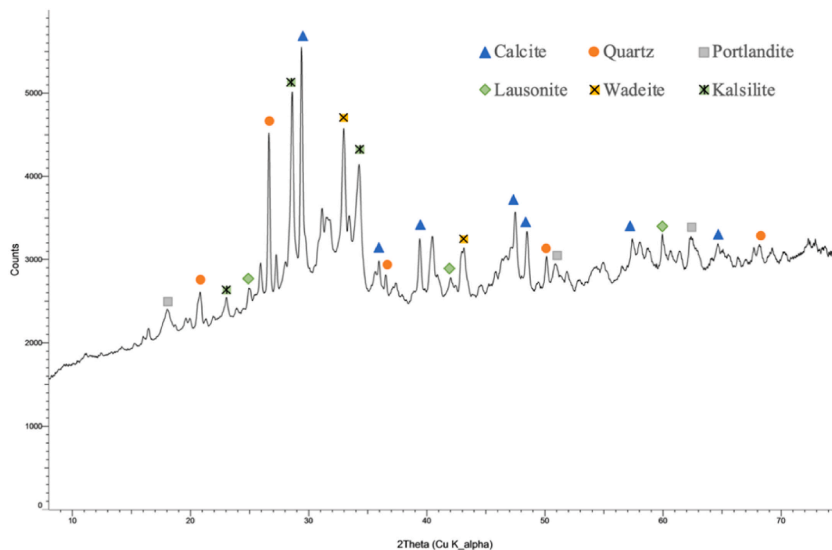


Fig. 4. X-ray diffraction of BBA.

Also, a certain curvature is shown, between 28 and 35 2Theta angle. This indicates that the sample is somewhat amorphous, resembling silica fume and hence its potential to provide hardness.

2.1.5. Water-reducing admixture (SP)

A high activity superplasticizer/water reducer admixture (SP) called Masterease 3530, supplied by Master Builder Solutions España, S.L., was used. Due to its characteristics, SP improves the rheology and workability of concrete, allowing the mixing water to be reduced while maintaining an adequate effective water/cement (w/c) ratio.

2.2. Dosages of mixes and material processes

Three types of series were elaborated with the incorporation of BBA, in which nine batches were manufactured by applying various incorporation rates of BBA with different treatment (Table 5).

In the first set, three batches were carried out replacing 25% of the NS or 35% of the EC, or 15% of the NS and 25% of the EC, with BBA dried to 60° (henceforth BBA-D), in each one.

Table 5
Incorporation rates of BBA.

Series name	Incorporation of material	Replacement of material (%)	Batches name
Series 1	BBA-D (BBA dried at 60 °C)	25% NS	BBA-D/25NS
		35% EC	BBA-D/35EC
		15%NS + 25%EC	BBA-D/15NS + 25EC
Series 2	BBA-H (BBA heated at 300 °C)	25% NS	BBA-H/25NS
		35% EC	BBA-H/35EC
		15%NS + 25%EC	BBA-H/15NS + 25EC
Series 3	BBA-CR (BBA crushed)	15% C	BBA-CR/15C
	BBA-CR + BBA-D + BBA-D	15% C + 15%NS + 25%EC	BBA-CR/15C-BBA-D/15NS + 25EC
	BBA-CR + BBA-H + BBA-H	15% C + 15%NS + 25%EC	BBA-CR/15C-BBA-H/15NS + 25EC

In the second set, there were three other groups: the first group was created by replacing 25% of the NS or 35% of the EC, or 15% of the NS and 25% of the EC, by BBA heated to 300° (henceforth BBA-H), in each one.

Finally, the third group was manufactured replacing 15% percentages of the C by BBA crushed (henceforth BBA-CR) in three of the batches. The other batches were performed replacing 15% of the NS and 25% of the EC by BBA-D or BBA-H.

The amount of cement used (300 kg/m³) was kept constant in all concretes manufactured. With the objective of maintaining a similar consistency, the amount of additive was modified for each batch.

The concrete mix proportions are listed in Table 6.

The methodology used for the manufacture the mixtures was the same for all concretes (Fig. 5). First, the EC was introduced into the mixer, followed by the BBA and 68% of the total mixing water and the absorption water of the BBA and EC, and it was mixed for 10 min. It must be explained that the absorption water of the EC was 15% (absorption coefficient) and the absorption water of the BBAs was 10.1% for BBA-D, 9.8% for BBA-H and 10% for BBA-CR, their absorption water coefficient. Then, the NCG, NMG and NS were introduced and mixed for 10 min. Next, the cement with 16% of the mixing water and 66% of the additive were added and mixed for 2 min, after which 16% of the mixing water and the rest of the additive (34%) were introduced and mixed for 2 more minutes. Finally, the specimens were manufactured and after 24 h the specimens were removed from their moulds. The specimens were then cured in the curing room at an ambient temperature of 20C and 100% relative humidity.

To determine the quantity of water to be added in the mixing water in concretes made with BBA, which have a higher capacity of water absorption than the natural aggregates (Table 2), the following procedure was conducted.

- 1 A container was filled up to the mark with BBA and weighed. Next, BBA was allowed to saturate in water for 10 min, the container was refilled and weighed. BBA was placed on a tray and placed in the oven until constant weight.

Table 6
Concrete mix proportions (kg/m³).

Serie	Cement (kg)	Natural aggregates			EC (kg)	BBA			Mixing water (kg)	W/C ratio	Absorption water (kg)	SP (kg)	Total (kg/m ³)
		NCG (kg)	NMG (kg)	NS (kg)		BBA-D (kg)	BBA-H (kg)	BBA-CR (kg)					
Control	300	340	80	901	159	-	-	-	165	0.55	23.9	3	1972
BBA-D/25NS	300	340	80	675	159	186	-	-	165	0.55	42.7	3.2	1952
BBA-D/35EC	300	340	80	901	104	207	-	-	165	0.55	36.6	3.3	2136
BBA-D/15NS + 25EC	300	340	80	765	120	260	-	-	165	0.55	44.1	3.4	2078
BBA-H/25NS	300	340	80	675	159	-	189	-	165	0.55	42.5	3.2	1955
BBA-H/35EC	300	340	80	901	104	-	211	-	165	0.55	36.2	3.3	2140
BBA-H/15NS + 25EC	300	340	80	765	120	-	264	-	165	0.55	43.8	3.4	2081
BBA-CR/15C	255	340	80	901	159	-	-	37	165	0.55	27.6	3	1968
BBA-CR/15C-BBA-D/15NS + 25EC	255	340	80	765	120	260	-	37	165	0.55	47.8	3.4	2073
BBA-CR/15C-BBA-H/15NS + 25EC	255	340	80	765	120	-	264	37	165	0.55	47.5	3.4	2077

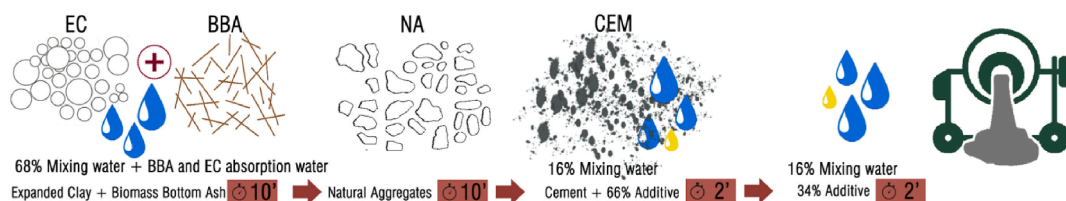


Fig. 5. Concrete manufacturing process.

- 2 Subsequently, the same mass of BBA was taken and saturated for 10 min. The container was refilled and weighed. The material was dried until the surface was dry and saturated. It was weighed, placed on a tray and placed in the oven until it reached a constant mass.
- 3 The relationship between the saturated mass, the mass with dry and saturated surface, and the dry mass of BBA was established. The water absorption in each series is listed in Table 7.

3. Experimental methods and results

In this section, the experimental tests results of hardened concrete are presented as follows.

3.1. Density and absorption of hardened concrete

The density and absorption percentage were determined in $150 \times 150 \times 150$ mm cubic specimens of hardened LWC. Each series was subjected to an immersion in water, dried in an oven and weighted. With this procedure, the apparent mass in the water, the saturated mass with a dry surface and the dry mass were obtained. With these data, the values were obtained in accordance with the UNE-EN 12390-7 standard. The test results are shown in Table 8.

The results show how the incorporation of BBA decreases the density and increases the absorption in all the mixtures (Table 8). The density directly depends on the density of the materials used to manufacture the concrete. In both series, the maximum BBA substitution corresponds to the lowest density and highest absorption values, this is since BBAs have a very porous structure in agreement with other authors [15,25].

All the mixtures manufactured showed densities below the 2000 kg/m^3 established in the Spanish Structural Code [26] to be considered lightweight concrete. It was observed that the replacement of NS and EC by BBA led to a decrease in density of up to 11%.

3.2. Compressive and flexural strength of test specimens

The compressive strength was determined on $100 \times 100 \times 100$ mm cubic samples for ages 7, 28, 90 days according to UNE-EN 12390-3. Flexural strength was measured at 28 days in prismatic specimens of $100 \times 100 \times 400$ mm according to UNE-EN 12390-5 standard. Table 9 shows the values of the strength and standard deviation (SD) obtained for each of the series.

Aggregate substitution by BBA led to a decrease in compressive strength, higher percentages of substitution increased the loss of strength. This pattern was shown in several previous studies [18,20,30,36]. However, the treatment given to the BBA significantly influenced the compressive strength values. The use of heated BBA in the manufacture of concrete instead of dried BBA led to an increase in 28-day compressive strength of up to 26%. The heating process reduced the organic content of BBA, allowing an improvement in compressive strength values [37].

Table 7
Absorption water of EC and BBA's by series (kg/m^3).

Series	Absorption water (kg/m^3)				Total
	EC	BBA-D	BBA-H	BBA-CR	
Control	23.9	–	–	–	23.9
BBA-D/25NS	23.9	18.8	–	–	42.7
BBA-D/35EC	15.6	21	–	–	36.6
BBA-D/15NS + 25EC	17.9	26.2	–	–	44.1
BBA-H/25NS	23.9	–	18.6	–	42.5
BBA-H/35EC	15.5	–	20.7	–	36.2
BBA-H/15NS + 25EC	17.9	–	25.9	–	43.8
BBA-CR/15C	23.9	–	–	3.7	27.6
BBA-CR/15C-BBA-D/15NS + 25EC	17.9	26.2	–	3.7	47.8
BBA-CR/15C-BBA-H/15NS + 25EC	17.9	–	25.9	3.7	47.5

Table 8
Absorption and density of concretes.

Series	Absorption (%)	Apparent density (kg/m^3)	Water accessible porosity (%)
Control	5.9	1860	11.0
BBA-D/25NS	9.2	1638	15.1
BBA-D/35EC	5.7	1807	10.4
BBA-D/15NS + 25EC	6.7	1658	11.1
BBA-H/25NS	7.4	1744	13.0
BBA-H/35EC	8.3	1826	15.1
BBA-H/15NS + 25EC	6.8	1877	12.8
BBA-CR/15C	8.3	1743	14.5
BBA-CR/15C-BBA-D/15NS + 25EC	7.7	1665	12.9
BBA-CR/15C-BBA-H/15NS + 25EC	7.9	1810	14.2

Table 9
Compressive and flexural strength.

Series	Flexural strength (MPa)		Compressive strength (MPa)					
	28 days	SD	7 days	SD	28 days	SD	90 days	SD
Control	8.1	± 0.8	25.9	± 1.7	27.3	± 2.2	30.0	± 0.3
BBA-D/25NS	5.9	± 1.1	18.4	± 1.8	19.6	± 1.9	21.1	± 2.0
BBA-D/35EC	7.5	± 0.3	17.2	± 2.2	20.1	± 2.1	20.0	± 1.9
BBA-D/15NS + 25EC	5.2	± 1.7	11.7	± 0.5	13.3	± 1.8	16.1	± 1.5
BBA-H/25NS	8.0	± 0.02	22.5	± 1.7	24.8	± 1.8	28.4	± 1.3
BBA-H/35EC	8.4	± 0.4	21.5	± 0.6	22.6	± 0.7	26.4	± 1.7
BBA-H/15NS + 25EC	8.2	± 0.4	24.8	± 0.6	26.9	± 0.9	29.3	± 0.8
BBA-CR/15C	7.2	± 0.04	17.7	± 0.5	19.6	± 1.5	20.0	± 1.0
BBA-CR/15C-BBA-D/15NS + 25EC	6.8	± 0.2	13.6	± 0.4	14.6	± 2.5	15.2	± 0.4
BBA-CR/15C-BBA-H/15NS + 25EC	7.0	± 0.4	19.1	± 0.6	21.1	± 1.6	23.0	± 0.02

As can be seen in Fig. 6, the mixes made with BBA-H as a substitute for natural aggregate and EC led to a reduction in compressive strength with respect to the control value by less than 1.5%. The rest of the mixes reduced the compressive strength between 9% and 51%.

All the concrete mixtures tested exceeded the minimum compressive strength value of 12 N/mm² established for mass lightweight concrete, established in the Spanish Structural Code [26]. The concrete mixtures made with BBA-D as a replacement for EC, and all the mixes made with BBA-H exceeded the value of 20 N/mm², which value is established for mass concrete that could be used in an X0 class exposure environment. The concrete mixtures made with BBA-H as a replacement for NS and EC exceeded the established limitation of 25 N/mm², and it can be used in reinforced or prestressed lightweight concrete, and in exposure environments of classes X0, XC1 and XC2.

3.3. Shrinkage

To determine the dimensional stability of the concrete, specimens of dimensions 100 × 100 × 285 mm were manufactured, the samples were cured in two different conditions; in a room at 20 ± 1 °C and 50 ± 5% humidity, and under water at 20 ± 1 °C. Shrinkage measurements were carried out at 1, 3, 7, 14, 28, 56 and 90 days according to the ASTM C157/C157 M – 17 standard. The results obtained for dimensional changes produced in each of the mixtures in the two curing conditions studied are shown in Fig. 7.

The mixes cured under ambient conditions (20 °C and 50% humidity) suffered greater shrinkage than those cured under submerged conditions. Under ambient conditions, lightweight concrete suffers higher shrinkage mainly due to the initial water absorbed by the BBA, as it is a very porous material. The continuous loss of this absorbed water may be the main reason for the high shrinkage of lightweight concrete with BBA [38].

Under submerged curing conditions most of the mixes performed resulted in expansion values. Medina et al. [19] also observed the increase in volume of mortars due to the sorptivity of C–S–H gels that tend to swell in contact with water [39,40]. When the concrete was cured in submerged conditions, it underwent greater variability and dimensional changes at early ages until it stabilised after approximately day 90.

No similar trend was observed in the two curing conditions. Under ambient curing conditions, the mixtures that showed the greatest shrinkage were BBA-D/35EC, BBA-D/15NS + 25EC and BBA-CR/15C-BBA-H/15NS + 25EC. However, under submerged curing conditions, the samples that showed the greatest expansion were BBA-H/25NS and BBA-CR/15C-BBA-D/15NS + 25EC.

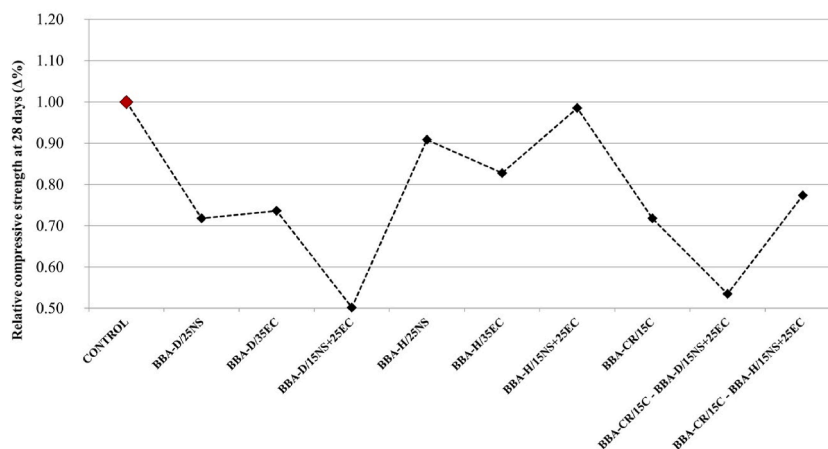


Fig. 6. Comparison of compressive strength in terms of relative resistance at 28 days.

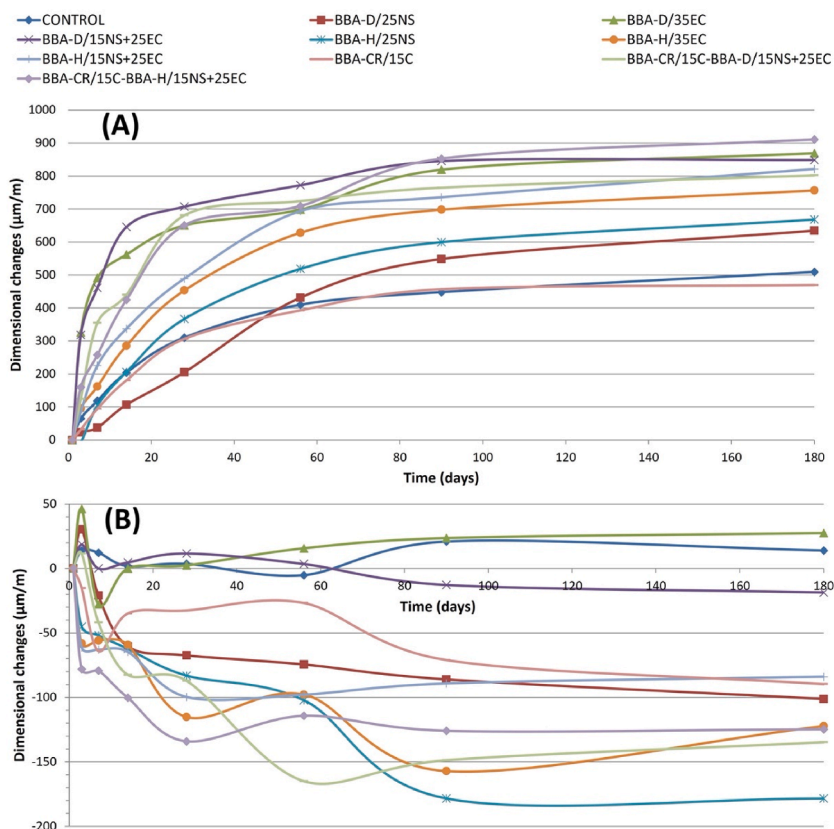


Fig. 7. Dimensional changes.

As shown in Fig. 7, the treatment given to the BBA and the higher degree of substitution did not influence the dimensional changes undergone by the lightweight concrete.

3.4. Thermal conductivity

A study of the thermal conductivity of the material was carried out using a heat flow measurement instrument (FOX 600 TA Instruments).

The thermal conductivity of the material depends on its internal structure, mineralogical composition, pore connectivity, particle size, water content, etc. [41–43].

For the analysis of thermal conductivity, concrete panels of dimensions $40 \times 40 \times 3.5$ cm were constructed. These panels were introduced into a heat flow meter; the panel was placed between two temperature-controlled plates. Two steps were established with a temperature difference of 10°C , first temperature step 15°C - 25°C and second step 25°C - 35°C .

A study of the thermal conductivity of lightweight concrete made with a high percentage of BBA as a substitute for NS and EC was carried out. Additionally, according to the results obtained for absorption and density, it was decided to evaluate the mixes in which the BBA had been subjected to heating and crushing treatments, since the mixes manufactured with BBA with these treatments resulted in an increase in absorption and a decrease in density, parameters that can provide greater thermal insulation [44]. For this reason, the BBA-H/15NS + 25EC and BBA-CR/15C-BBA-H/15NS + 25EC mixes were tested; mixes with the highest percentage of substitution (40% aggregate substitution and 15% cement substitution). Additionally, the control mix was studied to evaluate the influence of the use of BBA on the thermal properties of the concrete. The results obtained are shown in Table 10.

As can be observed in Table 10, the lightweight concrete manufactured with BBA presented a lower thermal conductivity value than the control as more BBA was added.

Table 10
Thermal conductivity at different temperature steps.

Series	W/m*K (15°C-25 °C)	W/m*K (25°C-35 °C)
Control	0.6567	0.6576
BBA-H/15NS + 25EC	0.5510	0.5524
BBA-CR/15C-BBA-H/15NS + 25EC	0.4751	0.4607

The mixes manufactured with 40% BBA as an aggregate substitute led to a 20% reduction in thermal conductivity, this reduction increased to 43% when 40% aggregate and 15% cement were replaced by BBA. Previous studies showed a 30% reduction in thermal conductivity in bricks when 90% BBA was applied compared to mixes with 10% BBA [18]. The high porosity and low density of BBA is directly related to a decrease in thermal conductivity [45–47].

3.5. Determination of ultrasonic pulse velocity

Ultrasonic pulse velocity (UPV) was determined by direct transmission according to UNE-EN 12504-4. This test is used to evaluate the quality of concrete due to its direct relationship with the density and porosity of the material through which the ultrasonic wave passes.

UPV was obtained for 7 days, 28 days and 90 days in Control, BBA-H/15NS + 25EC and BBA-CR/15C + BBA-H/15NS + 25EC (Fig. 8). As can be seen, UPV values reached by the Control series at the three ages were higher than in the series with the incorporation of BBA. UPV decreased between 9.6% and 35.9% for the BBA-H/15NS + 25EC series, and between 15.5% and 19.9% for the BBA-CR/15C + BBA-H/15NS + 25EC, compared to Control. This decrease in UPV was due to a decrease in the propagation capacity of the waves as a consequence of the lower density and greater porosity of these series. Others authors showed a reduction in UPV when BBA was used [25].

In general, UPV increased with curing time for all the series, reaching the maximum value at 90 days of age. The increase was up to 22.4% for Control, 2.8% for BBA-H/15NS + 25EC and 18.3% for BBA-CR/15C + BBA-H/15NS + 25EC. This increase is due to the growth of the cement hydration products and consequently to the decrease in the capillary pores of the cement paste [48].

3.6. Durability

3.6.1. Carbonation resistance

The carbonation of the concrete can lead to the loss of alkaline reserve, causing corrosion of the reinforcing bars, as well as a decrease in the permeability of the material and an increase in the compressive strength [40]. The carbonation resistance essentially depends on the diffusion capacity of concrete [49]. Since BBA have a higher porosity, it is expected that concrete with incorporation of BBA show lower resistance to the penetration of CO₂. This natural carbonation process develops slowly, so in order to assess its progress, the accelerated carbonation test was carried out in accordance with the procedure described in the UNE-EN 12390-12 standard.

The test was carried out on two 50 × 50 × 280 mm specimens from each series, according to the following sequence: curing the specimens in water to a minimum age of 28 days, preconditioning at room temperature for 14 days and an exposure time 7, 14, 21, 28, 49 and 70 days in a curing chamber with a carbon dioxide concentration of 1%, with a temperature of (20 ± 2) °C and a relative humidity of (57 ± 3) %. After the exposure time, the specimens were divided into two parts and the fracture surface was sprayed with a phenolphthalein solution. The carbonation depth corresponds to the average length of the uncoloured zone of the surfaces.

Carbonation depth values are shown in Table 11. The incorporation of BBA in the concrete increased the average depth of carbonation with respect to the Control concrete, being greater when cement was replaced by BBA-CR. According to the literature, Rosales et

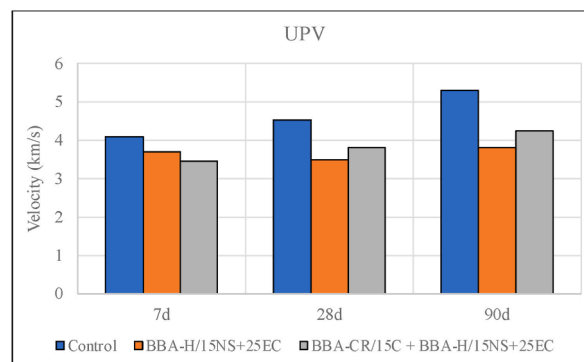


Fig. 8. UPV evolution for 7 days, 28 days and 90 days.

Table 11

Mean depth of carbonation over time *t* in mm.

Series	Mean depth (mm) of carbonation by time					
	7 days	14 days	21 days	28 days	49 days	70 days
Control	0.0	0.0	0.1	0.2	1.2	1.4
BBA-H/15NS + 25EC	1.1	1.5	3.5	4.0	4.2	6.8
BBA-CR/15C-BBA-H/15NS + 25EC	1.7	2.7	6.6	7.4	9.7	11.1

al. [25], these results could be due to the greater porosity of concrete with BBA, since BBAs have a very porous structure that facilitates the passage of CO_2 .

Regarding the advance of carbonation with exposure time, the increase in carbonation depth was observed in each of the series. Specifically, from 7 to 28 days, the carbonation depth increased 380% in the Control series, 264% in the BBA-H/15NS + 25EC series, and 345% for BBA-CR/15C + BBA-H/15NS + 25EC. However, between 28 and 70 days the same trend in the increase in carbonation depth was not maintained, being lower in the concretes with BBA incorporation (70% and 50%), while for the Control concrete the increase was up to 6 times.

Fig. 9 represents K_{AC} carbonation rate, in $\text{mm}/\sqrt{\text{days}}$, determined as a function of the mean carbonation depth in mm for each age and the square root of the exposure time in days.

The carbonation rate, K_{AC} , is the slope of the regression line determined by the results, and as can be seen, it increases with the incorporation of BBA in the concrete, being higher when cement is also replaced by BBA-CR. A good correlation can be observed.

3.6.2. Resistance to chloride ion penetration

To analyse the susceptibility to corrosion of the reinforcement in the concrete, a test on the penetration of the chloride ion was carried out. Specifically, the test detailed in Standard ASTM C1202-19 (RCP test) was carried out on a sample of each designed dosage.

This test method, outlined and illustrated in Fig. 10, consists of evaluating the electrical conductivity of concrete samples to provide a quick indication of their resistance to chloride ion penetration. To do this, the electrical current that passes through cylindrical

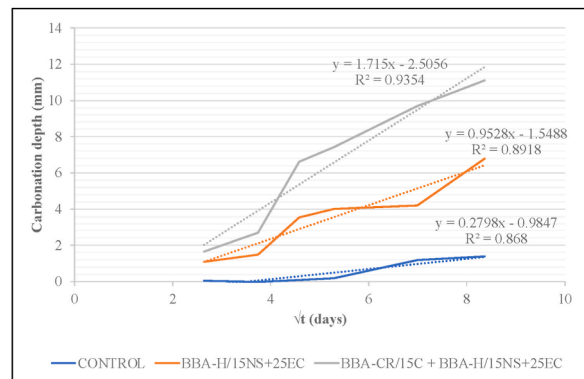


Fig. 9. Carbonation rate (K_{AC}): relationship between carbonation depth and exposure time ($\text{mm}/\sqrt{\text{days}}$).

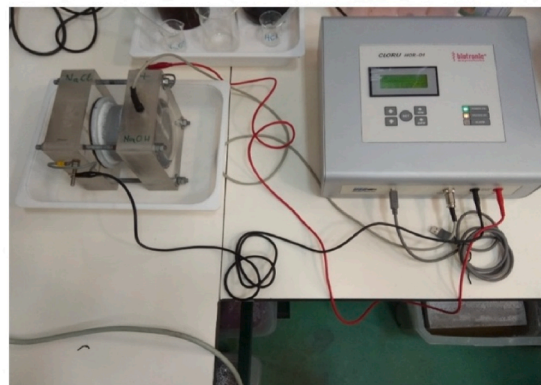
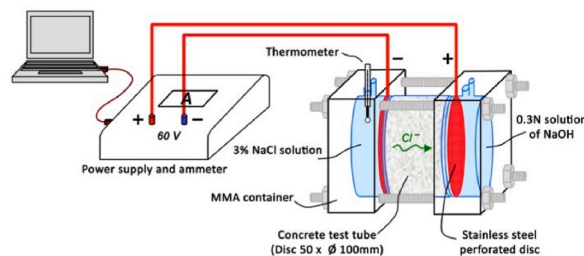


Fig. 10. Concrete's ability to resist chloride ion penetration test.

sections such as the one shown in Figs. 10 and 50 mm thick and 100 mm nominal diameter, must be monitored every 30 min at least for a period of time of 6 h and prior treatment of the masses according to what is indicated in the Norm. A potential difference of 60 V is maintained at the ends of the sample in two reservoirs, one of which is filled with a sodium chloride solution and the other with a sodium hydroxide solution. The total charge across the section, in Coulombs, is related to the resistance of the sample to chloride ion penetration. The lowest passage of current indicates high resistance to chloride penetration. This relation, extracted from the Standard used, is the one that is tabulated below (Table 12).

When comparing the load that passes through the sample during the test with the previous values, it is necessary to carry out a correction of this in accordance with the provisions of the aforementioned Standard:

$$Q_s = Q_x (95/x)^{A^2}$$

Where.

x is the diameter of the sample: 100 mm.

Q_x is the load that passes through the sample of diameter x, then $Q_x = Q_{100\text{mm}}$.

Q_s is the load that passes through a 95 mm sample, or what is the same: $Q_s = Q_{95\text{mm}}$

The passage of chloride ions from one reservoir to another reservoir was calculated through the RCP test. The RCP test values were determined by the concrete specimens of the studies samples and at two different ages, (56 days and 90 days).

The results are shown in Table 13. It is observed how the incorporation of BBA modifies the behaviour of the concrete, slightly increasing the permeability of the concrete to the chloride ion at 56 days. This modification is more favourable if the cement is replaced by BBA. At 90 days, the patency values are reduced when the cement is replaced by BBA-CR, while the replacement of NS and EC by BBA-H does not seem to influence the results of this test over time.

This trend was observed by Lessard et al. [50] whose results indicate a low penetration potential for chloride ions for concrete mixtures incorporating BBA. In any case, analysing the total amount of transmitted load, the level obtained is admissible based on what is included in the indicative specifications of the ASTM C1202 -19 standard (Table 12).

3.6.3. Penetration of water under pressure

Water penetration under pressure indicates the ease with which a fluid moves through the porous structure of a material under constant pressure applied to the liquid. The penetration of water under pressure test was carried out following UNE-EN 12390-8 standard testing the depth of penetration of water under pressure in a cylindrical specimen of 150 mm in diameter and 300 mm in height, cured in water for 28 days.

Table 14 shows the results of maximum and average penetration observed in the mixes. The results indicate that these mixes meet the impermeability requirement for most of the aggressive environments, according to the maximum limits defined by Spanish Structural Code [26] (Table 15). The incorporation of BBA reduced the value of the maximum depth of penetration up to 17%, although no significant differences were found for the value of the average depth. Furthermore, the substitution of 15% of cement by BBA-CR seems not to considerably affect the permeability of this concrete. This is inconsistent with other authors who concluded that the penetration of water under pressure increases with the incorporation of BBA [22,25].

Table 12
Concrete's ability to resist chloride ion penetration.

Charge Passing (Coulomb)	Chloride Ion Permeability
> 4000	High
2000–4000	Moderate
1000–2000	Low
100–1000	Very low
< 100	Negligible

Table 13
Values of rapid chloride permeability test and classification.

Series	$Q_{95\text{mm}}$ (C)56 days	$Q_{95\text{mm}}$ (C)90 days	Chloride ion penetrability/permeability
Control	1685.80	1942.69	Low
BBA-H/15NS + 25EC	2166.16	2166.00	Moderate
BBA-CR/15C-BBA-H/15NS + 25EC	1713.58	1538.40	Low

Table 14
Water penetration depth value.

Series	Maximum depth (mm)	Average depth (mm)
Control	45.0	30.2
BBA-H/15NS + 25EC	37.5	30.8
BBA-CR/15C-BBA-H/15NS + 25EC	39.0	30.4

Table 15

Maximum and average water penetration depth requirements.

Environmental exposure class	Maximum depth (mm)	Average depth (mm)
XS1, XS2, XD1, XD2, XD3, XF1, XF2, XF3, XF4, XM, XA1 (any case) XA2 (reinforcement or not elements)	≤ 50	≤ 30
XS3 and XA3 (any case) XA2 (only in case of pre-strengthened elements)	≤ 30	≤ 20

The environmental exposure classes are associated with minimum compressive strength values. As indicated in section 3.2., the concretes tested could be used in environmental exposure classes X0 (without risk of attack by corrosion), XC1 (reduced humid environment - RH < 65%) and XC2 (environment in contact with water or elements buried in non-aggressive soils). These classes do not correspond to the most aggressive exposure environments, as established by the Spanish Structural Code [26].

4. Conclusions

This research evaluates the use of BBA as a replacement material, replacing sand, expanded clay as a lightweight material and/or cement in the manufacture of lightweight concrete for construction elements. The design of dosages with different levels of substitution, incorporating BBA processed in an appropriate way, has allowed the following conclusions to be obtained.

- The density of BBA is greater than that of expanded clay, but with adequate doses, lightweight concrete can be achieved.
- The apparent density of the concrete with the incorporation of BBA were less than 2000 kg/m³, which allowed it to be classified as lightweight concrete in accordance with the Spanish Structural Code.
- The compressive strength values of the concrete made with BBA decreased with respect to the control concrete. However, the use of BBA pre-heated to 300 °C as a replacement for sand and expanded clay managed to achieve a compressive strength value at 28 days, similar to that of the control concrete. These BBA concrete mixes can be used as reinforced or prestressed structural lightweight concrete. Also, all concrete mixes that were produced with BBA-H, can be used as mass concrete. And finally, all the mixes tested could be used as lightweight mass concrete.
- The process applied to the BBA to achieve better properties in this waste, and the higher degree of substitution applied, did not affect the dimensional changes produced in the lightweight concrete.
- The thermal conductivity decreased up to 43% with respect to the control concrete, which allows these types of concrete to be used as insulators materials for construction.
- The ultrasonic propagation speed decreased in lightweight concrete with BBA, being the lowest value in lightweight concrete with replacement of sand and expanded clay due to the higher porosity and lower density of this series.
- Regarding durability, the average depth of carbonation increased in all the concrete, with higher carbonation penetration in the concrete with higher replacement of conventional materials by BBA.
- The permeability of lightweight concrete to the passage of chlorides increased with the incorporation of BBA, and it was similar to that of the control concrete when the cement was also replaced by crushed BBA, thus being able to classify it as low permeability, or moderate in most unfavourable case.
- The maximum depth of water penetration of the evaluated concrete mixtures was reduced up to 17% with the incorporation of BBA.

Finally, it can be highlighted that it is possible to manufacture lightweight concrete with BBA, replacing the expanded clay that is usually applied in this type of concrete, as well as part of the natural sand and cement. The ideal mixtures in which optimised amounts of BBA are applied, can give appropriate results, both in mechanical behaviour, and achieving a more insulating type of concrete in terms of thermal conductivity.

CRedit authorship contribution statement

Gloria M. Cuenca-Moyano: Experimental work, and Writing, **Manuel Cabrera:** Experimental work, and Writing, **Mónica López-Alonso:** Methodology, Experimental work, and Supervision, **M.J. Martínez-Echevarría:** Methodology, Experimental work, and Supervision, **Francisco Agrela:** Conceptualization, Financial support, and Review, **Julia Rosales:** Experimental work, and Writing.

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.

Data availability

No data was used for the research described in the article.

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Appendix

Standards used in the experimental work.

ASTM C1202 - 19. Standard test method for electrical indication of concrete's ability to resist chloride ion penetration.

ASTM C157/C157 M – 17. Standard test method for length change of hardened hydraulic-cement mortar and concrete.

UNE 146404:2018. Aggregates for concrete. Determination of the coefficient of friability of the sands.

UNE-EN 1097-3:1999. Tests for mechanical and physical properties of aggregates. Part. 3: Determination of loose bulk density and voids.

UNE-EN 1097-6:2014. Tests for mechanical and physical properties of aggregates. Part. 6: Determination of particle density and water absorption.

UNE-EN 1097-7:2009. Tests for mechanical and physical properties of aggregates. Part. 3: Determination of the particle density of filler. Pycnometer method.

UNE-EN 12390-12:2020. Testing hardened concrete. Part 12: Determination of the carbonation resistance of concrete. Accelerated carbonation method.

UNE-EN 12390-3: 2020. Testing hardened concrete. Part 3: Compressive strength of test specimens.

UNE-EN 12390-5:2020. Testing hardened concrete. Part 5: Flexural strength of test specimens.

UNE-EN 12390-7:2020. Testing hardened concrete. Part 7: Density of hardened concrete.

UNE-EN 12390-8:2020. Testing hardened concrete. Part 8: Depth of penetration of water under pressure.

UNE-EN 12457-4:2003. Characterization of waste. Leaching. Compliance test for leaching of granular waste materials and sludges. Part 4: One stage batch test at a liquid to solid ratio of 10 l/kg for materials with particle size below 10 mm (without or with size reduction).

UNE-EN 12504-4:2006. Testing concrete. Part 4: Determination of ultrasonic pulse velocity.

UNE-EN 1744-1-10:2010. Tests for chemical properties of aggregates. Part. 1: Chemical analysis.

UNE-EN 196-2: 2014. Methods of testing cement. Part 2: Chemical analysis of cement.

UNE-EN 933-1:2012. Tests for geometrical properties of aggregates. Part 1: Determination of particle size distribution. Sieving method.

UNE-EN 933-8:2012. Tests for geometrical properties of aggregates. Part 8: Assessment of fines. Sand equivalent test.

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