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ORIGINAL ARTICLE

Concrete made with treated bottom ash: mechanical and environmental study

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Abstract

This investigation evaluated the use of bottom ash in concrete. Two types of bottom ash powder were used: (1) Ground bottom ash (GBA) and (2) bottom ash Residue from grinding (BAR). In concrete, cement was replaced with GBA at 0, 10, 20, 30 and 40% levels and BAR was used as a sand replacement at the same levels. To assess concrete made with BAR and GBA, fresh proprieties, compressive strength, freeze–thaw test, Compliance test for leaching of bottom ashes and diffusion test were performed. The results revealed that compressive strength decreased when BAR–GBA content increased at an early age, but after 90 days, compressive strength of BAR–GBA concrete was similar to control concrete while compressive strength decreases at each cycle of freeze–thaw test. Moreover, leaching test revealed that the leached concentrations of heavy metals recorded were lower than those estimated by the standard.

Keywords Bottom ash · Concrete · Compressive strength · Freeze–thaw test · Leaching test

Introduction

Concrete is one of building materials used in the whole world. It is a composite material composed principally from water, hydraulic binder, fine aggregates and coarse aggregates. The portion of each constituent of the concrete determines its characteristics. Reducing the cost of concrete is becoming a challenge in the building sector. For this reason, several researchers are investigated to use some natural pozzolan materials like metakaolin [1, 2] or artificial pozzolan materials which are generally solid waste like fly ash [3, 4] as cementitious material in concrete to reduce cement demand. Recycling the solid waste in concrete contributes in reducing concrete costs and reducing CO_2 emissions. On the other hand, it allows to solve management problems of solid waste related to its storage and its environmental impact. Some of the most recycled solid waste in concrete is coal ashes generated from coal combustion.

In Morocco, electricity generation is based on coal combustion. There are three main thermal power plants: Jerada thermal power plant, Mohammedia thermal power plant and Taqa Morooco thermal power plant. The first one generates 312,000 tonnes of coal fly ash annually. These are evacuated simultaneously with the hearth ashes by hydraulic means to an ash basin located 2 km from the power plant. The second one generates about 80,000 tonnes of coal fly ash annually. For the 3rd thermal power plant generates more than 640,000 tonnes per year of solid waste where coal fly ash (CFA) represents 500,000 tonnes per year and the production rate of coal bottom ash (CBA) exceeds 50,000 tonnes per years [5]. In Morocco, CFA is used in cement manufacturing, however, CBA is stored in landfills without any reuse and the quantity tends to increase every year. As result, many problems are generated such as the cost for CBA disposal, loss of natural sites for CBA disposal and environmental impact surrounding CBA disposal.

Several studies confirmed the efficiency of CFA incorporation in concrete manufacturing as replacement of cement [6, 7]. Kabay et al. [8] studied the properties of concrete made with CFA as cement replacement. The authors concluded that the use of CFA had no impact on slump value and the results of compressive strength were comparable to control concrete. Huang et al. [9] examined the mechanical properties of concrete containing very high-volume of CFA.

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From the result of workability and compressive strength, they found that 80% of FA as cement replacement could be used in concrete with adequate Superplasticizer.

Saha [10] studied the effect of CFA on the durability properties of concrete. The researcher was found that the incorporation of CFA as a partial replacement of cement improves compressive strength at the long term. In the same context, Kurad et al. [11] determined the incorporation ratio of FA in concrete made with recycled concrete aggregates. They found that the maximum level of FA could be as cement replacement was 35%.

Contrary to a CBA, its large particles limited their uses as cementitious materials. However, its chemical composition encouraged researchers to use it as fine or coarse aggregate replacement in concrete. Singh and Siddique [12] evaluated the properties of concrete containing high volumes of CBA as fine aggregate. They found that CBA can be used as full sand replacement in concrete and observed that compressive strength at the early decrease slightly, but after 90 days of curing age, recorded values of compressive strength became superior that of control concrete. Hashemi et al. [13] assessed the mechanical proprieties of mortar made with CBA as partial or full replacement of sand. They reported that 40% of CBA sand replacement did not affect the compressive strength and up 40% decrease compressive strength of mortar due to the increase of water demand.

Using CBA as a fine aggregate in building materials was a way to manage these by-products and contributed to reserving natural resources, but it is still not enough to achieve the main objective in the building sector that consisting to reduce the cost of building materials. Reducing this latter implies the reduction of the volume of cement used in building materials. From this context, a challenge is made up by recently researchers to finding a solution based on the use of CBA as cementitious material such as fly ashes or other pozzolanic materials. Thus decreasing the particle size of CBA has been seen as the adequate solution that may offer the best results [14]. Moreover, Oruji et al. [15] focused on the use of BA with a high fineness as a partial replacement of cement in mortar. They found that pulverization of CBA improves their pozzolanic proprieties. They observed that the compressive strength of mortar with ultrafine CBA at 90 days were higher than control mortar and higher than mortar containing FA. Furthermore, Kim [16] investigated the effects of use ground BA as a binder on workability mortar. The authors concluded that the incorporation of ground CBA improves workability and hydration mortar. They found that effect of BA mortar on compressive strength mortar was similar to fly ash mortar. This finding was confirmed by another study carried out by Abdulmatin et al. [17] who reported that ground BA can be used as pozzolan material in the same way as fly ash with a condition that CBA needed to have particles retained on a No. 325 (45-mm) sieve at least 25% by weight to achieve the requirements for pozzolan class C and F as specified by ASTM C618. They found that mortar containing 25% of ground BA recorded the best values of compressive strength than control mortar.

However, CBA may contain heavy metals, which can be leached to the environment. Thus, the leaching test of building materials based on these by-products is mandatory. Assessment of leaching performance of construction material made with CBA has been conducted by only a few researches. Jang et al. [18] investigated the heavy metal leaching characteristics of porous concrete made with CBA as coarse aggregate and geopolymer (Fly ash and ground granulated blast furnace slag) as a binder. They reported that the concentrations of the heavy metals, which leached, were all below the drinking water regulatory level criteria (MCL/MAC) described in the International Standard [19] in all developed porous concrete samples. In addition, Sutcu et al. [20] investigated the properties of brick containing CFA and CBA. They reported that the concentration of heavy metals from developed bricks was lower than that of the limit concentrations. From the literature, it seems that leaching behavior depends on different parameters like the matrix nature, incorporation level of by-products in the mixture and the nature of by-products.

Although, the majority of recent investigations recommended to reduce the particle size of CBA to be used as a pozzolanic material [21, 22]. Argiz assessed the effect of using ground bottom ashes in concrete exposed to chloride environments. They concluded that chloride migration coefficient and diffusion coefficients of concrete made with 25% of ground bottom ash are lower than concrete made with coal fly ash for the same ash content of 25% [23]. Another study investigated the effect of using coal bottom ash with high fineness as a pozzolanic binder. They revealed that coal bottom ash with high fineness provides good results for high-strength concrete [24]. Furthermore, Mangi et al. concluded that 10% of ground CBA as cement replacement in concrete increases the resistance against aggressive environment [25]. Based on the previous studies [24, 25] focused on the use of CBA as pozzolanic binder. It seems that CBA with high fineness is a suitable material to be used as substitute cement in building materials [26]. From the literature [21–26], it was reported that pozzolanic proprieties of CBA were improved by the grinded process. However, the grinding process of CBA is an additional operation that could decrease the added value of recycling CBA. Therefore, finding a balance between the economic benefits of using these by-products and the grinding process is necessary. For this reason, our study proposes to generate two materials with different particle size from the original CBA by grinding and sieving process. The first one were used as a replacement for cement which was called ground bottom ash (GBA) and the second one was used as sand replacement which was

Table 1 Particle size distribution of GBA and BAR

Particle size (μm)	GBA (Wt%)	BAR (Wt%)
< 32	62.7	–
32–45	17.8	–
45–63	13.7	–
63–90	3.9	–
> 200	1.9	–
< 200	–	47.9
315–200	–	29.6
400–315	–	9.7
500–400	–	7.6
500–630	–	5.2

called bottom ash residues (BAR). Therefore, generating two materials from the original CBA and combine it in concrete as cement and sand replacement constitutes the novelty of our investigation. To evaluate the effect of using GBA and BAR generating from original CBA in concrete manufacturing an experimental program was designed. This latter was divided into two parts: The first one consisted to study fresh properties especially slump and air content. In addition, the mechanical properties were assessed through the compressive strength test and the freeze/thaw test. The second part consisted to investigate the environmental impact of incorporation theses by-products in concrete through a leaching test. At the end, cost evaluation were carried out to quantify the use of GBA and BAR in concrete manufacturing. The found results will be a data guideline for civil engineers.

Method and materials

Materials

Sampling and preparation of CBA

Coal bottom ash (CBA) used in this investigation was collected from Taqa Morroco thermal power plant. The chemical analysis of CBA was performed using an energy dispersive spectrometer (EDS) (see Table 1). It seems that CBA was mainly composed of silica, alumina, and iron with small amounts of calcium, magnesium, sulfate. The used CBA was compared with CBA from other studies as shown in Table 1. It seems that chemical composition of CBA used in this study was closely to CBA from the literature. In addition, the chemical composition of CBA after grinding did not have a significant change. Before any mixture, firstly, CBA samples were dried for 3 h at 120 °C to remove moisture. Then, about 10 kg of the original CBA was crushed using a ball mill for 20 min at 150 rpm. After grinding, it was sieved to generate two types of materials. The first one was called ground bottom ashes (GBA) and the second one was called bottom ash residues (BAR). Table 1 shows the particle size of each one. The specific gravity of the original CBA was 1.88 while the specific gravity of GBA and BAR were 2.83 and 2.33, respectively (See Table 3).

Table 2 Chemical composition of BA, GBA and cement

Constituents wt%	SiO_2	Fe_2O_3	Al_2O_3	CaO	MgO	SO_3	Na_2Oeq	TiO_2	P_2O_5
CBA (our work)	52.07	23.34	8.86	1.92	1.09	1.87	1.65	0.98	0.18
GBA (our work)	51.7	23.13	7.81	2.1	1	1.69	1.64	0.87	0.17
CBA [16]	45.74	25.33	6.86	0.99	1.25	3.71	–	0.19	–
CBA [17]	56	26.7	5.8	0.8	0.6	–	–	–	–
CBA [18]	34	36	16.80	2.4	–	5.9	–	–	–
Cement	21.3	3.4	5.58	62	1.85	2.41	–	0.3	–

Table 3 Characteristics of Materials used in concrete mixture

Parameters	Aggregate I 6.3/16 mm	Aggregate II 3.15/8 mm	Sand 0/4 mm	CBA	BAR	GBA	Norm concrete B2
Specific gravity	2.63	2.64	2.66	1.88	2.33	2.83	–
Apparent density (T/m^3)	1.42	1.36	1.65	–	–	–	–
Cleanliness %	0.5	1.6	–	–	–	–	≤ 4%
Los-angeles coefficient %	18	19	–	–	–	–	≤ 35%
Flattening coefficient %	5	8	–	–	–	–	≤ 25%
Methylene blue value	–	–	0.7	–	–	–	–
Fineness modulus	–	–	2.77	–	–	–	–

Cement

Portland cement used in this study is CPJ45 produced according to the Moroccan norm [27]. Its chemical composition is given in Table 2. Initial and final setting times of cement were 180 and 210 min, respectively. Its specific gravity was 3.15. Compressive strength of cement at 7 and 28 days was 30 MPa and 40 MPa, respectively.

Sand and aggregate

To assess the quality of the aggregates, samples were subjected to the following test: Determination of the specific mass [28, 29], particle size distribution curve, determination of density [30], Cleanliness test [31], determination of the flattening coefficient [32], LOS-ANGELES hardness test [33] and equivalent sand test. The results are depicted in Table 3. Sand equivalent (S.E.) was 71%, a value in accordance with the specifications of the Moroccan standard [34], which recommend an (S.E.) ≥ 70% for concrete class B2. Fineness modulus of sand was 2.72, which can be classifying it as medium sand. As regard aggregate I and aggregate II, it seems that Cleanliness, Los-angeles coefficient and Flattening coefficient respected the Moroccan standard (NM 10-01-008) [34] which recommends the listed values for a concrete class B2. Particle size distribution curve of aggregate I, aggregate II and sand are presented in Fig. 1.

Mixture and fresh properties

In this investigation, concrete was made up of 350 kg/m^3 of cement and with a design strength of 25 MPa at 28 days. This concrete was classified class B2 according to Moroccan norm. The concrete mixture was made using the Dreux-Gorisse method [35]. The effective W/C was 0.53 for all cases of study. Five cases for mix proportions were prepared. In the manufactured concrete, GBA and BAR were used as a partial replacement of cement and sand, respectively, with 0%, 10%, 20%, 30% and 40% levels as shown in Table 4. After mixture, slump and air content were measured according to ASTM standards.

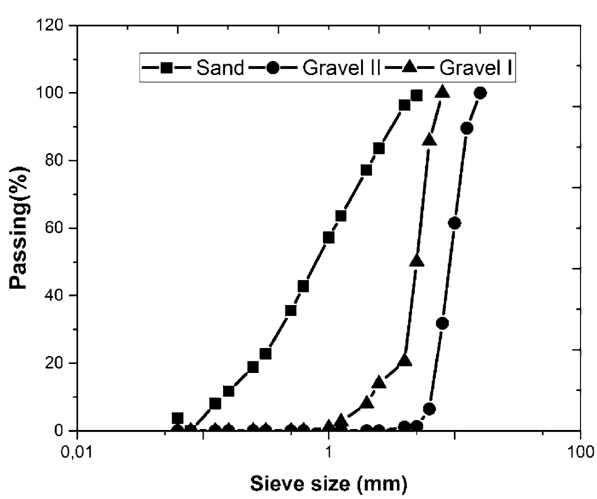


Fig. 1 Particle size distribution curve of gravel I, gravel II and sand

Compressive strength

To verify the mechanical strengths of the studied concrete, different cylindrical specimens (160*320 mm) were made at the laboratory. It was stored for 24 h and placed in a moist humidity room of more than 95% at the quasi-constant temperature of 20 °C and it was subjected to the compressive compression test at the age of 7, 28 and 90 days according to European Norm [36].

The freeze–thaw resistance

Concrete samples (100 × 100 × 400 mm) were made and subjected to the rapid freeze–thaw testing complying with procedure B of standard (ASTM C666) [37]. The samples were placed into a freeze–thaw chamber configured to freeze the samples in the air at − 18 ± 2 °C and thaw them at 5 ± 2 °C in water. All of the samples were subjected to a total of 300 freeze–thaw cycles. The compressive strength of samples was performed at the end of each 100 cycles.

Compliance test for leaching of CBA

To predict the behavior of CBA, leaching test was performed. The leaching study was carried out in accordance with standard (BS EN12457-2) [38]. CBA was leached with demineralized water according to a liquid/solid ratio of 10 L·kg^{-1}. The leaching was carried out under agitation for 24 h. The agitation was stopped for 15 min for allow the solid phase to settle. The eluates were then filtered on a cellulose acetate filter membrane with porosity equal to 0.45 µm. The concentration of the eluates was measured immediately by ICP-AES and ICP-MS.

Diffusion test for monolithic samples

To assess the leaching behavior of heavy metals in monolithic samples, a leaching test was performed. The Tank Leach Test was chosen in this study. The protocol adopted was taken from the Dutch standard [39]. Cylindrical specimens were placed in a reservoir containing leachant. The leachant used for the test was the demineralized water at pH = 6.8. The leaching solution was changed and analyzed at seven predetermined intervals (0.25, 1, 2.25, 4, 9, 16, 36, 64 days). The leachate was collected and filtered through

Table 4 Mix proportions of concrete (1 m^3) and fresh properties

	Aggregate I kg/m^3	Aggregate II kg/m^3	Water l/m^3	Sand kg/m^3	BAR kg/m^3	Cement kg/m^3	GBA kg/m^3	Fresh density kg/m^3	Slump (mm)	Air content (%)
Control C0	931	234	187	695	0	350	0	2397	40	4
C10	931	234	187	626	61	315	31	2384.5	39	3.8
C20	931	234	187	556	122	280	63	2373	37	3.2
C30	931	234	187	487	183	245	94	2360.5	33	3
C40	931	234	187	417	243.5	210	126	2348.5	30	2.7

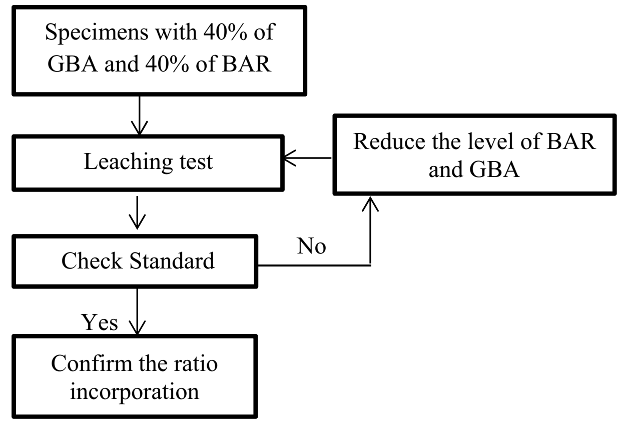


Fig. 2 The logic used for leaching test of monolithic samples

a filter paper (pore size 0.45 μm) at each period. Then, the heavy metals concentration in the collected leachate was measured with ICP-AES and ICP-MS. It was to highlight that diffusion test was carried out for specimens containing 40% of GBA and 40% of BAR as replacement of cement and sand, respectively. This incorporation ratio meets the mechanical proprieties. For this reason, we choose to evaluate the leaching for the specimens which had a high substitution ratio. Figure 2 illustrates the logic used for leaching test to minimize the number of experiences.

Results and discussion

Mechanical study

Fresh properties of concrete

Table 4 shows the effect on use of GBA and BAR as a substitute of cement and sand, respectively, on fresh properties of concrete especially fresh concrete density, slump and air content. From the obtained results, it seems that the density of concrete decrease with the increase of GBA and BAR levels. The density values of fresh concrete were ranged between 2348.5 and 2397 kg/m^3. This finding can be attributed to the lower density of GBA and BAR compared with cement and sand, respectively. As regard slump values, it ranged between 30 and 40 mm. The slump value of control concrete was 40 mm while the recorded values of concrete C10, C20, C30 and C40 were 39, 37, 33 and 30, respectively. This decreasing of slump values might relate to the high fineness of BAR and GBA with increases the surface area as result decreasing of free water available between particles. Consequently, the contact between particles was higher which generated friction. Contrary results were reported by other investigations who found that the use CBA in raw form as a fine aggregate didn't affect slump values compared to control concrete [40].

The obtained results show that the air content of the concrete mixture varied from 2.7% and 4%. As the replacement ratio of GBA and BAR increases, the air content decreases. Based on the literature, it seems that the air content in fresh concrete depends on its rheological properties [41, 42]. This decreasing of air content of concrete mixture can be explained by the fact that the bulk density of GBA and BAR is lower than that of cement and sand, so, with the increase of GBA and BAR, the bulk density of mixed material decreases, the total volume of solid particles increases. Meanwhile, more free water is absorbed. Hence, the free water in the mixture decreases which improves the internal friction. Thus, the apparent viscosity increased [43]. Other study confirmed that the use of fine material as cementitious material like fly ashes decreased air content in a mortar [44]. Another explanation of phenomena in lacking air content was found [45]. GBA full into the gaps of cement particles, which resulted in a denser packing of paste [45]. Similar explanation was reported by Kim et al.[40]. They illustrated the process of bubbles air generation during the mixing process. They declared that water and cement paste was entrapped in craters on the CBA particles during the mixing and curing. Due to the pores and craters absorbed in the fresh cement paste and the water during the mixing process, some amount of air bubbles, which escaped from the pores of craters, was entrapped in cement paste. Consequently, air bubbles became harder to escape from the cement paste. Thus lower bubbles air generation. In addition, another reason for decreasing the air content of concrete was reported by other researchers [47]. They showed that the bottom ashes contain carbon particles of incomplete combustion, which can adsorb the tiny bubbles in concrete mixture hence, air content decreases [46].

Compressive strength and resistance to freezing and thawing

The results of compressive strength of the different mixtures concrete at various ages are given in Fig. 3. It seems that the compressive strength of concrete mixtures was lower than the control mixture at 7 days. It was within a range of 21.3 and 15.3 MPa as compared to 22.5 MPa of control concrete mixture. At 28 days, the compressive strength of concrete mixtures with GBA and BAR was within a range of 27.3 and 25 MPa. It can be seen a decrease in compressive strength of CBA concrete mixtures varied between 9.8% and 32% at 7 day of curing age. It was also observed that compressive strength in CBA concrete mixtures decrease with 4.2% and 12.3% compared to control mixture C0 at 28 day of curing age. However, at 90 days of curing age, compressive strength

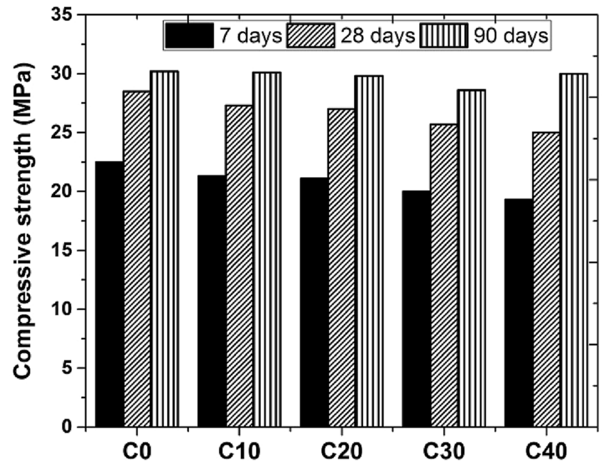


Fig. 3 Compressive strength of Samples at 7, 28, and 90 days

values of all four concrete mixtures with GBA and BAR were comparable to that of the control concrete mixture. This significant compression strength of the CBA concrete mixtures at 90 days of maturity was attributable to the pozzolanic activity of CBA. A study carried out by Singh and Siddique [47] found that pozzolanic activity of CBA did not start at an early age and it started reacting after 90 days of curing period. It can be concluded that the compressive strength results are satisfactory. It appears that 40% of BAR and 40% of GBA constitutes the optimal substitution rate. However, measuring the compressive strength is not enough to conclude the effectiveness of the concrete based on BAR and GBA. Additional durability tests are necessary such as the freeze/thaw test. The rapid freeze–thaw tests were performed on the concrete samples containing BAR and GBA ratios of 0%, 10%, 20%, 30% and 40%. The compressive strength values for the samples were measured at the end of each 100 freeze–thaw cycles as shown in Fig. 4. The results obtained from all of the samples at the beginning of freeze–thaw cycles were within the range of 28.6–30.2 MPa. It can be observed that the compressive strength decreased with the increasing of cycles. It seems that the compressive strength of all concrete mixture C10–C20–C30 and C40 reduced about 54%, 56%, 55% and 53%, respectively, at the end of 300 cycles. This finding can be explained by the fact that in each cycle of freezing caused a migration of water to pores of hardened concrete where it can freeze. These pores become fine cracks, which are enlarged by the pressure of the ice and keep enlarged during thawing when it became filled with water. Consequently, freezing repeated the development of pressure and the insufficient air content did not reduce the pressure. Normally when pressure occurs during freezing, a sufficient air content allows reducing it. However, from obtained results, it can be observed that freezing and

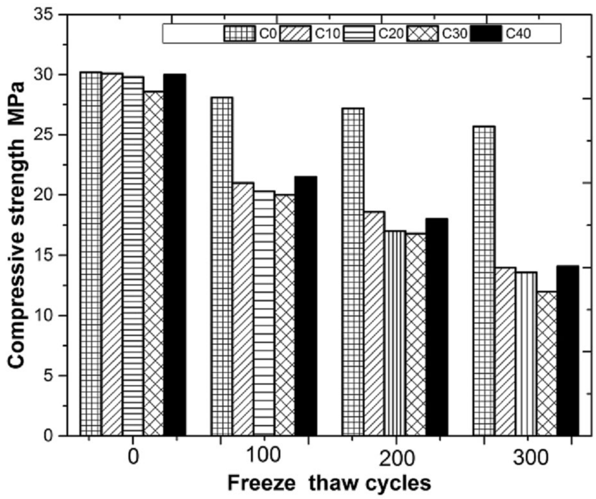


Fig. 4 Compressive strength of concrete samples at each cycle of consecutive freeze–thaw

thawing resistance of C40 was better than C10, C20 and C30. This can be attributed to the porosity of C40. More the level of GBA and BAR increased, the higher compactness and lower water absorption of hardened concrete.

It can be concluded that the deceasing of freezing and thawing resistance was mainly related to two parameters: the decreasing of air content; the water absorption of materials used in concrete mixture as a results of porosity of hardened concrete.

Since air content is considered as a key parameter influencing freezing and thawing. An entrained air agent will be recommended to this concrete mixture made up from GBA and BAR since the incorporation of this latter gave the best satisfactory results toward compressive strength. Similar results were recorded in other study [48], which concluded that weakness of freezing and thawing resistance was dependent on porosity and water absorption of paving blocks made up of marble waste, concrete waste and fly ash.

Environmental study

Heavy metals concentrations in CBA

Before preceding the leaching test of concrete specimens, Firstly, it is essential to measure heavy metal levels in CBA. For this, an analysis using ICP heavy metals was carried out. The results obtained of heavy metals concentrations in CBA are shown in Fig. 5. From the obtained results, it seems that CBA contained significant levels of heavy metals. However, the environmental assessment of the by-product cannot be based solely on the total composition of the material. Thus, analyzing heavy metals concentrations in CBA is not a valid method to judge the environmental impact of the by-product. Therefore, environmental endpoints are essentially based on the leaching behavior of materials. For this reason leaching test is mandatory in our investigation.

Results of compliance test for leaching

Results of the compliance test for leaching of *C*BA used for preparing the concrete mixtures are listed in Table 5. Also the results were compared with the total contents of heavy metals in CBA as shown in Fig. 5a. According to the recorded data, it seems that the elements arsenic (As), cadmium (Cd), nickel (Ni) and lead (Pb) were not detected. The leaching results showed a satisfactory ash behavior for their recycling.

In accordance with the European directive on the landfill of waste, there are three very categories waste, which are the

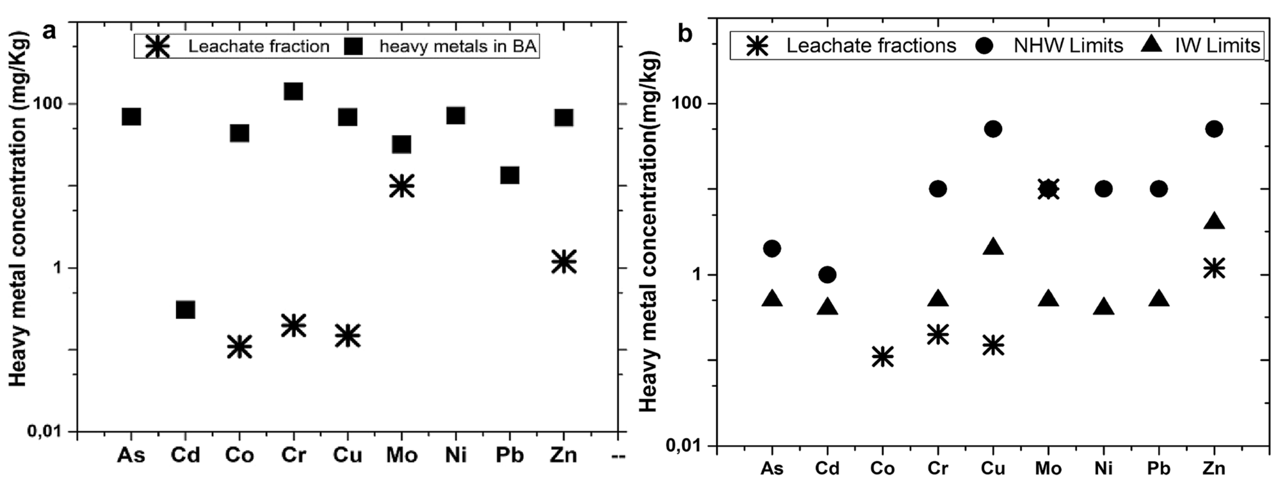


Fig. 5 Leachate fractions compared with total heavy metals in BA (**a**) and compared with NHW limits and IW limits (**b**)

Table 5 EN 12457–2 leaching test results (mg/kg)

As	Cd	Co	Cr	Cu	Mo	Ni	Pb	Zn
< 0.01	< 0.005	0.11	0.2	0.15	10	< 0.001	< 0.05	1.2

inert waste "IW", non-hazardous waste "NHW" and hazardous waste "HW". Waste for which the concentration limit of metals are lower than the inert thresholds can be valued in different areas without any treatment. Waste for which the concentration limit of metals are higher than the inert waste thresholds but lower than the non-hazardous waste thresholds are acceptable for storage in a municipal landfill. It can also be reused in construction according to the specific thresholds for the different scenarios chosen in construction (for example, on the road, in building, etc.) (EULFD) [49].

Waste for which concentration limit of metals are higher than the non-hazardous waste thresholds but lower than the "dangerous" thresholds are admissible in a landfill for hazardous waste. To classify these waste (CBA), the concentrations of leached heavy metals were compared with these thresholds as shown in Fig. 5b. From the Comparison, it can be observed that the elements detected did not exceed the "NHW" category of the discharge thresholds.

Diffusion test for monolithic samples

Control specimens and specimens based on BAR and GBA were prepared for the diffusion test. The evolution of conductivity and the pH are depicted in Fig. 6a, b. From the results, it can be observed that the pH values of control concrete ''CC'' eluate were ranged between 10.7 and 11.7. As regard concrete made with BAR and GBA, the pH values of C-BA eluate were ranged between 11.2 and 11.9 which correspond to normal values for cementitious materials. The conductivity of C-BA eluate was ranged between 250 and 1000 µS while the conductivity of ''CC'' eluate was between 300 and 1500 µS. The lower conductivity values for concrete containing GBA and BAR indicated that the GBA and BAR were well stabilized in this concrete mixture. Among all the elements measured, some were not detected in the eluates like Mo, Cu and Co. This finding indicated that the incorporation of GBA and BAR in the concrete allowed to stabilize these elements. Only chromium and zinc were detected. The results obtained for these two elements are presented in Fig. 7a, b. Based on the obtained results, it seems that cement-based solidification process was able to reduce the mobilization of heavy metals found in original CBA. Several investigations confirmed the ability of cement-based solidification process to immobilize heavy metals of ashes [50, 51].

To better understand the mobility of heavy metals, the releasing rate was calculated. For each extraction, the releasing rate can be calculated for the period with the experimental data of released quantities of the elements. The releasing rate is given by the following Eq. (1):

$$V_t = \frac{C_t}{\Delta t} \tag{1}$$

or

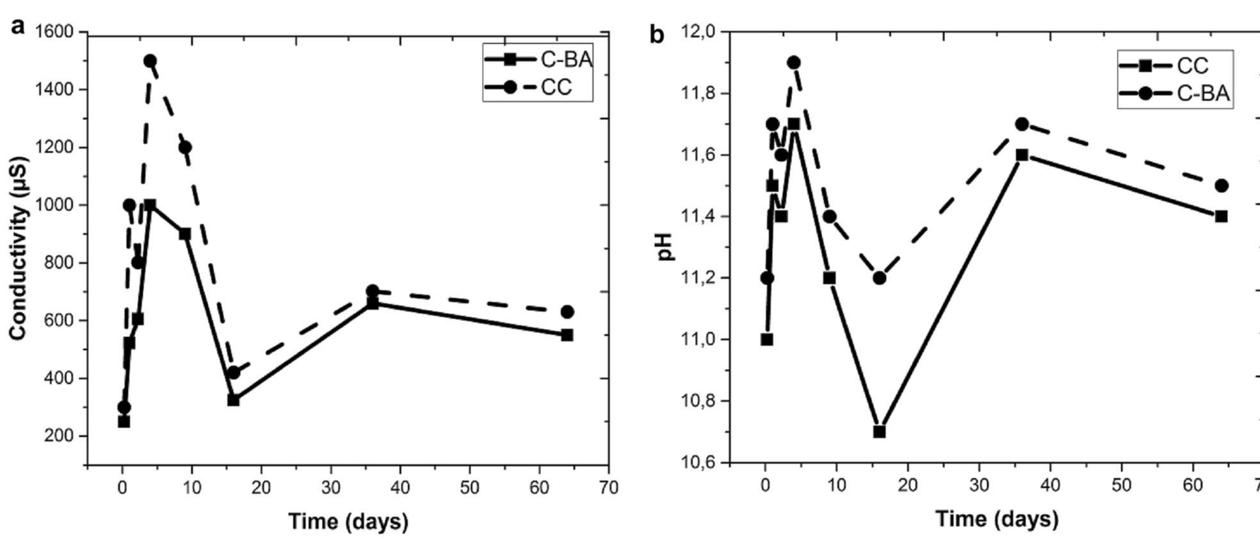
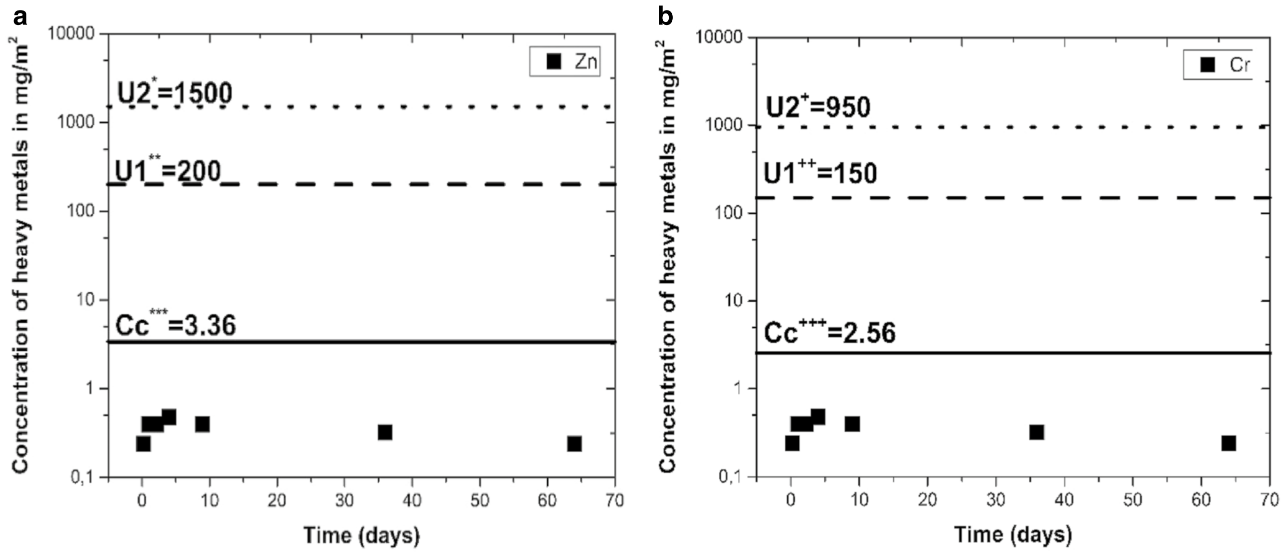


Fig. 6 Evolution of the conductivity (**a**) and of the pH (**b**) of the eluates during the diffusion test



(*) Upper limit for Zn according to Leaching limits set by the Netherlands Tank Leaching Test (NEN 7345)
(**) Lower limit for Zn according to Leaching limits set by the Netherlands Tank Leaching Test (NEN 7345)
(***) Cumulative amount of Zn during 64 days

(+) Upper limit for Cr according to Leaching limits set by the Netherlands Tank Leaching Test (NEN 7345)
(++) Lower limit for Cr according to Leaching limits set by the Netherlands Tank Leaching Test (NEN 7345)
(+++) Cumulative amount of Cr during 64 days

Fig. 7 Concentrations of Zn (**a**) and Cr (**b**) obtained by leaching test NEN 7345 Expressed in mg/m^2

Vt The releasing rate for the period (in $mg/m^2 \cdot day$); *Ct* The released concentration for an eluate sample corresponding to the time (in mg/m^2); *Δt* The period between eluate sampling corresponding to time "" and the previous sampling (in days).

We found that the releasing rate of the first and last sampling for chromium was 0.96 $mg/m^2 \cdot day$ and 0.009 $mg/m^2 \cdot day$, respectively. While, the recorded values of releasing rate of the first and last sampling for Zinc were 1.92 $mg/m^2 \cdot day$ and 0.014 $mg/m^2 \cdot day$, respectively. From the obtained results that the values of releasing rate for zinc and chromium decreased. This finding can be attributed to very low diffusion between concrete and water due it high compactness or depletion of mobile constituents.

To assess the results of the diffusion test, cumulative concentration of heavy metals detected were calculated and compared with leaching limits set by the Netherlands Tank Leaching Test (NEN 7345). Firstly, the cumulative quantities of anions and elements were calculated according to the following Eq. (2) and according to European standard (EN 15,863) [52].

$$C_c = \sum_{i1-8} C_i \tag{2}$$

or:

Cc is the cumulative amount (in $mg \cdot m^{-2}$); it is the leached concentration corresponding to the *i*th sample.

According to the norm NEN 7345, building materials are classified in relation to the leachability test in two categories: (a) materials without any environmental restriction (< U1), and (b) materials having a restricted use (< U2). Materials whose total leachability is comprised between U1 and U2 values do not have any environmental restriction as far as their use in building, but the pollutant that exceeds the U1 threshold should be removed at the end of the product life (dismantling). Finally, materials whose leachability thresholds are above U2 should have restricted use in building and dismantling [53].

From the obtained data, it can be observed that the cumulative concentrations Cc (mg/m^2) of both heavy metals (Zn and Cr) were so far below the U1 limits and U2 limits as indicated in Fig. 7a, b. So, the adopted mixture of concrete based on BAR and GBA can be used in construction without any environmental restrictions.

Cost evaluation of using GBA and BAR

Reducing the cost of building materials is a challenge for the construction sector. Since concrete is the basic building materials, all scientific are focused to reduce the cost of

Table 6 Comparison between cost of control concrete and cost of concrete with GBA and BAR

	C0	C10	C20	C30	C40
Amount of cement in concrete kg/m^3	350	315	280	245	210
Amount of sand in concrete kg/m^3	695	626	556	487	417
Amount of GBA in concrete kg/m^3	0	31	63	94	126
Amount of BAR in concrete kg/m^3	0	61	122	183	243.5
Amount of cement economized kg/m^3	–	35	70	105	140
Amount of sand economized kg/m^3	–	69	139	208	278
Cost of grinding and sieving process (2.3 €/ton)	–	2.3	2.3	2.3	2.3
Cost of sand (23€/m^3)	–	–	–	–	–
Cost of cement (38 €/ m^3)	–	–	–	–	–
Cost of 1 m^3 of concrete (€)	70.23	65.37	60.51	56.1	51.1
Percentage of reduction of concrete cost (%)	–	7.3	13.8	20.1	27.2

concrete. To achieve this aim, different researchers investigated the use of different materials as an alternative material to cement in concrete including industrial by produts [54] and waste materials [55]. In this study, GBA and BAR were used as an alternative material to cement and sand in concrete production.

Currently, TAQA Morocco has recycled nearly 80% of CFA in the local cement industry [56] but CBA were stored. The area of the storage site of CBA is about 140,000 m^2 and its depth is more than 20 m, which generates cost of storage [57]. Therefore, the use of GBA and BAR generated from grinding and sieving of original CBA can reduce concrete cost. The initial cost of raw bottom ashes is free of cost by the thermal power plant. The cost of grinding and sieving process at industrial scale of CBA including drying, maintenance of grinding and sieving machine and workers was estimated approximately to 2.3 € per ton [56] and can be sold to the customer approximately to 3 € per ton [56]. Transportation of GBA and BAR from the thermal power plant to concrete plants constitutes another factor for estimation cost of concrete. The cost of GBA and BAR transportation was calculated based on the fuel cost, labor cost and maintenance cost. In our case, we aimed to market GBA and BAR to a local customer who produces concrete in El jadida city. The fuel cost, labor cost and maintenance cost were estimated to 0.28 €/Km, 3.79 €/h and 0.17 €/Km. The distance between the thermal power plant and concrete plant located industrial area in EL Jadida city is 26.5 km. Transportation cost was estimated for 1 trip. Thus, the transportation cost of GBA and BAR is estimated approximately to 0.38 € per ton.

The cost of cement, sand and aggregate are 38 €/m^3, 23 €/m^3 and 20.2 €/m^3, respectively. The cost of these basic materials was supplied by a local concrete supplier. It should be noted that the cost of the components of concrete is related to the season and purchase amount. In addition, other parameters existed that affect the cost of concrete namely transportation, labor costs and tax. Estimation costs of these parameters depend on the size and location of the project. Therefore, in this study, we focus on the analysis cost of concrete based on its components and the cost of developed bottom ashes to highlight the benefit of using the developed bottom ashes.

Based on data of concrete mix illustrated in Table 4 and the cost of each component of concrete, the cost of concrete was calculated. The cost of concrete control was compared with concrete made up with GBA and BAR at different replacement ratio. The obtained data are depicted in Table 6. From Table 6, it seems that incorporating GBA and BAR as replacement of cement and sand in concrete at 10% to 40% levels economized 35–140 kg/m^3 of cement and 69–278 kg/m^3, while the cost of concrete was reduced as the levels of GBA and BAR increase. The cost of concrete made with GBA and BAR was reduced from 70.23 € to 51.1 €.The percentage of reduction of the concrete cost was ranged from 7.3% to 27.2%. Thus, the use of GBA and BAR as replacement of cement and sand in concrete suggested double benefits: the first one consists to solve the problem of CBA storage and the second one, the cost of concrete will be reduced.

Conclusion

This investigation was carried to assess the suitability of a combination of BAR and GBA as partial replacement of sand and cement in concrete. The obtained data can be summarized as follows.

(a) Slump, the density of fresh concrete and air content decreases with the increasing of BAR and GBA levels in the concrete mixture.
(b) The use of BAR and GBA reduces the concrete strength at early ages, but a significant improvement in concrete strength was observed at the ages of 90 days.

(c) With the increase of the number of cycles, the compressive strengths of concrete decreased for all contents of BAR and GBA. This reduction was quantified by more than 50% after the freeze–thaw test.
(d) According to standard NF EN12457-2, it can be observed that the elements detected did not exceed the "NHW" category of the discharge thresholds.
(e) Based on the results from NEN 7345 leaching test, it can be concluded that there are no environmental restrictions on the use of concrete made with BAR and GBA.
(f) 40% of GBA and 40% of BAR as replacement of cement and sand appeared the best combination in concrete mixture.
(g) Cost evaluation reveals that using GBA and BAR reduces cost of concrete from 70€ to 51€ for 1 m^3.

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Data availability All data, models, and code generated or used during the study appear in the submitted article.

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