USE OF BOTTOM ASH ADDITIONS IN THE PRODUCTION OF CONCRETE WITH RECYCLED AGGREGATES

P.R. Silva[1,2], R.V. Silva[2], J. de Brito[2]

1 CERIS, Instituto Superior de Engenharia de Lisboa, Instituto Politécnico de Lisboa. R. Conselheiro Emídio Navarro 1, 1959-007 Lisboa

2 CERIS, Instituto Superior Técnico, Universidade de Lisboa, Av. Rovisco Pais, 1049-001 Lisboa, Portugal

e-mails: silvapm@dec.isel.pt; rui.v.silva@tecnico.ulisboa.pt; jb@civil.ist.utl.pt

Abstract: This paper provides a literature review on the use of bottom ashes in the production of concrete with recycled aggregates. Three types of bottom ash were studied, namely: biomass bottom ashes, coal bottom ashes and sewage sludge bottom ash. The characterization of these ashes focused on the analysis of their physical, chemical, and mineralogical properties. The effect of these ashes was subsequently studied on the fresh, mechanical, and durability-related performances of concrete. Bottom ashes generally present lower pozzolanicity than that typically observed, for example, in coal fly ashes. Their use as partial cement replacement normally leads to some loss in performance of the resulting cementitious composites. Also, using them as aggregates or in combination with recycled aggregates of other sources similarly causes an overall loss in performance. Nevertheless, such decline is still acceptable and often within manageable limits for the production of concrete under specific conditions including some structural applications. The use of these by-products including recycled aggregates may assist in solving a two-fold problem. Firstly, it reduces the consumption of cement and, consequently, the extraction of natural resources, also including the decrease of the consumption of natural aggregates to produce concrete. Furthermore, it solves the problem of the final destination for the significant quantities of bottom ashes produced by different industrial processes. In general, it is possible to conclude that, in moderate contents and when adequately processed, bottom ashes can be considered as viable substitutes of cement with manageable losses in terms of mechanical and durability-related performances. The use of coal bottom ashes was also found to significantly reduce the drying shrinkage strain of concrete.

Keywords: recycled aggregates, concrete, biomass, bottom ash, coal, sewage sludge.

1 INTRODUCTION

Given the intensive construction activities worldwide, mainly in developing countries with ongoing economic growth, a huge effort has been placed on the research for more sustainable construction practices. The use of various types of industrial wastes as supplementary cementitious materials (e.g. ground granulated blast furnace slag - GGBS; coal fly ash - FA; fillers - ground limestone) has become an important part of this matter, as these constitute a cost-effective waste management solution and provide the cement industry with additions capable of replacing cement, the production of which is highly energy-intensive.

FA from coal combustion, for example, is obtained by electrostatic or mechanical precipitation of the dust from the combustion gases from the burning of boilers fed with pulverized coal (from thermoelectric power plants). These ashes are without a doubt the most common artificial pozzolan used in the World for the production of concrete as partial cement replacement[1]. FA is one of the additions specified in EN-197-1[2] for the production of common cement. There is, however, a gradual decommissioning of coal-fired power plants and, in consequence, the use of FA will end over the next years in many countries. For this reason, there is considerable scope in using other potentially pozzolanic additions as adequate alternatives (i.e. bottom ashes) to replace cement. Three types of bottom ashes were identified to be produced in enough quantities to answer the demand of the cement industry: biomass bottom ashes, coal bottom ashes and municipal sewage sludge bottom ashes.

In addition to the reasons presented, the urgent need to find a solution for these ashes, which are produced today in considerable quantities and with a very significant annual increase, must also be stressed. These ashes are already used in numerous applications; however, the major share is landfilled with significant environmental impacts. In this sense, it would be possible to solve a two-fold problem: on the one hand, reducing cement consumption and, on the other hand, giving a valued destination to several problematic by-products. In the search for a more sustainable concrete, it is important to consider the use of recycled aggregates as a valid solution, which is currently well studied with interesting results.

The use of these industrial wastes as partial cement or aggregate substitutes or even together with recycled aggregates from other sources for the production of concrete is essential for four main reasons, namely:

- Energy consumption reduction throughout the production of cement;
- CO_2 emissions reduction related with cement production;
- Reduction in the mining of natural resources for the production of cement and natural aggregates (NA);
- Improved waste management with reduced amount of waste sent to landfills.

Therefore, in order to assimilate the use of bottom ashes in the production of concrete with recycled aggregates, which is progressively regarded as a future standard practice in the construction industry, their properties and potential interaction with recycled aggregates must be adequately evaluated.

2 BIOMASS BOTTOM ASH

The use of wood chips or other types of wood waste for combustion fuel as an energy source in power plants produces significant amounts of biomass bottom ash (BBA). Two types of ash are produced in wood waste combustion: biomass fly ash BFA and BBA, with a ratio depending on the type of waste used, but the latter typically comprises 60% to 90% of the total ash produced[3]. In general, after the complete combustion of the biomass waste, these ashes are the inorganic and non-combustible part of the fuel that remains[4, 5].

The total amount of BBA produced worldwide depend on numerous factors such as the availability of biomass or even the type of biomass combustion fuel source. However, it should be noted, for example, that countries such as Austria, Denmark or France produce values below 150,000 t per year, while countries like Russia, USA or Brazil reach values between 150,000 and 500,000 t, China, Germany or Canada already produce values above 1 Mt, and China reaches an average annual value of 1.61 Mt[4, 6]. The industry in general already has some uses for these ashes consuming considerable quantities, namely:

- Cement raw meal addition;
- Cement and concrete filler;
- Use in forestry;
- Soil amendment/fertilizer;
- Asphaltic filler;
- Underground mining.

One of the most efficient ways of producing energy corresponds to burning biomass wastes in boilers. This type of direct combustion of residues may, in the near future, represent one of the main forms of electricity generation mainly in industrialized countries[4, 6]. It is possible to state that this process can be considered as an “environmentally friendly” solution for heat and electricity production. For every 483 TWh of electricity produced using biomass waste burning, approximately 10 Mt of ashes are generated[6]. It is, therefore, necessary to find a viable solution for the use of these ashes to avoid jeopardizing the countless environmental benefits of using biomass waste.

2.1 Biomass bottom ash properties

BBA particles have a heterogeneous shape (spherical, lamellar and, in general, very irregular particles), are formed by very porous particles, generally below 4 mm[3, 7], and, depending on their origin, may include unburned wood residues[8, 9]. The BBA main components are silicon dioxide (SiO_2), aluminium oxide (Al_2O_3), iron oxide (Fe_2O_3) and calcium oxide (CaO) (Table 1). The main elements present in BBA (In Table 3, it is possible to observe the reference values for specific gravity, water absorption and organic matter content of BBA. The origin and type of biomass burnt, as well as the treatment conditions for BBA that vary from job to job are the main causes of the variability of the specific gravity, water absorption, and organic matter content values. These values fall well outside the range typically observed for other supplementary cementitious materials. The organic matter content values also present some disparity and are relatively high from what one would expect from a binder.

Table 2) are Si, Ca and K, followed by Fe, Mg, Al, Ti and Na.

Table 1 - Oxide composition of BBA

Chemical composition (%)	Reference values		
	Maximum	Minimum	Average
SiO_2	67.7	14.8	40.7
Al_2O_3	25.2	2.5	8.4
Fe_2O_3	25.0	2.2	6.8
CaO	84.1	0.5	28.3
MgO	9.9	0.1	3.3
K_2O	23.2	1.1	9.4
TiO_2	0.3	0.1	0.2
MnO	1.0	0.4	0.6
KO	10.2	7.3	8.8
P_2O_5	5.1	1.0	3.4
Na_2O	14.5	0.1	3.2
SO_3	4.2	0.2	1.5
Loss on ignition	9.4	2.4	4.7

Sources: Arenas *et al.*[10], Herman *et al.*[9], Nunes *et al.*[11], Rosales *et al.*[12], Kępys[13], Maschowski *et al.*[8], Vaičiukynienė *et al.*[14]

As a result of the incomplete combustion of biomass waste, these ashes contain high amounts of organic carbon[8]. There is also the relatively high heavy metal content and the presence of organic pollutants that can jointly compromise their use in some applications, including landfilling due to possible environmental pollution of adjacent water bodies. For this reason, BBA is often classified as hazardous materials[9].

In Table 3, it is possible to observe the reference values for specific gravity, water absorption and organic matter content of BBA. The origin and type of biomass burnt, as well as the treatment conditions for BBA that vary from job to job are the main causes of the variability of the specific gravity, water absorption, and organic matter content values. These values fall well outside the range typically observed for other supplementary cementitious materials. The organic matter content values also present some disparity and are relatively high from what one would expect from a binder.

Table 2 - Elemental composition of BBA

Element (Concentration (wt %))	Reference values		
	Maximum	Minimum	Average
Fe	1.9	1.0	1.5
Si	30.9	21.9	25.1
Ca	17.2	11.0	15.4
K	16.9	1.9	12.7
Mg	3.2	1.6	2.4
Al	1.2	0.5	0.8
Ti	1.5	0.1	0.3
P	2.0	1.0	1.5
Na	0.6	0.2	0.4

Herman *et al.*[9], Rosales *et al.*[12], Cabrera *et al.*[15], Cabrera *et al.*[16], Beltrán *et al.*[17], Rosales *et al.*[12], Cabrera *et al.*[18]

Table 3 - Physical properties of BBA

Physical properties	Reference values		
	Maximum	Minimum	Average
Specific gravity	2.5	1.7	2.0
Water absorption (%)	38.7	19.0	24.9
Organic matter content (%)	12.3	3.1	5.0

Sources: Beltrán *et al.*[19], Rosales *et al.*[20], Herman *et al.*[9], Cabrera *et al.*[15], Cabrera *et al.*[16], Beltrán *et al.*[17], Rosales *et al.*[12], Cabrera *et al.*[18], Agrela *et al.*[7]

2.2 Performance of cementitious composites containing biomass bottom ash

BBA has been typically used in the substitution of fine aggregates to produce mortars and concrete due essentially to the particle size distribution equivalent to that of natural sand. There are also some studies on the use of BBA as partial replacement of cement, reporting a significant loss in mechanical performance with increasing BBA content. Nonetheless, due to the very distinct compositions of this type of ash that can vary significantly depending on their chemical composition, there is some potential for their incorporation into blended cement.

Despite the few studies carried out regarding the use of BBA in concrete with recycled aggregates, the following should be noted: Rosales *et al.*[20] carried out work on the replacement of NA and mixed recycled aggregates from construction debris by BBA in the production of lightweight concrete with the addition of expanded clay. They produced a series of mixes, with constant expanded clay content, using either only mixed recycled aggregates or the former blended with BBA. The authors observed a gradual decline in the compressive strength with increasing BBA and mixed recycled aggregates contents in comparison with the control concrete. However, all mixes presented compressive strength values within the range of 15-20 MPa, thus corresponding to the limit established for structural and non-structural lightweight concrete. The authors also analysed the environmental impact of BBA in mixes with mixed recycled aggregates in structural layers of roads, essentially through leaching assessment[16]. The results showed that 50% of the BBA samples could be classified as hazardous, whereas 13% were non-hazardous and 37% inert. As, Hg, Cr, Ni, Cu, Se and Mo were the main metals released (in order of relevance). The authors analysed the most contaminated BBA in mixes with the two types of the aggregates used. It was observed that, even for the most contaminated BBA sample mixed with NA or with mixed recycled aggregates, the leached dangerous compounds decreased, proving the viability of using these mixes.

In the study of Cabrera *et al.*[15], BBA was used as aggregate replacement besides NA or RA (0%, 15% and 30%, by volume) to produce soil-cement mixes. The BBA resulted from the combustion of biomass with nearly 40% of olive cake and 60% of wood biomass (poplar, olive, and pine). The authors stated that the presence of 15% BBA contributed to an increase in compressive and splitting tensile strengths and in modulus of elasticity when compared to the control concrete. However, a loss in performance was observed for 30% BBA mixes.

To reduce the amounts of organic matter content and a high percentage of lightweight particles (two common problems in BBA), Agrela *et al.*[7] used processed BBA (Pr-BBA) and conducted a study on the use of coarse recycled aggregates to replace coarse NA, and BBA (and Pr-BBA) to replace sand. The BBA resulted from the combustion of olive pruning. Due to the higher porosity and lower density of BBA particles, the results demonstrated a loss in mechanical performance (with BBA and Pr-BBA as FNA replacement). The mixes with Pr-BBA showed promising results when compared to unprocessed BBA mixes. Relative to drying shrinkage, Agrela *et al.*[7] reported an increase of 45% to 76% with the combined use of recycled aggregates with BBA and Pr-BBA at replacement ratios of 15% to 30% when compared to the control concrete. The authors pointed out the deformability of recycled aggregates as the main cause for the considerable increase in shrinkage.

Nasr *et al.*[21] analysed the partial replacement of cement by BBA and sanitary ceramic waste (SCW). The authors produced: four mixes with 5%, 10%, 15% and 20% BBA as cement replacement; four mixes with 5%, 10%, 15% and 20% of SCW in substitution of cement; and four mixes combining BBA/SCW with 5% + 5%, 10% + 10%, 5% + 10% and 10% + 5% instead of cement. The authors reported a decrease in compressive strength in all mixes, except for the 20% SCW mix, which showed almost 94% of the control concrete's compressive strength. The authors indicated that the main cause for this decrease was the low pozzolanic activity of BBA and SCW, though more prominent in BBA. Concerning the flexural strength, mixes with SCW exhibited slightly higher values (2-9%) than those of the control concrete. This improvement in SCW mixes was attributed to the filler effect of SCW.

3 COAL BOTTOM ASH

Despite the numerous developments in the production of heat and energy, coal remains one of the main fuels used in thermal power plants worldwide, accounting for around 70% of all electricity produced[22, 23]. Nevertheless, the combustion of coal leads to the production of by-products, namely coal bottom ash (CBA) and FA. Five million tonnes of CBA were produced in Europe alone in 2018, while FA represented approximately 20 million tonnes in the same year also in Europe[24]. While FA is almost entirely consumed by several industries, such as in cement production, the less reactive CBA holds a considerable fraction without an adequate destination. Despite the numerous uses of CBA, ≈ 45% is used mainly for road pavement construction, used as aggregate in concrete masonry units and raw feed material for the production of Portland cement. The remaining 55% are deposited in landfills[22]. Replacing aggregates (fine and coarse) or cement in concrete production, as well as its combination with recycled aggregates from other sources, the use of CBA by the construction industry is considered a viable alternative to landfilling disposal.

3.1 Coal bottom ash properties

CBA's physical and chemical properties vary not only according to the source of the coal but also depend on day-to-day production of the power plant where the ash is produced. Naturally, this strongly affects its performance in concrete. CBA has a colour that can vary between grey and brown, although it can be completely black, and its shape is usually angular. CBA chemical composition can be considered similar to FA, presenting, however, a significantly reduced pozzolanic activity[25].

Depending on the composition of the coal used, CBA is usually less dense than NA of equivalent dimensions. Table 4 shows a survey of the main physical properties reported in different publications. Comparing the properties presented in Table 4 with those typically observed for aggregates used in concrete, it is possible to verify that the values for specific gravity and water absorption are lower and considerably higher, respectively. These differences are associated with the treatment conditions of CBA and necessarily dependent on the following factors: the lower iron content and higher carbon content of CBA for a lower specific gravity[26, 27]; more porous structure of CBA particles that cause not only an increase in water absorption but also a decrease in specific gravity[28].

Table 4 - Physical properties of CBA

Physical properties	Reference values		
	Maximum	Minimum	Average
Specific gravity	2.7	1.3	2.2
Water absorption [%]	31.6	2.1	12.1
Fineness modulus	2.1	1.5	1.8

Sources: Aggarwal *et al.*[29], Kou and Poon[30], Park *et al.*[31], Abubakar and Baharudin[32], Kadam and Patil[33], Aggarwal and Siddique[34], Singh and Siddique[35], Onprom *et al.*[36], Zhang and Poon[37], Argiz *et al.*[38], Ngohpok *et al.*[39], Mangi et al.[45], Singh *et al.*[40]

Regarding the chemical composition, it can be seen in Table 5 that CBA presents values above 70% of ($SiO_2 + Al_2O_3 + Fe_2O_3$) and CaO values below 7%, which corresponds to a class F fly ash according to ASTM-C618[41]. According to these conditions, CBA can be considered somewhat pozzolanic and, therefore, suitable to be used as constituents of concrete. In the same sense, the loss on ignition values are very low (maximum below 5.8%) with an average value of 3.1%.

Table 5 - Oxide composition of CBA from various studies

Chemical compound	Reference values (%)		
	Maximum	Minimum	Average
SiO_2	66.9	44.2	53.2
Al_2O_3	31.5	17.7	23.9
Fe_2O_3	12.4	4.8	8.6
CaO	11.5	1.6	4.6
MgO	4.9	0.4	1.6
K_2O	3.7	0.5	1.5
TiO_2	3.4	0.9	1.7
Ti_2O_5	1.5	1.5	1.5
SrO	0.4	0.4	0.4
P_2O_5	0.7	0.3	0.4
Na_2O	2.4	0.1	0.7
BaO	0.2	0.1	0.2
ZrO_2	0.2	0.2	0.2
Sulphates	2.5	0.7	1.3
Loss on ignition	5.8	0.9	3.1

Sources: Kou and Poon[30], Park *et al.*[31], Sani *et al.*[42], Awang *et al.*[43], Arenas *et al.*[10], Aggarwal and Siddique[34], Singh and Siddique[35], Zhang and Poon[37], Onprom *et al.*[36], Jang *et al.*[44], Argiz *et al.*[38], Mangi *et al.*[45], Kumar and Singh[46]

3.2 Performance of cementitious composites containing coal bottom ash

Regarding the use of CBA in concrete with recycled aggregates, few studies have been carried out. This section presents some results regarding the mechanical properties of concrete produced with CBA instead of natural aggregates, recycled aggregates or cement. The importance of the fineness of CBA on the properties of concrete is also addressed. Argiz *et al.*[38] replaced cement with CBA and FA from the same power plant, producing blends of cements with a composition similar to several commercial cements according to EN-197-1[2], namely: CEM II/A-V, CEM II/B-V and CEM IV/A(V). The authors observed a decrease in compressive strength with the increase in CBA and FA. The authors also observed a delay in cement activity in early ages for both CBA and FA. Mixes with CBA and a composition type CEM II/A-V and CEM II/B-V had a compressive strength evolution more favourable than the mix with a composition type CEM IV/A(V) corresponding to 35% replacement of cement with CBA. The authors identified 35% as the maximum limit for replacing cement with CBA (considering 28 days of age). The authors pointed out the lower reactivity of both CBA and FA as the main cause for the delay of the mixes' hydration reactions. Argiz *et al.*[38] indicated that both CBA and FA contributed to reducing the number of capillary pores as well as reducing their average size.

Mangi *et al.*[47] replaced 10%, 20% and 30% of cement with CBA ground for 20 h, 30 h and 40 h. Although it may have been the intention of the authors to produce very fine powders in order to increase reactivity and minimize strength loss, these grinding times are well beyond those that cement is typically subjected to and may significantly increase the cost of the material. In general, all mixes presented lower compressive strength values than those of the control without CBA. However, for a grinding time of 20 h and 30 h and with 10% CBA replacing cement, the compressive strength was equivalent to that of the control. For replacement levels of 20% and 30%, the decline in compressive strength was more significant, whereas replacement levels of 10% with 20 h and 30 h of grinding time showed greater potential. The results presented by Mangi *et al.*[47] are in line with those of other studies, such as Argiz *et al.*[38] and Mangi *et al.*[45]. The authors stated that the worst results of mixes with a higher grinding time (40 hours) were due to the fact that the finer particles of CBA have a larger specific surface area capable of absorbing more water from the mix, consequently causing an interruption of the hydration process. Therefore, it is possible to state that the physical properties of CBA are strongly conditioned by the grinding process and the CBA's specific surface area increased as the grinding time increased. Comparing the results obtained by the different types of CBA, Mangi *et al.*[45] concluded that they exhibited properties comparable with those of Portland cement. However, the 20 h grinding time was found to be a more appropriate and less expensive process for replacing cement in future studies.

Kou and Poon[30] replaced 25%, 50%, 75% and 100% of fine NA with recycled aggregates, crushed fine stone and CBA. With the increase in recycled aggregates and CBA contents, the authors observed a decrease in compressive strength. The main cause for this decrease was attributed to the high initial free water content used. This free water caused bleeding and thus weakening of the interfacial transition zone. In the same sense, Bai *et al*[48] observed a notable compressive strength decline with the incorporation of 30% of CBA replacing fine NA. In both investigations (Kou and Poon[30], Bai *et al.*[48]), the porous structure of CBA was identified as the main reason for the compressive strength decline. Regarding drying shrinkage, Kou and Poon[30] found that, for a water to cement ratio of approximately 0.50 ± 0.05, CBA mixes presented lower shrinkage strains than those of the control concrete, except for the 100% CBA mix. This enhanced performance was due to the high water absorption of CBA (i.e. 28.9%), which caused a gradual release of water to the cement matrix during the curing of concrete. Weber and Reinhardt[49] and Bentz and Snyder[50] stated that the same porous structure of CBA that limits the compressive strength can be very beneficial in reducing the drying shrinkage of concrete by means of the slow release of water contained in the particles' porous structure, causing an internal curing effect.

Singh *et al.*[40] studied self-compacting concrete with CBA replacing 10% of fine NA and coarse recycled aggregates replacing 25%, 50%, 75% and 100% of coarse NA. For replacement levels up to 50% of coarse recycled aggregates, there was no significant variation and the compressive strength was similar to that of the control concrete. For replacement levels over 50%, the authors found that the increase in recycled aggregate content caused a decrease in compressive strength of approximately 20%. Regarding the direct influence of CBA, the authors reported some improvement in the composites' mechanical performance possibly as a result of the waste's pozzolanic activity. The authors also mentioned that, for higher replacement ratios (75% and 100%) of coarse NA, the negative effect of recycled aggregates superseded the presence of CBA.

4 SEWAGE SLUDGE BOTTOM ASH

The treatment of sewage waste from households and commercial/industrial activities in wastewater treatment plants leads to the generation of a by-product - sewage sludge (SS). The total amount of sludges and liquid waste from waste treatment in the European Union amounted to around 10 million tonnes in 2018[51] and is expected to increase further with the progressive expansion of urban areas and their corresponding wastewater networks. This waste is generally disposed of in one of two ways:

recycled in agriculture and composting for nutrient recovery or land rehabilitation; and energy recovery[52]. The incineration with energy recovery is usually carried out on dewatered sludges to facilitate combustion and can reduce the volume of the waste by 90%[53]. However, the incineration of SS is a potential source of harmful compounds such as dioxins, furans, and heavy metals, which are present both in flue gases and in the residual ash[54]. The incineration of SS is known to result in two distinct by-products[55]: ashes from the air pollution control system and those obtained at the bottom of the furnace (fly ashes and bottom ashes, respectively). This distinction is not emphasized in the literature and studies often just refer to sewage sludge ash (SSA).

4.1 Sewage sludge bottom ash properties

Analysis of the characteristics of the ashes showed that most studies concern the use of bottom ashes, which are generally coarser (mean diameters ranging from 50-260 μm[56]), thereby requiring a milling treatment stage, and have SiO_2 as the major oxide, followed by Al_2O_3 and CaO (averages of the literature of about 34%, 14% and 13%, respectively[56]). Fly ashes, collected at the multi-cyclones and baghouse dust filters from air pollution control systems, are characterized by their relatively high CaO content, albeit with significant variation[55], from the hydrated lime injection treatment of the flue gases[55, 57]. One of such fly ashes from sewage sludge contains the following major oxides: CaO - 38.96%; SiO_2 - 22.46%; P_2O_5 - 10.74%; SO_3 - 5.67%; Al_2O_3 - 4.97%; Fe_2O_3 - 3.05[55, 57].

4.2 Performance of cementitious composites containing sewage sludge bottom ash

In the literature on mortar and concrete production, bottom ash from the incineration of SS has been used either as partial cement replacement or as natural aggregate substitute (i.e. recycled aggregate), though more research has been carried out in the former. In spite of some positive experiences on the use of SSA[58], the use of the by-product as partial cement replacement generally leads to a decline in performance[59], dependent on many factors. The most important parameter for the use of SSA as partial cement replacement is its pozzolanicity, which is a key factor in strength development as well as improved durability-related performance. Several studies on the strength activity index of mixes containing SSA up to 20% to 25% as partial cement replacement have largely shown signs of pozzolanic reactions with slower strength development[56]. In some cases, mixes with SSA have shown equivalent 28-day compressive strength[58, 60]. Furthermore, pozzolanicity has also been verified in SSA via the

Frattini test[60] and thermogravimetric analyses, in which progressive consumption of $Ca(OH)_2$ was observed with increasing SSA content[61, 62]. The reactivity of SSA is highly dependent on the temperature of the incineration[63-65] and the existence of a milling stage in the case of bottom ashes[66-68] (Figure 1).

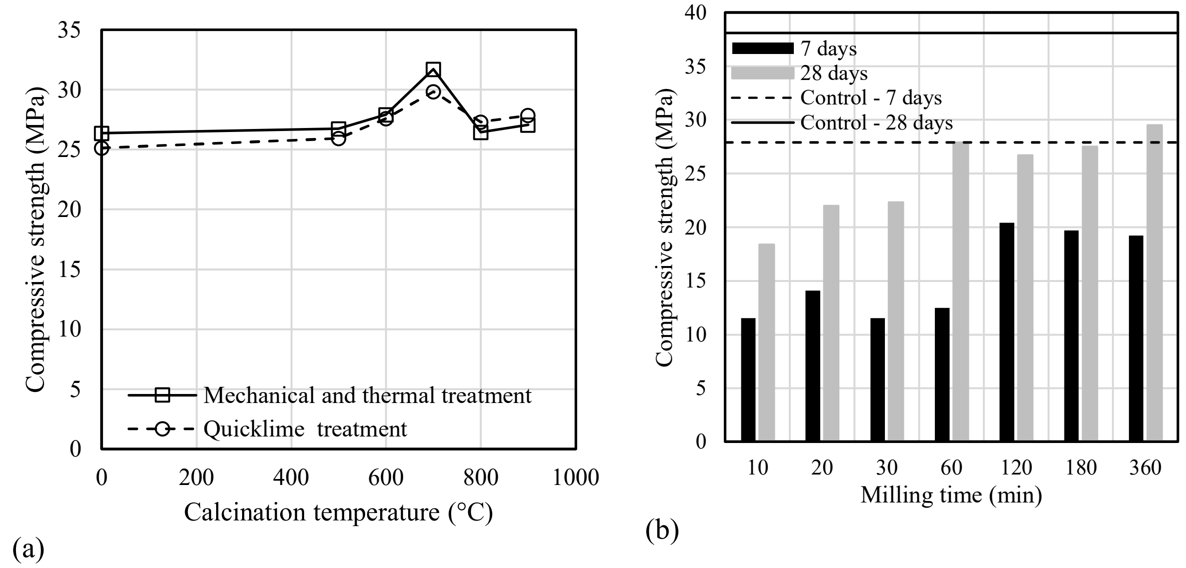

Figure 1 - Effect on the compressive strength of (a) calcination temperature (adapted from Cong et al.[65]) and (b) milling time (adapted from Pan et al.[67])

Higher temperatures are likely to produce a more reactive material[57]; Cong *et al.*[65] and Lu *et al.*[69] studied the effect of several calcination temperatures and observed that mixes with SSA exposed to 700-800 °C exhibited similar mechanical performance to that of the control concrete. A 30-min microwave treatment stage of dried SS was studied by Doh *et al.*[70] and the resulting mixes achieved equivalent 28-day compressive strength values for mixes with 5% SSA, but the performance declined for higher contents. Another treatment of SSA involves the extraction of phosphorous, which usually exists in high quantities in this waste and can extend the initial and final setting time considerably[66, 71]. Electrodialytic separation is capable of extracting up to 90% of the existing phosphorous in SSA and may improve strength development depending on the treatment duration[72].

Concerning the milling treatment stage, it has been observed that it decreases the fineness of SSA particles thus mitigating strength loss with increasing SSA content. Pan *et al.*[67] studied the effect of SSA fineness on several properties of mortars. As the specific surface area increased with increasing milling time (up to 360 min), initial and final setting times increased, slump flow increased, and strength activity index also increased. Krejcirikova *et al.*[73] have found that the use of 30% ground SSA led to a strength reduction around 35%, whereas mortars with unground SSA showed up to 65% reduction in comparison with control specimens. Others have also observed that the use of up to 30%

milled bottom SSA as partial cement replacement was found to result in a linear strength decline of almost 30% after 90 days[66, 74].

The partial substitution of Portland cement with SSA generally results in a decline of the workability of mortar, which can be explained by two factors: the irregular morphology of SSA particles; and the high water absorption of SSA. Because of these two factors, when adding superplasticizers, it is possible to observe a considerable loss in effectiveness with increasing SSA content (Figure 2) likely due to their adsorption in SSA particles' surface[75].

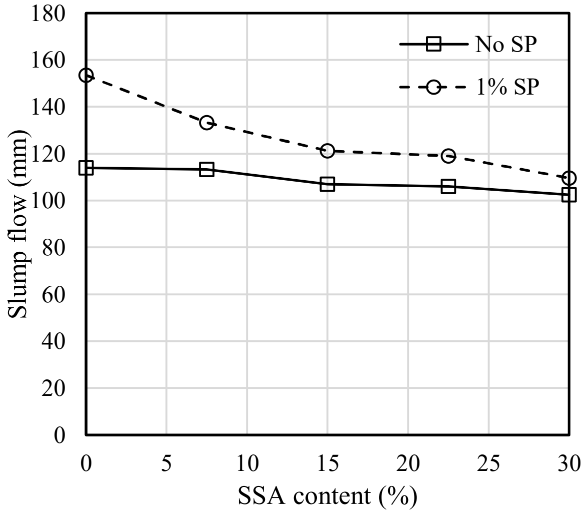

Figure 2 - Slump flow of mixes without and with 1% superplasticizer (adapted from Monzo et al.[75])

Concerning the durability of cementitious composites containing SSA, it was found that mixes made with the ash are likely to show a higher shrinkage than control mixes[76], and more so with increasing ash content (30% SSA led to shrinkage increase of over 40% [74]) and as the size of the addition decreases[60]. Nevertheless, it was also noticed that the performance of specimens subjected to high temperatures (i.e. higher residual compressive strength) may improve in the presence of the ash[62]. Additionally, due to the pozzolanicity of milled SSA, mixes containing it are likely to exhibit lower expansion due to alkali silica reaction when compared with the control concrete[76].

Concerning the use of bottom SSA as fine aggregate replacement, little research has been carried out. However, existing findings point towards a decline in performance with increasing content; the incorporation of 20% bottom SSA as aggregate led to a decrease of about 25% in the 28-day compressive strength with a similar trend observed in the flexural strength and in the water absorption by capillary action[77]. This worse performance is likely due to the considerable porosity of SSA[78]. Nevertheless, positive experiences have been reported in the production of concrete paving blocks[79] and using them in a bound form is better in terms of the materials' leaching behaviour when compared to its use in an unbound application[80].

Even though the scope of this paper concerns the use of bottom ashes as partial cement replacement or as aggregate in cementitious composites, it is worth mentioning the influence of using fly ash from the incineration of SS to highlight the differences between the two materials. Nakic *et al.*[57] evaluated the effect of such fly ashes (90% CaO) treated to temperatures of 800-1000 °C on the properties of mortar and concrete mixes and observed that ashes subjected to higher temperature treatment led to mixes with mitigated strength loss; nevertheless, the use of 20% SSA as partial cement replacement resulted in almost 30% loss in the 28-day compressive strength. In the study of Rutkowska *et al.*[81], the fly ashes contained 25.5% of SiO_2, 19.4% of CaO and 19.0% of Al_2O_3 and presented an average particle size of about 50 μm. All mixes with up 25% SSA showed comparable or slightly higher compressive strength than that of the control concrete. Rutkowska *et al.*[82], in another study, demonstrated that mixes with fly ashes from SS presented an equivalent performance in compressive strength, freeze-thaw resistance and leaching behaviour to mixes with either low and high calcium FA from coal power plants as well as control cement mixes. Similar findings were observed by Salihoglu and Mardani-Aghabaglou[55] when studying the influence of SSA from multi-cyclones and baghouse dust filters; water absorption of mortars was similar to or lower than that of the control and reasonable strength activity index had been achieved after 28 days (i.e. ~85%) with an 8% loss in 90-day compressive strength. Nevertheless, it has been observed that there are some cases wherein the SSA may exhibit poorer performance and fail to comply with EN-450-1[83] on FA for concrete. Such variations in performances are linked with the composition of the feed waste in the incinerators as well as the treatment process of the air pollution control systems.

5 CONCLUSIONS

The construction industry is undoubtedly one of the sectors with the highest environmental impact due to numerous factors including extraction of natural resources, consumption of water, energy expenditure, generation of waste, and emission of CO_2. In this sense, it is essential to find more sustainable solutions, not only through the application of new techniques and new construction technologies but also through the application of new, more efficient materials as well as by the reuse of waste from both the industry itself and sub-industry products from other economic activities. One of the most feasible approaches to reduce the ecological footprint within the construction sector is to use industrial by-products as partial replacement of cement or even as an aggregate substitute. In this sense, among the additions with potential to be used in the production of concrete, this study focused on bottom ashes from the incineration of biomass, coal and sewage sludge, all of which still represent an environmental issue given the amounts produced worldwide and that are sent to landfills.

Regarding the effects of the combined use of the aforementioned bottom ashes with recycled aggregates from other sources, the literature largely suggests an overall decline in mechanical performance. In general, these ashes have higher porosity and a lower level of pozzolanicity in comparison, for example, with conventional FA. In addition, it should also be noted that recycled aggregates, mainly from construction and demolition wastes, are also widely known to have lower performance than NA, essentially due to the adhered mortar, and when combined with the bottom ashes are likely to increase the water requirement of concrete due to the higher porosity of both components.

Overall, the use of biomass bottom ashes is likely to result in a generalized decline in performance essentially derived from the presence of lightweight particles. In addition to this, it is also worth mentioning the boiler type and size, the subsequent ash treatments and mainly the type of wood are factors that strongly influence the final properties of the ashes and thus on the resulting concrete. This variability limits the process of specification and needed regulation of this material.

In the case of coal bottom ashes, its positive influence on the performance of concrete should be noted when used as sand replacement. The water stored in the porous microstructure of the ash particles causes an internal curing effect in concrete leading to a significant decrease in drying shrinkage strain. This fact can represent a significant added value in the production of concrete prone to present significant deformation due to shrinkage, such as in concrete with recycled aggregates.

Concerning the use of sewage sludge bottom ashes, it can be said that relatively little research has been carried out considering the potential of the material for the production of cementitious composites. Even though the ash is likely to exhibit lower pozzolanicity when compared to conventional FA, they have, nevertheless, shown interesting strength activity indexes, adequate strength development over time and reasonable durability-related performance. Oddly enough, studies in the literature rarely distinguish bottom ashes from fly ashes coming from the incineration of SS, which results in an incorrect categorization of two considerably different materials. Existing findings on fly ashes from SS, which are severely underresearched, suggest that the material already presents an adequate particle size and specimens containing them may demonstrate notable strength development due to pozzolanic reactivity.

In spite of the performance losses with increasing incorporation of the aforementioned types of bottom ashes, it is possible to foresee some potential within an optimal incorporation interval in high-end applications, including those in structural concrete. Their use, and of other similar by-products, is especially important considering the ongoing decommissioning of coal-fired power plants, by favouring more sustainable alternatives, and the subsequent phasing out of FA.

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