Influence of forest biomass bottom ashes on the fresh, water and mechanical behaviour of cement-based mortars

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Abstract

Renewable energies' production is increasing globally over the years. Biomass is considered a renewable source of energy that can be produced by organic matter. The biomass energy production, although generating low CO_2 emissions, creates wastes during the production process, namely ashes. The increase of renewable energies' production and the consequent biomass energy production is also responsible for a higher production of these ashes. Most of these ashes are sent to landfills. This should be avoided since it is responsible for several soil, air and human environmental impacts. The fine ashes particles can lead to respiratory human health problems, as well as contaminate the soils, ground water and the air. Therefore, it is necessary to find new applications for these ashes in order to reduce their deposition in landfills.

In this research, an eco-solution is presented to reduce the cement content of the mortars and, at the same time, the biomass deposited in landfill by their incorporation in renders, replacing cement at 5%, 10% and 15%, by volume. The use of biomass ashes in cement-based mortars was investigated through their fresh, water and mechanical behaviour.

It was possible to conclude that cement can be replaced up to 15% by a forest biomass ash waste in render applications, without compromising the global behaviour. The incorporation of the waste led to similar fresh and water behaviour to that of a reference mortar, better deformability and slightly lower mechanical strengths, which did not affect the scope of the mortars application, according to EN 998-1.

Keywords:

Biomass ash, Mortar, Render, Eco-mortar, Industrial Waste, Reuse, Sustainability

1. Introduction

Today renewable energies' production is increasing globally due to the environmental problems induced by fossil fuels use, such as CO_2 emissions, acid rain and the depletion of the ozone layer [1]. Renewable energies come from sources that are constantly replenished. Solar, wind, hydropower, geothermal energies and biomass are some examples of renewable sources of energy [2]. Among these resources, biomass is considered a renewable and CO_2 neutral energy source, when the consumption rate is lower than the growth rate [3], making biomass attractive to use for electricity and heat production [4]. Usually, organic wastes are burnt to reduce their volume or to obtain energy [5]. Biomass energy comes from the transformation of organic matter, from animal or vegetal sources, which produce electricity, heat or fuel [6] [7] through thermochemical, biological or chemical processes [2] [6]. In the first ones, biomass fuels are sent to incineration, pyrolysis or gasification methods, as for biological technology; microorganisms are used in processes such as alcoholic fermentation or anaerobic digestion [6].

In Portugal, in 2016, 72% of the total energy used in electricity consumption came from renewable energies' sources [8]. In this country, two thermal power plants, dedicated to electricity production and connected to the national electric grid, produce energy from forestry biomass as their main fuel [3]. In addition, nine co-generation power plants are installed in forestry sector industries, which use biomass for combined heat and power production [3]. According to Rosales *et al.* [9], in Andalusia, Spain, there are 17 biomass combustion plants that are able to produce 23% of the total primary energy consumed in the area. In fact, power generation industry is gradually shifting towards the use of biomass for fuel and energy production, helping to supplement national electric gridlines [7] [9].

Biomass combustion, independently of the source, generates wastes, namely ashes [9] [10]. In combustion technology, there are two different ashes produced in the process: bottom and fly ashes [9] [10] [11]. The first ones are deposited at the bottom of the boilers and the others are small particles, which are collected by flue gas cleaning systems. The amount of each type of ash depends on the biomass combustion technology, according to Modolo *et al.* [10]. In a grate furnace, the bottom ashes represent the highest percentage, in weight, of the total ashes produced. On the other hand, according to Modolo *et al.* [10], in a bubbling fluidized bed combustor, the bottom bed ashes represent 5% to 60%, in weight, of the total ashes produced.

Most of the biomass ashes produced in thermal power plants are disposed of in landfills or are recycled through deposition in forests [5] [12] [13] or in agricultural fields, functioning as a soil supplement [7] [14]. According to González-Kunz *et al.* [5], 70% of the wood fly ash produced is sent to landfill, 20% is recycled as supplement to improve the alkalinity of soil and the remaining 10% is used in other applications, where construction materials are included. In fact, most of the wood fly ashes are disposed of in landfills [15] and often without any form of control [12]. These fine particles can be easily rendered airborne by wind, which can be problematic when disposed in landfills [15]. They can cause respiratory human health problems [7] by the inhalation of these particles and can as well contaminate the ground water resources by leaching of heavy metal contents of ash or by seepage of raining water [15].

Biomass can result from organic matter from different sources; therefore, there is a large amount of biomass fuel that can be used to produce energy, such as eucalyptus wood [16] olive [1] [5] [9] [14] [17], forest residues, cork [5], bamboo leaf [5], palm oil waste [5] [13] [18], rice husk [5] [13] [17], sugar cane bagasse [5] [13], coconut shell [5], agave [5], corn cob [5], wheat straw [5] or waste paper sludge [5]. The amount of ashes created in biomass energy production depends on the organic matter used as fuel [5] [13]. Wood wastes, in comparison with other biomasses, such as herbaceous and agricultural wastes, are preferable fuels for biomass furnaces since their incineration produces less fly ashes [13] [3] or other residual materials [15]. The quantity and quality of ashes is influenced by several aspects, namely the heat treatment temperature, type and process of furnace and type of organic matter used as fuel [3] [7] [11] [13] [14] [15] [19]. Combustion temperature of fuel waste inside the furnace strongly governs both the yield and chemical compositions of the resulting wood waste ash [7] [15]; higher temperatures generally result in a lower amount of the ash produced [15]. For temperatures up to 500 ºC, the presence of carbonates and bicarbonates, especially calcite, is predominant in wood ashes [15]; however, the biomass energy production usually reaches higher temperatures, sometimes beyond 1000 ºC. When the temperatures achieve this high value, there is a decrease of carbonate content due to the chemical decomposition of the aforesaid chemical biomass compounds (carbonates and bicarbonates) [15] which occurs near 900 ºC, and oxide compounds such as quick lime become predominant in the chemical phase of the ashes [15]. In fact, the crystallinity and mineralogy depend on the combustion technique used [7], namely on the combustion temperature achieved. The temperatures used in the biomass energy production process also affect the organic matter content of the ashes, which will affect the particle size distribution, water absorption, porosity, shrinkage and mechanical strengths of the future materials [9].

In fact, there are several aspects that influence the biomass ashes' chemical and physical composition, as their biomass fuel, the biomass energy production process or, in the case of combustion process, the temperature achieved during the energy production process. As mentioned, biomass energy production is increasing, which increments the volume of biomass ashes generated, namely in the combustion energy process. The amount of ashes production creates an environmental concern. In this sense, it becomes necessary to explore its possible uses [11] [14]. Several authors have been carrying out studies to incorporate fine biomass ashes in mortars or concrete as fillers or binders, replacing sand or cement [1] [5] [9] [12] [13] [14] [16] [17] [18] [20]. It is important to take into account that different types of biomass ashes may produce different characteristics of mortars. In fact, the literature review highlighted different results concerning water absorption or mechanical strengths. Therefore, the analysis of the influence of biomass ashes on mortars or concretes is specific to each given material and the scope of this theme is not exhausted.

Cement is the most used material worldwide, consuming a great amount of raw materials, such as sand and limestone, and energy, while at the same time releasing high quantities of carbon dioxide into the atmosphere [15]. According to the European Cement Association (CEMBUREAU), a tonne of cement produced releases 738 kg of carbon dioxide into the atmosphere [21]. The replacement of cement by biomass ashes reduces both the emissions of CO_2 into the atmosphere, and the amount of waste sent to landfill, reducing some environmental problems such as respiratory human health problems or pollution of the ground water.

In general, researches on the incorporation of ashes in mortars are more focused on mechanical strength, such as compressive and flexural, and on total water absorption of these new mortars, in comparison with ordinary mortars. In fact, these tests are important as they are able to identify the general behaviour of the mortars, but there are more specific tests for renders that influence their behaviour and are not usually considered. Thus, in this research, forest biomass ashes (particles under 63 μm) from a Portuguese power plant were used as binder, partially replacing ordinary Portland cement in renders, and a deep analysis was performed. The influence of biomass ash incorporation in cement-based mortars was investigated through their fresh, water and mechanical behaviour. The water behaviour was analysed through workability, bulk density and water retention. The mechanical behaviour was analysed through compressive and flexural strengths (as is generally analysed by other authors) but also adherence strength and resistance to impact. The water behaviour was analysed in the first minutes (fast absorption) and until saturation (for about a month). Drying over time was also analysed in the different water transport mechanisms: liquid transport, mix transport and vapour transport.

2. Experimental plan

2.1. Materials

An ordinary Portland cement CEM II/B-L 32.5N, usually used in renders applications, was used as main binder in this research. The natural aggregate was natural silica sand, previously washed and calibrated, with a particle size distribution between 0.1 μm and 2.0 mm. In this research, forest biomass bottom ashes (FBA), from a Portuguese power generation industry were used as partial cement replacement.

The properties of the natural aggregate and the FBA were identified and disseminated in a previous research of our group. In that previous research, X-ray diffraction analysis and chemical elements identification through the electron microprobe technique were performed [22]. In the X-ray diffraction analysis of biomass ashes, the presence of quartz, calcium carbonate and potassium chloride was noticed as the major phases, and others in smaller proportion [22]. The main chemical elements of the biomass ashes were identified as: C (12.53%), O (32.57%), Na (1.79%), Mg (2.12%), Al (4.32%), Si (8.19%), P (0.82%), S (4.17%), Cl (6.54%), K (8.77%), Ca (14.15%), Mn (0.62%), Ti (0.09%) and Fe (3.39%) [22]. Thus, no contaminant elements, such as As, Ba, Co, Cr or Zn, were found. These ashes will be involved by the cement matrix; nevertheless, in future developments the studies analysis should be deeper in what concerns the analysis of leaching compounds [23] [24]. In the previous research, the bulk density, water absorption, organic matter and activity index of the biomass ashes were also analysed, and the results obtained are presented in Table 1. The activity index was determined, and it was found that biomass ashes can present some pozzolanic activity. The waste was not considered pozzolanic by the standard classification but the values were close to the limits, meaning it is likely that some pozzolanic activity occurs [22].

The influence of the biomass ash on render's application was analysed in this research. Renders are sacrificial layers that intend to protect the substrate from external actions as climatic or human actions. Renders, contrary to other types of mortars as masonry's, are poor in cement. Therefore, a volumetric ratio of 1:4 (binder: aggregates) was chosen. Biomass ashes, on the other hand, were studied as a cement replacer at four ratios: 0%, 5%, 10% and 15% (in volume). The mortars are designated REF, 5FBA, 10FBA and 15FBA; the first corresponds to the reference mortar and the others to mortars with FBA, where the number is indicative of the percentage in volume of cement replaced.

Table 1. Constituents characteristics (Data from Farinha *et al.* [22])

Constituent	Density (kg/m^3)		Water absorption (%)	Organic matter content (%)	Activity index (%)	
	Bulk	Particle			28 days	90 days
Sand	1511.7	2526.2	0.72	-	-	-
Cement	988.0	-	-	-	-	-
FBA	695.0	2455.0	0.67[1]	3.2	72.1	76.7

[1] Mix of 10% of FBA and 90% of sand (in volume).

2.2. Test methods

In this research, the incorporation of forest biomass bottom ashes, as possible partial replacement of cement, was analysed through their fresh, mechanical and water behaviour.

The mortars' mixing procedure, in the fresh state, was performed according to European Standard EN 1015-2 [25]. Prismatic specimens (40x40x160 mm^3) were used to perform the water and mechanical behaviour tests. The specimens were prepared according to European Standard EN 1015-11 [26].

The fresh behaviour analysis included workability, analysed through consistency in the flow table, bulk density and water retention. All tests were performed according to European Standards, respectively EN 1015-2 [25], EN 1015-6 [27] and prEN 1015-8 [28]. These tests were selected for providing better evidence of the properties of the mortars in the fresh state. Workability is one of the most important characteristics of a render or plaster mortar. Without a proper workability, the mortar cannot be applied on vertical surfaces [29]. The bulk density test indicates, in the fresh state, the possible compaction of a mortar, giving some information about the possible mechanical strength and water behaviour of the mortars. Finally, the water retention is the capacity of the mortars to retain their mixing water, when in contact with a porous substrate.

The water behaviour was evaluated through water absorption and drying. Absorption was measured through the water absorption by capillarity test (performed according to European Standard 1015-18 [30]). The drying test started immediately after the water absorption by capillarity test and followed European Standard EN 16322 [31]. Through the drying curves, the drying index (area under the curve) and the drying rates of the different phases identified during test (liquid phase and mix phases) were measured.

Concerning the mechanical behaviour, the flexural, compressive, and adherence strengths and resistance to impact tests, performed according to the European Standards EN 1015-11 [26], 1015-12

[32] and EN 477 [33], were analysed. A universal force equipment ETI-HM-S/CPC from PROETI (Madrid, Spain) was used to perform the flexural and compressive tests with 2 kN and 200 kN load cells. A dynamometer, model CONTROLS C 215/D, with a 0 to 5 kN scale with resolution 50 N, was used to quantify the adherence strength. Flexural strength is related with tensile strength, which provides the ability of the mortar to withstand thermal stresses, movements of the substrate and also possible formation of ice and salts crystallization in the pores [29]. Compressive strength is an indicator of the overall mechanical strength of the mortar [29]. Adherence strength represents the ability of a mortar to adhere to a substrate. The resistance to impact test is associated with the compressive strength of the mortars and their deformability. The analysis of these tests gives information about the general mechanical behaviour of the render. Mechanical strength, however, cannot prevent micro-cracking, since it is necessary to allow some deformation. Therefore, the deformation of the mortars was also analysed in this research through the dynamic modulus of elasticity determination (by frequency of resonance and by ultrasound pulse velocity). The modulus of elasticity by frequency of resonance was performed according to the European Standard EN 14146 [34], using the equipment of frequency of resonance ZRM ZEUS 2005. The modulus of elasticity by ultrasound pulse velocity was performed according to an internal procedure from LNEC Fe Pa 43 [35], based on EN 12504-4 [36], using the ultrasonic tester MP-7 equipment from UltraTest GmbH Dr Steinkamp and Büssenschütt (Bremen, Germany) provided with software WinUltraSonic/BP-7. Besides the modulus of elasticity tests, the deformability of the mortars was also analysed through the flexural strength curves (force *versus* deformation) using two coefficients: failure tensile energy (G) and resistance coefficient to cracking evolution (R). The G coefficient of each mortar is quantified by the area below the force/deformation curves and the R coefficient is measured by the failure tensile energy using the maximum flexural force (Fm), thus R=G/Fm [37]. These coefficients are influenced by the flexural strength and by the deformation of the mortars. The analysis of these coefficients complements the modulus of elasticity (by resonance frequency and by ultrasound pulse velocity), hence they include the plastic phase of the mortar's behaviour. In both coefficients the deformation ability before complete failure is measured, which means some ductility [37]. The G coefficient is strongly dependent on the maximum flexural force, but in the R coefficient the force component is not taken into account. The larger the R, the larger the energy needed to produce micro-cracking, so the less probable that evolution is [37].

3. Test results

3.1. Fresh state behaviour

The fresh behaviour of the mortars with FBA was analysed through workability, bulk density and water retention tests and results are presented in Table 2.

Workability is an essential characteristic of a render, since without proper workability a mortar cannot be applied on a vertical substrate. In order to ensure this characteristic, the consistency by flow table test is performed and a flow range value is defined. For these mortars, the flow table for adequate workability was found to be 165±5 mm. The w/b ratio was defined in order to assure the consistency defined for the mortars. The results of the consistency and w/b ratio are presented in Table 2.

Table 2. Fresh state tests results

TEST RESULTS		**Consistency (mm)**	**Water/binder ratio**	**Bulk density (kg/m^3)**	**Water retention (%)**
FRESH STATE	**REF**	161.2 ± 1.8	1.3	1975.2 ± 6.9	67
	5FBA	170.2 ± 1.2	1.3	2058.6 ± 5.0	-
	10FBA	169.3 ± 2.8	1.3	2061.6 ± 6.7	-
	15FBA	167.2 ± 3.1	1.4	2044.7 ± 17.4	74

The incorporation of FBA up to 15% of replacement of cement did not affect the workability of the mortars, resulting in a similar water/binder (w/b) ratio for all the mortars analysed (about 1.3 w/b ratio). With this w/b ratio, a similar workability was achieved in the mortars (consistency by flow table about 165 ± 5 mm). Only the 15FBA presented a slight increase of w/b ratio of 8%, which is not considered significant. For what concerns bulk density, the incorporation of FBA also did not to affect significantly this property. The incorporation of FBA in renders, up to 15%, produced an increase of bulk density of only 4%. The water retention was measured in the mortar with higher volume of waste (15FBA) and REF. The REF mortar retained 67% of the total water of the mix and the 15FBA retained 74%. The mortars are usually applied on a porous substrate that will absorb part of the render's mixing water. This absorption can improve the bond between render and substrate, which is essential to the adherence strength, but can hinder cement hydration because there is less water available. Thus, a greater water retention of the FBA can allow a better cement hydration, in comparison to the one provided by the reference mortar. In fact, considering the set of analysed properties, it can be concluded that the incorporation of FBA in mortars seemed not to significantly influence their fresh properties.

An equivalent workability, when cement is replaced with low content of forest biomass ashes was also found by other authors [3] [7] [12].

3.2. Water behaviour

The water behaviour of the mortars was analysed through water absorption and drying, since they are essential characteristics of a render that can influence their durability and the protection of the substrate. Water absorption and water drying were analysed at 28 days and 365 days. The absorption was evaluated through the capillary coefficient and total water absorption. Drying was evaluated through the drying rate in the different phases identified (liquid phase and mix phases) and the drying index. The test results are presented in Table 3, Figure 1 and Figure 2.

Table 3. Water permeability tests

Mortars	WATER ABSORPTION				WATER DRYING							
	Tests performed according to EN 1015-18 [30]				Tests performed according to EN 16322 [31]							
	CAPILLARY COEFFICIENT		TOTAL WATER ABSORPTION		WATER TRANSPORTATION (3 PHASES)						Drying index	
					Liquid transportation		Mix transportation					
							Predominately liquid		Predominately in vapour			
	Water absorption rate between 10 and 90 minutes of test		Amount of water absorption at the end of test		Water drying rate during the 1st phase		Water drying rate during the 2nd phase		Water drying rate during the 3rd phase			
	kg/(m^2.min$^{0.5}$)		kg		kg/m^2.h		kg/m^2.h$^{0.5}$		kg/m^2.h$^{0.5}$			
	28 days	365 days	28 days	365 days	28 days	365 days	28 days	365 days	28 days	365 days	28 days	365 days
REF	1.45±0.03	1.55±0.07	17.31±0.13	17.47±0.31	0.10	0.22	0.76	1.42	0.24	0.19	0.25	0.09
5FBA	1.14±0.05	1.53±0.03	15.53±0.24	17.48±0.12	0.19	0.07	0.79	1.48	0.27	0.16	0.14	0.09
10FBA	1.47±0.09	1.70±0.03	17.74±0.31	18.05±0.13	0.17	0.09	0.96	1.41	0.32	0.17	0.16	0.09
15FBA	1.50±0.10	1.70±0.01	17.65±0.48	18.00±0.28	0.18	0.09	0.92	1.33	0.32	0.21	0.16	0.09

Concerning water absorption, it was noticed that 5FBA was the only that presented lower capillary coefficient than that of REF's, for both ages analysed. The remaining mortars presented a capillary coefficient slightly higher than that of REF's, between 7% and 10%, depending on the age. The total water absorption of 5FBA was lower than that of REF's at 28 days and similar at 365 days. The remaining mortars (10FBA and 15FBA) presented at both ages a similar total water absorption. The incorporation of FBA replacing cement at over 10% moderately influenced the water absorption of mortars. Through these tests results, it is possible to conclude that these modified mortars, in contact with water, absorbed it slightly faster when compared with a reference mortar (as concluded by the capillary coefficient test results). Although they absorbed water faster, the total amount was similar (as concluded by the total water absorption test results). Thus, the absorption was different in the first minutes and over time, and that should be justified by the size and distribution of the capillary pores. The mortars with FBA over 10%, within the capillary range, have probably larger pores, which are responsible for an increase in the capillary coefficient, but probably had a similar volume of capillary pores, resulting in a similar total water absorption. On the contrary, an increment of total water absorption with the replacement of cement with biomass bottom ashes was found by other authors probably due to different mortars and biomass ashes compositions [9] [18].

In Figure 1 and Figure 2, the drying curves of REF are represented, in Figure 1 the curves are presented per time and in Figure 2 per square root of time. These figures represent the different water transports during drying [29]. In the first figure, the liquid water transportation (first phase) is represented and in the second figure three other water transportations are observed: a mixed transportation predominantly liquid (second phase), a mixed transportation predominantly in vapour (third phase) and a vapour diffusion transportation [29]. The drying rate of the different phases was quantified by the slope of the line tangent to the drying curves. The drying index is a mathematical tool quantified by the area under the curve, a smaller index representing a mortar with more ability in Table 3.

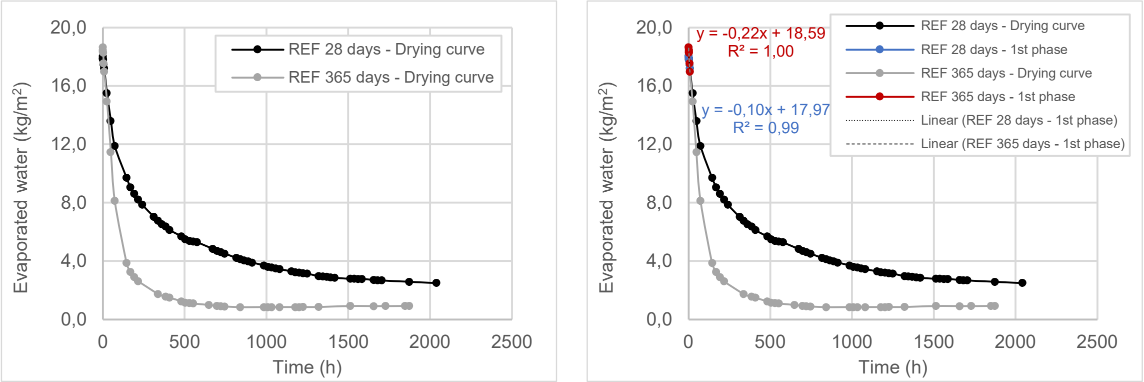

Figure 1. Drying curves of REF mortar (evaporated water per hour)

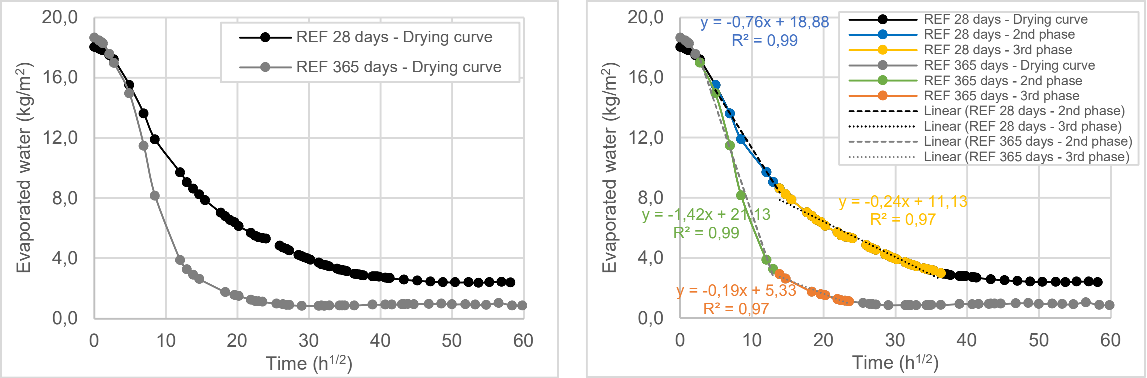

Figure 2. Drying curves of REF mortar (evaporated water per square root of time)

At 28 days, in the initial phase, a higher first drying rate was noticed in the mortars with FBA than in the REF mortar, which indicated a faster liquid transport from these mortars. However, at 365 days the trend changed, and it was the REF mortar that presented a higher first drying rate. In the mixed transport predominantly liquid (second phase) at 28 days the mortars with FBA also presented a faster drying rate. Although at 365 days only the 5FBA had a faster drying, the remaining mortars presenting a slightly lower drying rate (about 6%). In the mixed transport predominantly in vapour, the trend was similar: at 28 days the mortars with biomass had more ability to dry but, after 365 days, the reference mortar presented higher drying rates than the modified mortars, and in this phase the differences were more noticeable with a reduction in the mortars 5FBA and 10FBA of about 27%. In fact, in early ages, the FBA improved the drying ability of the mortars, which was noticed not only by the drying rates in the different phases analysed but also the drying index. At 365 days, no advantage of the FBA was found, and the mortars presented a similar drying behaviour when compared with the reference mortar. It was also noticed that drying improved over time, which means the mortars lose more easily the water absorbed. This improvement of drying was noticed in the drying curves, through the drying ratio and the drying index. The drying index was reduced by over 35% in all the mortars under analysis.

In conclusion, the water behaviour tests showed: slightly higher capillary coefficients for high contents of

FBA, similar total water absorption by capillarity and similar drying behaviour over time of modified mortars in comparison with REF's. In fact, the mortars with FBA, for what concerns water behaviour, can be considered similar to the reference mortar. As a whole, it may be considered that the incorporation of FBA as a replacement of cement, up to 15%, does not significantly affect the water behaviour.

3.3. Mechanical behaviour

The mechanical behaviour of the mortars with FBA was analysed through the flexural strength, compressive strength, adherence strength and resistance to impact tests. As already mentioned, the mechanical strengths are essential to ensure resistance to thermal stresses, possible movements or stresses due to the possible formation of ice and salts crystallization in the pores [29]. However, the mechanical strengths by themselves cannot prevent mortars' micro-cracking, which can affect the mechanical performance of a render. Some degree of deformability is essential to accommodate these stresses, preventing mortar cracking.

In this research, the mortars deformability was evaluated through two tests of dynamic modulus of elasticity (by resonance frequency and by ultrasound pulse velocity), by the failure tensile energy coefficient and by the resistance to cracking evolution coefficient. These tests were performed from 28 days until 365 days or 730 days, depending on the tests, and the results are presented in Table 4.

The results of the modulus of elasticity tests (by resonance frequency and by ultrasound pulse velocity) are presented in Table 4 and Figure 3. In general, it was noticed that the modulus of elasticity decreased with the FBA content. At 90 days, the modulus of elasticity was higher in the mortars 5FBA and 10FBA, in comparison with the REF mortar; however, at all the other ages analysed, the REF mortar presented a higher modulus of elasticity. At 730 days, the REF mortar presented a modulus of elasticity, determined by resonance frequency, higher by 23%, 32% and 35%, than the 5FBA, 10FBA and 15FBA, respectively. The replacement of cement by FBA resulted in mortars with lower modulus of elasticity, therefore more deformable than REF.

The ductility of the mortars was also analysed by G and R coefficients over time, from 28 days until 365 days, and the results are presented in Table 4 and Figure 4.

For the mortars under analysis, the 5FBA mortar was the one with higher failure tensile energy and higher resistance coefficient to cracking evolution, presenting an increase of ductility just before failure. The mortars with higher volume of FBA (10FBA and 15FBA) revealed a major influence on the G and R coefficients at 365 days, incrementing these coefficients in comparison with the REF's mortar.

In the elastic phase, analysed through the modulus of elasticity by frequency of resonance and by ultrasound pulse velocity, an increase of deformability was found when FBA replaced cement. In the plastic phase, the improvement of deformability depended on the FBA incorporation ratio and the testing age. The 5FBA presented better ductility than REF's at all ages under analysis; however, the 10FBA and 15FBA only presented higher ductility for longer ages, namely at 365 days.

Table 4. Deformability and mechanical strengths test results

TEST RESULTS				REF	5FBA	10FBA	15FBA
DEFORMABILITY	Modulus of elasticity (GPa)	By frequency of resonance	28 days	10.2 ± 0.7	9.9 ± 0.4	9.4 ± 0.7	8.1 ± 0.5
			90 days	8.0 ± 0.3	9.0 ± 0.3	8.2 ± 0.4	7.4 ± 0.4
			180 days	8.7 ± 0.9	7.6 ± 0.4	7.1 ± 0.2	5.7 ± 0.5
			365 days	9.7 ± 0.3	7.6 ± 0.7	6.8 ± 0.3	5.7 ± 0.5
			730 days	10.1 ± 0.8	7.7 ± 0.4	6.9 ± 0.2	6.6 ± 0.2
		By ultra-sounds	28 days	8.1 ± 0.0	8.0 ± 0.1	6.6 ± 0.1	6.6 ± 0.1
			365 days	7.7 ± 0.0	6.4 ± 0.1	5.7 ± 0.0	5.3 ± 0.0
	Failure tensile energy (N.mm)		28 days	184.4 ± 41.7	161.3 ± 25.8	149.4 ± 13.5	100.8 ± 21.7
			90 days	99.8 ± 23.6	138.3 ± 26.1	90.2 ± 17.3	134.0 ± 21.6
			180 days	145.7 ± 45.7	201.2 ± 44.5	107.3 ± 24.6	101.8 ± 15.5
			365 days	64.1 ± 12.9	166.0 ± 40.6	149.6 ± 29.9	97.3 ± 17.0
	Resistance coefficient to cracking evolution (mm)		28 days	0.20 ± 0.03	0.20 ± 0.02	0.20 ± 0.01	0.17 ± 0.02
			90 days	0.16 ± 0.02	0.18 ± 0.03	0.16 ± 0.03	0.19 ± 0.04
			180 days	0.19 ± 0.04	0.23 ± 0.03	0.17 ± 0.01	0.17 ± 0.01
			365 days	0.09 ± 0.02	0.20 ± 0.03	0.18 ± 0.04	0.16 ± 0.01
MECHANICAL STRENGTHS	Bulk density (kg/m^3)		7 days	2054.5 ± 8.4	2077.0 ± 7.9	2094.3 ± 16.5	2055.0 ± 12.2
			28 days	1860.8 ± 9.1	1890.9 ± 9.3	1895.4 ± 12.6	1870.7 ± 7.6
			90 days	1810.0 ± 10.0	1894.4 ± 8.8	1892.8 ± 5.6	1895.5 ± 9.6
			180 days	1830.1 ± 6.9	1891.3 ± 11.4	1888.5 ± 13.5	1873.8 ± 16.7
			365 days	1875.7 ± 28.6	1896.2 ± 21.4	1881.7 ± 12.2	1874.4 ± 18.6
			730 days	1875.3 ± 19.5	1892.6 ± 11.2	1890.6 ± 8.6	1893.9 ± 9.9
	Flexural strength (MPa)		7 days	1.30 ± 0.12	0.71 ± 0.14	0.48 ± 0.12	0.56 ± 0.03
			28 days	2.10 ± 0.32	1.89 ± 0.15	1.80 ± 0.07	1.37 ± 0.14
			90 days	1.54 ± 0.19	1.79 ± 0.17	1.43 ± 0.18	1.49 ± 0.19
			180 days	1.79 ± 0.16	2.03 ± 0.27	1.46 ± 0.21	1.35 ± 0.16
			365 days	1.94 ± 0.17	2.14 ± 0.28	1.53 ± 0.27	1.38 ± 0.14
			730 days	2.00 ± 0.31	1.60 ± 0.09	1.46 ± 0.16	1.42 ± 0.15
	Compressive strength (MPa)		7 days	3.35 ± 0.27	2.14 ± 0.16	1.73 ± 0.21	1.63 ± 0.11
			28 days	5.19 ± 0.45	5.55 ± 0.24	4.71 ± 0.31	4.30 ± 0.52
			90 days	3.58 ± 0.22	4.96 ± 0.21	4.43 ± 0.21	3.82 ± 0.38
			180 days	3.96 ± 0.42	4.41 ± 0.39	3.71 ± 0.40	2.92 ± 0.41
			365 days	5.86 ± 0.58	4.51 ± 0.37	3.69 ± 0.35	2.87 ± 0.51
			730 days	5.98 ± 0.79	4.24 ± 0.41	3.52 ± 0.33	3.32 ± 0.19
	Adherence (MPa)		28 days	0.47 ± 0.05 (Fracture pattern B)	-	-	0.26 ± 0.04 (Fracture pattern B)

Note: Fracture pattern A - Adhesive fracture (in the interface mortar/substrate); Fracture pattern B - Cohesive fracture (in the mortar); Fracture pattern C - Cohesive fracture (in the substrate).

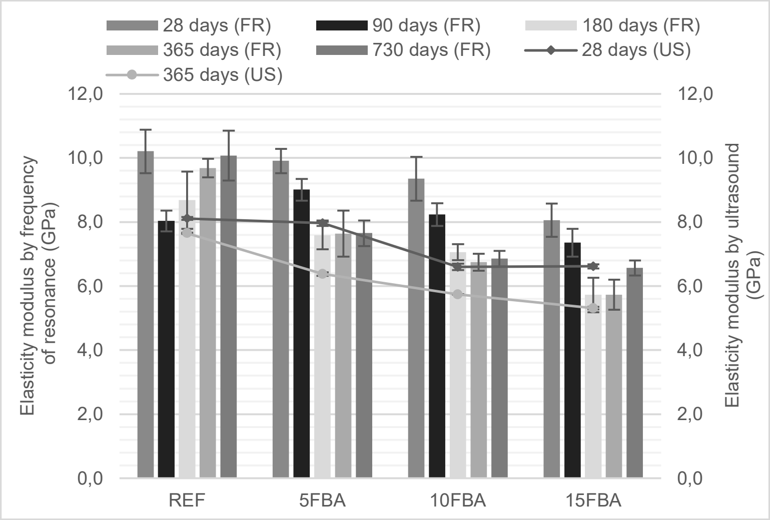

Figure 3. Modulus of elasticity by frequency of resonance and by ultrasound waves

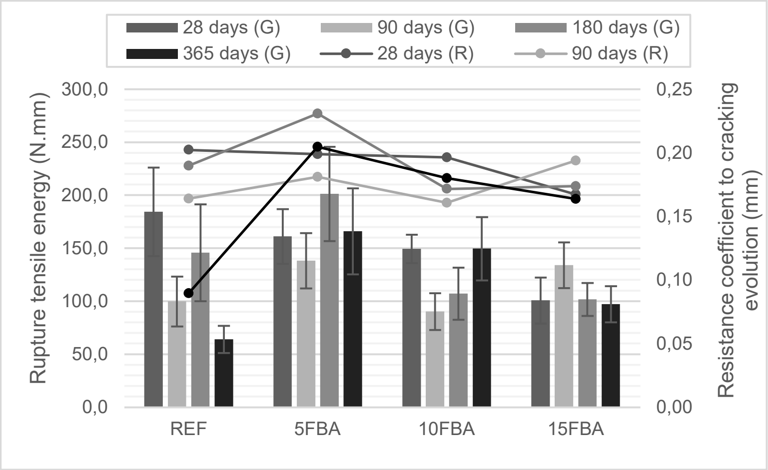

Figure 4. Failure tensile energy and resistance coefficient to cracking evolution

The bulk density of all mortars, in the hardened state, was measured from 7 days until 730 days (Table 4). The replacement of cement by FBA up to 15% did not affect the bulk density of the specimens, since the increments of bulk density were lower than 1%, which was also noticed in the fresh state. A similar bulk density could indicate similar mechanical strengths, for what concerns the physical mechanisms, but the FBA replaced cement and the chemical reactions, as well as the resulting compounds, are distinct. For lower contents of biomass ashes, other studies also noticed that the replacement of cement with forest biomass bottom ashes does not significantly affect the bulk density of the mortars [7] [3]; however, for higher ratios, higher than 20%, the bulk density of the mortars is modified, due mainly to the difference of bulk density of cement and the biomass ashes [9].

A pozzolan is a material that is not naturally a binder but contains amorphous phases of silica and/or alumina that, under given circumstances, in the presence of water and at current temperature, can be combined with the calcium oxide present in the cement, giving rise to stable elements with binder properties [38]. In the activity index test, performed in an early research on the FBA particles, the waste was not classified as pozzolanic by this standard but, nevertheless, the values obtained indicated some pozzolanic reactivity, which was also sustained by the XRD pattern (the main phase being quartz) and size distribution particles (maximum around 20 μm) [22].

Flexural and compressive strengths were analysed from 7 days until 730 days and the results are presented in Table 4, Figure 5 and Figure 6. The mortar with less FBA content (5FBA) presented from 90 to 365 days higher flexural strength than that of REF; however, the increment in compressive strength was only visible from 28 to 180 days. The remaining mortars (10FBA and 15FBA) presented lower flexural and compressive strengths than those of REF. The decrease in strengths was predictable due to the reduction of cement content. The FBA may have some pozzolanic reactivity, but it cannot replace cement without some decrease in strength. At 730 days, the reduction in flexural strength was between 20% and 30%: 5FBA presented a reduction of strength of 20%, 10FBA a reduction of 27% and 15FBA a reduction of 29%. Concerning compressive strength, at 730 days, the reduction was even higher, between 29% and 45%. In fact, the incorporation of FBA decreased these strengths, when compared with a reference mortar. So, the hydraulic compounds resulting of the pozzolanic reaction of the biomass ashes partially replace the cement hydraulic compounds, but they are not as efficient, causing lower strength. Although the strengths were reduced, in comparison with the REF mortar, it is necessary to analyse the values of the flexural and compressive strengths of these modified mortars. The 15FBA presented at 28 days a flexural strength of 1.37 MPa and a compressive strength of 4.30 MPa. According to EN 998-1 [39], a generic plaster or render is classified as CS III if the compressive strength (at 28 days) is between 3.5 MPa and 7.5 MPa. Thus, according to this European Standard, the REF mortar (5.19 MPa) and the 15FBA mortar (4.30 MPa) are in the same strength category, even with a reduction of strength. In this sense, the reduction of mechanical strengths in comparison with the REF mortar cannot be considered restrictive of the mortar's application as render or plaster.

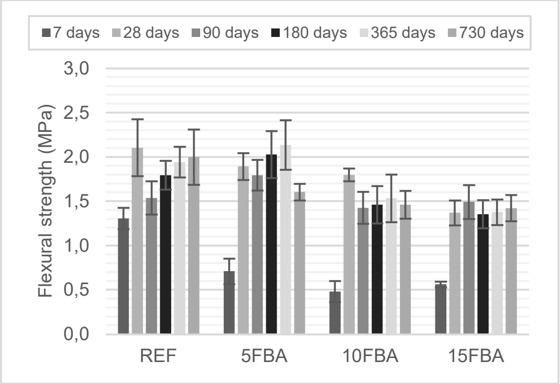

Figure 5. Flexural strength test results

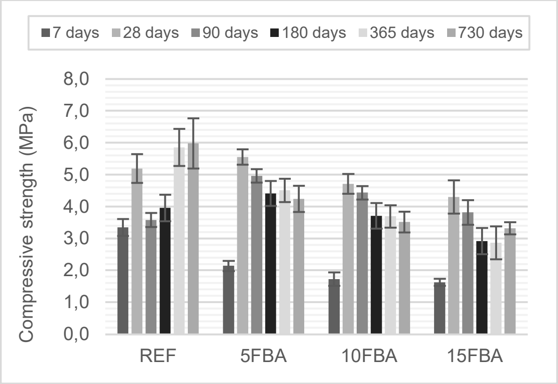

Figure 6. Compressive strength test results

The influence of biomass ashes on compressive and flexural strengths depends on the biomass type, origin, organic matter content and volume of waste incorporated. A reduction of the mechanical strengths, due to the replacement of cement with biomass ashes, at early ages, was also found by other authors [7] [9] [18]. However, at longer ages, due to the late pozzolanic reaction, some authors considered that the incorporation of this waste improves the mechanical strengths of mortars [7]. The pozzolanicity level depends on the amorphous nature of reactive biomass compounds, which is related with the temperature achieved by the ashes, during the biomass energy production. In this sense, differences between this research and other with different types of biomass were expected.

The adherence strength was analysed for REF mortar and for the mortar with higher volume of forest biomass ashes (15FBA), at 28 days. The incorporation of 15% of FBA decreased the adherence by about 45%, in comparison with REF's, which was in accordance with the flexural strength of the modified mortar at 28 days. Both mortars presented a fracture pattern B that represents a cohesive fracture in the mortar. Therefore, the value of adherence strength is higher than the one obtained by the test, which is limited by the tensile strength of the mortar. The reduction of adherence strength of the mortar is related with the reduction in flexural strength. Once more, even though there is a reduction of adherence strength, the value obtained was reasonable and according to the national requirements referred in a report from LNEC [40], since the adherence strength of the mortar meets the minimum strength required to be applied as a render (higher than 0.30 MPa or cohesive failure).

The resistance to impact was evaluated in the REF and 15FBA mortars at 28 days and the results are presented in Figure 7 and Figure 8. The resistance to impact consists in the fall of a mass with 1 kg from several heights, starting at one meter height and increasing 0.1 meters until failure occurred. For each height the surface of the specimens was analysed and registered the critical height for the occurrence of first crack and of failure.

The impact energy necessary to create the first crack and failure was quantified through the critical heights. The diameter and depth of the dent occurred in the specimens, when the first crack occurred, were also quantified, as well as the first crack width. The impact energy necessary for the first crack to occur was higher for the 15FBA (11.8 J *versus* 10.8 J for the REF mortar) and the cracking width was also smaller in the mortars with 15FBA (0.1 mm *versus* 0.4 mm). The mass fall created a dent in the drop area, the diameter and depth of which was also determined. The dent diameter and depth created when the first crack of the FBA mortar occurred were larger and deeper than the REF's: diameter about 15 mm *versus* 12 mm and depth about 1.6 mm *versus* 1.3 mm, respectively.

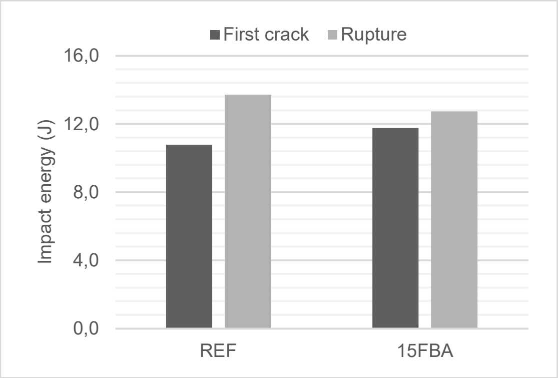

Figure 7. Impact energy

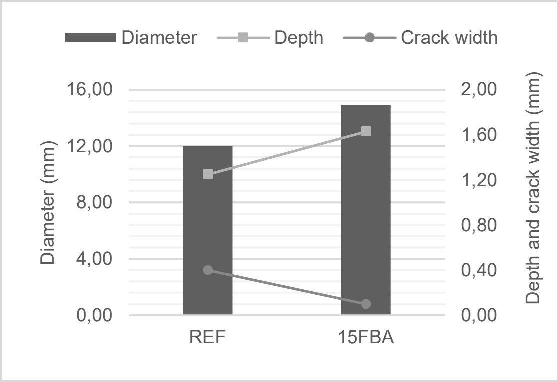

Figure 8. First crack (diameter, depth and width)

In failure, the impact energy, contrary to which was noticed until the first crack, was smaller in the

15FBA mortar in comparison with the REF mortar (Figure 7), about 12.7 and 13.7 J, respectively. After failure occurred, REF mortar presented a single fissure wide throughout the length of the specimen, dividing the specimen in two distinct parts (Figure 9). This pattern indicates a fragile failure. The 15FBA mortar, on the other hand, presented distributed thinner fissures over the specimen when failure occurred (Figure 9), which indicates that even after failure occurs the mortar is able to withstand small stresses, indicating a more ductile fracture pattern.

The resistance to impact results are related to the deformability and compressive strength of the mortars. Deformability influences the impact energy until the first crack occurs, as well as the pattern at failure, which can be more fragile or more ductile, depending on the mortars. A better deformability is an advantage until failure occurs, since it delays the occurrence of the first crack. When the applied force reaches the maximum value, failure occurs, exceeding the mortar's load capacity, which is related to its compressive strength. The pattern at failure is also influenced by the deformability of mortars. A fragile failure is characterized by a single and wide crack, while a ductile failure is characterized by several thinner and more superficial cracks. Thus, the compressive strength has a direct influence on the energy impact at failure, since it affects the capability of the mortars to withstand the impact and the deformability allows a delay in the occurrence of the first crack and it improves the failure pattern of the mortars.

The 15FBA mortar was more deformable, presenting a lower modulus of elasticity, and less strong, presenting lower compressive strength. The higher deformability of the mortar increased the impact energy of the mortars, which resulted in a higher impact energy until the first crack appeared, in a higher diameter and a higher depth of the dent. A more ductile fracture pattern of the 15FBA mortar, in comparison with the REF mortar, was also found (Figure 9). On the other hand, the mortar with 15FBA presented a lower impact energy in failure, which was due to the lower compressive strength of the mortar when compared to that of REF.

The mechanical behaviour was analysed through flexural strength, compressive strength, adherence strength and resistance to impact tests. The replacement of cement with FBA led to a decrease of flexural and compressive strengths. At 730 days, a reduction of flexural strength between 20% and 30% and a reduction of compressive strength between 29% and 45% were noticed. However, the reduction of these mechanical strengths, did not influence the strength category according to EN 998-1 [39], which means these mortars are similar for that use in what mechanical behaviour is concerned. In the adherence strength test, a reduction in the adherence value was also noticed; however, failure was cohesive and the value obtained was reasonable and, according to the national requirements of a report from LNEC [40], achieving the minimum value required for adherence in renders. In the resistance to impact test, a better behaviour was noticed in the FBA mortar until the first crack occurred, due to its higher deformability. However, this mortar presented failure for a smaller height, which was expected and is in accordance with the compressive strength results. In fact, the mortars with FBA showed a worse mechanical behaviour than that of REF; however, according to European and National standards or reports, the mechanical behaviour of the REF mortar and modified mortars with FBA is similar for use as renders or plasters. On the other hand, the mortars with FBA gave indication that they may have better cracking behaviour, due to their higher deformability. FBA mortars reduced the modulus of elasticity and also presented, at longer ages, more ductility than that of the reference mortar. This improvement of deformability was evidenced in the impact resistance test, where it was observed that for the first crack to occur it was necessary a higher impact energy. A better deformability can improve the cracking behaviour due to the major ability of the mortar to support movements or stresses provided by external factors. Thinner and more superficial cracks affect to a lower degree the ability of the render to avoid water penetration until the substrate.

Figure 9. Resistance to impact (failure) - REF (left) mortar and FBA (right) mortar

4. Conclusions

In this research, the influence that forest biomass bottom ashes' incorporation has on renders was analysed through their fresh state, water and mechanical behaviour. The biomass ashes came from a Portuguese power generation industry and were used to partially replace the cement in renders. The ashes replaced the cement at 5%, 10% and 15%, in volume.

It was noticed that the replacement of cement with forest biomass bottom ashes did not negatively influence the fresh state behaviour of the mortars, which presented similar workability and bulk density. In addition, the water retention increased when FBA was incorporated, which can be favourable to the mortar's hydration. The water behaviour also was not significantly modified by the incorporation of FBA, presenting slightly higher capillary coefficients, similar total water absorption by capillarity and similar drying behaviour over time.

The deformability of the mortars was improved by the use of the FBA. A proper deformability is essential in a render application, since the mortars have to be able to accommodate the stresses produced by thermal variations, ice or salts formation, mortars' shrinkage, substrate deformations or others. Only with a proper deformability can the mortar withstand these stresses without cracking, preventing this anomaly and increasing the mortar's durability. The incorporation of this waste improves this property of the mortars, which was also noticed in the failure pattern of the impact resistance test: the REF mortar presented a more fragile failure than that of 15FBA mortar, indicating a lower deformability at failure of the REF mortar as well as lower ductility.

The mechanical behaviour was influenced by the replacement of cement with forest bottom biomass ashes, as was expected. The FBA does not have the properties of a binder and, although it may have some pozzolanic activity, it is not classified as a pozzolan according to existing standards. This lack of binder properties had, as expected, a negative influence on the mechanical strengths. The reduction was higher in compressive strength, achieving almost 45% in some cases. This reduction means a worse mechanical behaviour of the mortars with FBA, when compared with the reference mortar. However, although the reduction of mechanical strength is considered a disadvantage, it was necessary to analyse the actual values, instead of relative values between the reference mortar and the modified mortar and, in fact, according to European Standards and to national requirements, the values of the mechanical strengths of the mortars with FBA led to similar strength classes as the reference mortar and met the strength requirements of these documents. Therefore, even if a worse behaviour may occur in these modified mortars by comparison with the reference mortar, the level of reductions verified means no significant restriction on their application as renders from the mechanical strength point of view.

The incorporation of this residue in mortars requires that it contains no significant amounts of contaminants, in order to have no negative impacts on the environment. In a previous study, no contaminants were found. However, a deeper study of the leaching compounds should be performed before an effective use is carried out.

In conclusion, in this research it was possible to notice that cement can be replaced up to 15% in weight with a forest biomass ash waste in render applications, without compromising their global behaviour. In this research, a specific application in render mortars was analysed. However, since the major negative influence of the waste was a moderate reduction of the mechanical behaviour, the authors consider that these mortars can be applied to other types of applications, as long as the mechanical strength is not a major conditioning feature. As it is known, cement production is responsible for causing great environmental impacts, namely CO_2 emissions into the atmosphere. It is necessary to find new eco-solutions to reduce the incorporation of this material in concrete or mortars applications. In this research, a solution is presented that simultaneously reduces the cement content and incorporates a waste that, without a recycling solution, would be deposited in landfill.

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