Chapter 12

Mechanical properties of recycled aggregate concrete with bottom ash additions

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 chapter presents a literature review on the influence of using bottom ashes in the properties of recycled aggregate concrete. Three types of bottom ashes are analysed: coal bottom ashes; municipal solid waste incinerator bottom ashes; and biomass bottom ashes. Their physical, chemical and mineralogical properties are discussed, as well as their effect on the fresh, mechanical and durability-related performances of concrete. Bottom ashes from incineration of municipal solid waste or biomass waste, usually exhibit extensively varying chemical compositions, due to the variability of the input waste (i.e. different kinds and amounts of waste materials from households - aluminium cans, batteries, ceramic and glassware, etc. - and different species of wood and/or plants - pine, mahogany, olive husk or kernel, wheat straw, etc.). Bottom ashes can exhibit some pozzolanicity, though less than that observed in conventional coal fly ash, which can mitigate part of the decline in performance that is typically observed when using them. These industrial by-products, when used in high amounts and in conjunction with recycled aggregates, are likely to result in a combination of negative effects, leading to a significant decline in performance. However, in moderate contents, adequately processed bottom ashes from municipal solid waste can enhance the mechanical performance of concrete, as well as the resistance to chloride ion penetration. The use of coal bottom ashes was also found to significantly reduce the drying shrinkage strains of concrete.

Keywords: recycled aggregates, concrete, bottom ash, coal, biomass, municipal solid waste.

6.1 Introduction

A tremendous effort has been placed on the research for more sustainable construction practices given the ongoing economic growth of developing countries and subsequently their intensive construction activities. The incorporation of different 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 essential part of this issue, as it constitutes a cost-effective waste management solution and provides the cement industry with additions capable of replacing cement, the production of which is highly energy-intensive.

FA from coal combustion, for example, are obtained by electrostatic or mechanical precipitation of the dust dragged from the combustion gases from the burning of boilers fed with pulverized coal (essentially from thermoelectric power plants), according to EN-450-1 (2012). The FA are in the form of spherical particles with a diameter between 1 and 100 μm, with approximately 50% of them below 20 μm, which represents an average diameter of about 7 to 12 μm. FA is a material made of approximately 60% of a binary oxygen and silicon compound, silicon dioxide (SiO_2) and 30% aluminium oxide (Al_2O_3) in an essentially amorphous form. FA show some degree of pozzolanicity, reacting with calcium oxide (CaO) or with calcium hydroxide ($Ca(OH)_2$) in the presence of water at room temperature (Wesche, 1991, Siddique, 2007). It is without a doubt the most common artificial pozzolana in the world (Neville, 2011). According to Bilodeau and Malhotra (2000), 600 million tonnes/year of FA are produced worldwide and only approximately 10% are used in the manufacture of concrete, with a significant part of them, approximately 80%, landfilled, causing serious environmental problems. The remaining 10% is used in secondary applications, essentially as a filler for roads.

The aforementioned addition is currently one of those recognized in EN-197-1 (2011) for the specification of common cements. However, since there is a progressive decommissioning of coal power plants, the use of FA will phase out over the next few years in many countries. For this reason, there is considerable promise in using other potentially pozzolanic additions to replace cement and bottom ashes have been identified as adequate alternatives. Three types of bottom ashes are produced in enough quantities to answer the demand of the cement industry: coal bottom ashes; municipal solid waste incinerator bottom ashes; and biomass bottom ashes. The use of such industrial by-products in the production of concrete is essential for four main factors, namely:

- It can lead to the reduction of energy consumption during cement production;
- It lowers CO_2 emissions associated with cement production;
- It may represent a reduction in the extraction of natural resources for the production of cement and/or natural aggregates (NA);
- It makes waste management more efficient.

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

6.2 Coal bottom ash

Coal is a material used worldwide as one of the main sources of energy production, and is generally quite heterogeneous and somewhat complex because of a series of transformation processes, not only biological, but also physical and chemical. Coal is the second largest fuel source to produce electricity worldwide, at around 27% in 2018, after oil (IEA, 2020). Despite the numerous advances in the production of electricity, heat and energy, coal remains one of the main fuels used in thermal power plants worldwide, accounting for approximately 70% of all electricity produced (Singh, 2018). However, the combustion of coal leads to the production of by-products including FA and bottom ash (CBA). In 2008 alone, five million tonnes of CBA were produced in Europe alone (Feuerborn, 2011). At the initial phase of using coal for electricity production, the remaining ash was seen as a waste about which little was known and most of it was disposed of in landfills. Currently, as a result of numerous studies, these ashes are reused as by-products mainly by the construction industry, which have shown a significant receptivity to their application in more sustainable uses (Ramme and Tharaniyil, 2013). Despite the numerous uses of CBA, approximately 55% (IEA, 2020) of this material is still deposited in landfills with the remaining 45% reserved mainly for transportation applications, used as aggregate in concrete masonry units and raw feed material for the production of Portland cement (Feuerborn, 2011). In transportation, its use is very diverse, ranging from structural fills, road base material, ice control products, among others. The use of CBA by the construction industry, through the production of concrete by replacing fine and coarse aggregates, by replacing cement and more recently in concrete produced with recycled aggregates, is thereby a real alternative to the landfilling of this industrial waste.

The two types of ash mentioned (i.e. coal FA and CBA), resulting from the burning of coal, should not, however, be confused with each other. On the one hand, CFA represents the portion of ash that escapes with the flue gas, whereas CBA is the non-combustible residues that settle at the bottom of a furnace. CFA constitutes about 80% of total coal ash while CBA represents nearly 20% of total coal ash (Singh, 2018). Comparing these ashes, it should be noted that CBA does not yet have the same level of implementation of its use in the construction industry when compared to CFA. While CFA is significantly used in the production of composite cements, CBA has had a more alternative use, mainly as aggregates in the production of concrete and road pavement construction, among others (Ramme and Tharaniyil, 2013).

6.2.1 Physicochemical properties of coal bottom ash

The surface of CBA is usually of angular shape and has a colour that can vary between brown and grey, although it can be completely black. In general, CBA has a chemical composition that can be considered similar to CFA's, without, however, presenting a significant pozzolanic reaction (Ramme and Tharaniyil, 2013). CBA's physical and chemical properties vary not only according to the source of the coal but also depending from day-to-day production of the power plant where the ash is produced. Naturally, this strongly affects its performance in concrete.

CBA is usually less dense than natural aggregates of equivalent dimensions, but this property can vary significantly depending on the composition of the coal used. Regarding the main physical properties, Regarding water absorption, the values collected vary between 2.1% and 31.6% with an average of 12.1%, and are considerably higher than those usually observed in aggregates for concrete production (≈ 1% to 2.5%). This variability is associated with the treatment conditions of CBA. The main causes for these values are associated with factors including: CBA's lower iron content and higher carbon content for a lower specific gravity (Benson and Bradshaw, 2011, Chindaprasirt et al., 2009); more porous structure of CBA particles that cause not only an increase in water absorption percentage but also a decrease in specific gravity (Lovell et al., 1991).

Table 1 and **Error! Reference source not found.** show a survey of the most common values reported in different works and thus corresponding to different origins. The typical specific gravity values vary between

1.30 and 2.66 with an average of 2.19. It is found that the referred average value is lower than that usually observed in aggregates used for concrete production (≈ 2.5 to 2.7).

Regarding water absorption, the values collected vary between 2.1% and 31.6% with an average of 12.1%, and are considerably higher than those usually observed in aggregates for concrete production (≈ 1% to 2.5%). This variability is associated with the treatment conditions of CBA. The main causes for these values are associated with factors including: CBA's lower iron content and higher carbon content for a lower specific gravity (Benson and Bradshaw, 2011, Chindaprasirt et al., 2009); more porous structure of CBA particles that cause not only an increase in water absorption percentage but also a decrease in specific gravity (Lovell et al., 1991).

Table 1 - Physical properties of CBA in various studies

Publication	Specific gravity	Water absorption (%)	Fineness modulus
Aggarwal et al. (2007)	2.66	12.0	
Kou and Poon (2009)	2.19	28.9	1.83
Park et al. (2009)[a]	2.41	2.43	-
Park et al. (2009)[b]	2.48	2.11	-
Abubakar and Baharudin (2012)	1.90	19.0	-
Kadam and Patil (2013)	1.93	10.1	
Aggarwal and Siddique (2014)	1.93	-	1.60
Singh and Siddique (2014)	1.30	31.6	
Onprom et al. (2015)	2.10	6.18	2.10
Zhang and Poon (2015)	2.21	11.2	-
Argiz et al. (2017)	-	-	-
Ngohpok et al. (2018)	2.19	2.80	-
Mangi et al. (2019b)[c]	2.41	-	-
Mangi et al. (2019b)[d]	2.44	-	-
Mangi et al. (2019b)[e]	2.50	-	-
Singh et al. (2019)	2.08 ± 0.02	6.80 ± 0.55	1.50 ± 0.02

[a] grading 5-13 mm
[b] grading 13-20 mm
[c] CBA ground for 20h
[d] CBA ground for 30h
[e] CBA ground for 40h

Table 2 - Particle size distributions of coal bottom ash according to different authors

Sieve size (mm)	Cumulative percentage passing (%)				
	Kou and Poon (2009)	Awang et al. (2011)	Abubakar and Baharudin (2012)	Zhang and Poon (2015)	Singh et al. (2019) and Kumar and Singh (2020)
37.5	-	-	-	-	-

20.0	-	-	-	-	-
14.0	-	-	-	-	-
10.0	-	-	-	100	100
5.00	100	100	100	83	91
2.36	95	70.0	70	61	69
2.00	-	64.4	63	-	60
1.18	80	45.2	43	46	44
0.850	-	36.4	37	-	31
0.600	64	29.6	30	36	24
0.500	-	26.4	24	-	-
0.425	-	24.4	21	-	18
0.300	57	18.8	20	28	12
0.150	40	8.8	10	19	-
0.075	3	5.6	-	-	2

It is possible to observe some differences in the chemical composition of CBA according to their origin. In Table 3, CBA presents values of SiO_2+Al_2O_3 + Fe_2O_3 significantly higher than 70% (average in consulted works = 85.63%) and a CaO content mostly below 7% (average in works consulted = 4.29%), which corresponds to a class F fly ash according to ASTM-C618 (2019). Under these conditions, according to ASTM-C618 (2019), this CBA can be considered, in general, as having pozzolanic properties and, therefore, suitable to be used as constituents for the concrete production, either in substitution of aggregates or also in partial replacement of cement. In the same sense, the loss on ignition (LOI) values are very low, always below 6%, varying between 0.89% and 5.80% and with an average value of 3.10%.

Table 3 - Oxide composition (%) of CBA from various studies

Publication	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	K_2O	TiO2	Ti_2O_5	C	SrO	P_2O_5	Na_2O	BaO	ZrO_2	SO_3	SO_4	Cl	LOI
Kou and Poon (2009)	60.7	18.3	6.56	3.25	1.28	2.12	0.95	-	-	-	-	0.89	-	-	0.82	-	-	4.13
Park et al. (2009)	47.9	25.9	4.76	2.48	1.10	0.67	0.86	-	-	-	-	1.38	-	-	-	-	-	-
Sani et al. (2010)	54.8	28.5	8.49	4.20	0.35	0.45	2.71	-	-	-	0.28	0.08	-	-	-	-	-	2.46
Awang et al. (2011)	46.6	26.1	12.4	8.31	1.26	1.34	1.84	-	-	-	0.62	0.62	0.13	-	-	-	-	-
Arenas et al. (2013)	52.3	25.1	9.23	2.37	1.84	3.72	1.45	-	-	-	0.25	0.66	-	-	0.03	-	-	1.07
Aggarwal and Siddique (2014)	57.8	21.6	8.56	1.58	1.19	1.08	-	-	-	-	-	0.14	-	-	0.02	-	0.01	5.80
Singh and Siddique (2014)	56.4	29.2	8.44	0.75	0.40	1.29	3.36	-	-	-	-	0.09	-	-	0.24	-	-	0.89
Zhang and Poon (2015)	52.1	18.3	12.0	6.61	4.85	1.57	0.87	-	-	-	-	2.43	-	-	-	0.72	-	4.13
Onprom et al. (2015)	46.0	22.3	10.6	11.5	3.45	2.37	-	-	-	-	-	0.07	-	-	1.76	-	-	4.03
Jang et al. (2016)	44.2	31.5	8.90	2.00	2.60	-	2.40	-	-	-	-	-	-	-	-	-	-	-
Argiz et al. (2017)	52.2	27.5	6.00	5.90	1.70	0.6	-	1.53	-	-	0.74	-	-	-	0.13	-	0.001	1.80
Mangi et al. (2019a)	53.8	18.1	8.70	5.30	0.58	0.85	1.20	-	0.10	0.35	0.29	0.17	0.18	0.15	0.90	-	-	4.02
Kumar and Singh (2020)	66.9	17.7	6.50	1.56	0.51	-	-	-	-	-	-	-	-	-	-	-	-	2.65

6.2.2 Fresh, mechanical and durability-related performance in concrete

Regarding the use of CBA in concrete with RA, few studies have been carried out. Kou and Poon (2009) produced concrete, where they replaced 25%, 50%, 75% and 100% of fine natural aggregates (FNA) with crushed fine stone, CBA and fine RA. The authors highlighted the decrease in compressive strength with increasing fine RA and CBA contents. The authors identified the high initial free water content used as the main cause for the decrease, which caused bleeding and the weakening of the aggregate-cement paste bond. In the same sense, Bai et al. (2005) stated that, in concrete with CBA replacing FNA, after 30% of replacement, a compressive strength decline was noticeable. Like Kou and Poon (2009), Bai et al. (2005) identified the porous structure of CBA as the main cause for the compressive strength decline. Kou and Poon (2009) also studied the drying shrinkage of these concrete mixes and found that, for a W/C ratio of approximately 0.50 ± 0.05, mixes with CBA presented lower shrinkage strains than that of the control concrete, except for the mix with 100% CBA. This trend can be directly attributed to the behaviour of CBA, which, due to its high water absorption (i.e. 28.9%), gradually released water to the cement paste matrix during the curing of concrete, thereby significantly decreasing the drying shrinkage. Regarding drying shrinkage, Kou and Poon (2009) found that CBA presented lower drying shrinkage in all mixes when compared to fine RA (except for mixes with 100% CBA). In the same sense, Weber and Reinhardt (1997) and Bentz and Snyder (1999) reported that the same CBA porous structure that compromises 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 CBA porous structure, causing an internal curing effect.

De Maeijer (2013) carried out a study on RAC (RA fractions 4/8 mm and 8/11.2 mm) from original concrete, where cement was replaced with CBA and waste glass powder. The author stated that the influence of CBA on the quality of RA is notoriously positive, with emphasis on the superior values of compressive strength in mixes with CBA relative to the other wastes used, though the values were lower than that of control concrete.

Ngohpok et al. (2018) studied pervious concrete containing RA and CBA instead of NA. The authors observed a decrease in compressive, flexural, and splitting tensile strengths with an increase in CBA content when compared to the control concrete. The authors pointed out the large amount of voids in CBA as the main cause for the decline. Comparing the mixes with RA and CBA, it is found that, in the compressive strength, the differences are minimal in the mixes with 40% and 60% substitution. However, in the mix with 100% CBA, a slightly higher compressive strength was observed relative to the mix with RA. In terms of flexural and splitting tensile strengths, the differences obtained between the mixes with RA and CBA are minimal, with no significant influence of RA and CBA on the performance of pervious concrete being detected.

Singh et al. (2019) studied self-compacting concrete prepared with CBA and RA replacing 10% of FNA and 25%, 50%, 75% and 100% of can, respectively. Regarding the mechanical behaviour, the authors evaluated the compressive and the tensile strength at 28, 56 and 91 days of age. In general, the authors found that the increase in RA caused a decrease in compressive strength. However, for the replacement levels up to 50%, there was no significant variation and the compressive strength remained in the same order of magnitude as the control concrete. This reduction, of approximately 20%, was reported for mixes with 75% and 100% substitution for RA. Regarding the direct influence of CBA on SCC mixes, the authors reported some improvement from the expected outcome. Singh et al. (2019) highlighted the possible additional pozzolanic activity due to the presence of CBA with the main cause for the improvement (albeit slight ≈ 7%) of the compressive strength compared to the control concrete. The referred improvement associated with the presence of CBA was observed in mixes with lower and intermediary RA content. In this study, the authors also mentioned that, for higher substitution ratios (75% and 100%) of NA with RA, the negative effect of RA superseded the presence of CBA, causing a reduction in compressive strength. All the referred trends observed by the authors were common to all test ages. Regarding tensile strength, Singh et al. (2019) reported results with trends equivalent to those obtained for compressive strength. Kumar and Singh (2020) performed a similar work on the influence of recycled concrete aggregates and CBA on various properties of high-volume fly ash self-compacting concrete , where they replaced the fine NA with 10% CBA and the CNA with 25%, 50%, 75% and 100% coarse RA. The authors observed the same trends as Singh et al. (2019) and presented similar conclusions.

Siddique et al. (2012) stated that the most common substitution ratios of fine NA with CBA are between 10% and 30%. Ibrahim et al. (2015) mentioned that the optimal replacement ratio of fine NA with CBA is 10% (by weight). Other authors mentioned that for replacement ratios between 10% and 20% the general mechanical behaviour of the concrete presented a significantly improved performance (Abidin et al., 2014, Ibrahim et al., 2015). In this sense, Aggarwal and Siddique (2014) pointed out that the main reasons for the referred advantage in replacing fine NA with CBA in the referred ratios are essentially due to the similar particle size distribution of both and to the additional pozzolanic properties of CBA.

Argiz et al. (2017) presented a study made on mortars, where they directly replaced cement with CBA and CFA (from the same power plant), producing blended cements with a composition similar to CEM II/A-V, CEM II/B-V and CEM IV/A(V), according to EN-197-1 (2011). The control concrete was produced with CEM I 42.5 N. The authors observed that, for increasing CBA and CFA contents, the compressive strength decreased. However, at 28 days of age, all mixes reached the minimum value of 32.5 MPa established in EN-197-1 (2011). The authors also observed a delay in cement activity in early ages in mixes of both CBA and CFA. The compressive strength evolution was more favourable in mixes with CBA and a composition type CEM II/A-V and CEM II/B-V than in the mix with CEM IV/A(V) with 35% replacement of cement with CBA. Taking 28 days of age as a reference, the authors singled out 35% as the maximum limit for replacing cement with CBA. As expected, the authors emphasized the lower reactivity of both CBA and CFA, which obviously caused a delay in the hydration process of cement. Regarding the microstructure development, Argiz et al. (2017) stated that both CBA and CFA contributed to reducing the number of capillary pores as well as reducing their average size. In general, the authors pointed out that CBA presented very promising results to produce blended cements with replacement ratios of up to 35%.

Mangi et al. (2019b) replaced 10%, 20% and 30% of cement with CBA with three levels of CBA grinding (20, 30 and 40 hours). The authors observed that, in general, all mixes have lower compressive strength values than that of the control without CBA. However, concrete with a grinding time of 20 and 30 hours and with 10% CBA replacing cement showed compressive strength values equivalent to that of the control (after 7 days, control, the mix with 10% CBA milled for 20 h and the mix with 10% CBA milled for 30 h presented compressive strength values of 27.3 MPa, 29.4 MPa and 29.4 MPa, respectively). The authors pointed out that, for 20% and 30% of replacement levels, the decline in compressive strength was more significant, thus replacement levels of 10% with 20 and 30 hours of grinding time showed greater potential. The results presented by Mangi et al. (2019b) are in line with those of other studies, such as Argiz et al. (2017) and Mangi et al. (2019a). The authors stated that the worst overall performance of mixes with a higher grinding time (40 hours) is due to the fact that the finer particles of CBA have a larger available specific surface that absorbs more water from the mix, consequently causing an interruption of the hydration process.

Mangi et al. (2019a) evaluated in detail the effect of the grinding process of CBA on the properties of cement pastes. The authors evaluated grinding times of 2, 10, 20 and 40 hours in cement pastes with 10%, 20% and 30% replacement levels of cement with CBA. The authors stated that the grinding process significantly affected the physical properties of CBA. Naturally, the CBA's specific surface area increased as the grinding time increased. Mangi et al. (2019a) compared the results obtained by the different types of CBA and concluded that they exhibited properties comparable with those of Portland cement. However, considering the economic aspect of the process, the 20 h grinding time was found to be more suitable for replacing the cement for the next studies, though it is also considered relatively high. The authors also pointed out that the initial and final setting times of mixes containing CBA was considerably higher than those of ordinary cement paste, although almost similar values were observed for 10% cement replacement with CBA.

6.3 Municipal solid waste incinerator bottom ash

Municipal solid waste (MSW) is produced in vast quantities worldwide, with an output approaching 1.3 billion tonnes per year in 2012 and this is expected to increase to 2.2 billion tonnes per year by 2025. This represents a significant increase in waste generation per capita, from 1.2 to 1.42 kg per person per day (Hoornweg and Bhada-Tata, 2012). In the incineration of MSW, municipal incinerated bottom ash (MIBA) is the most significant by-product, accounting for 85% to 95% of the residual wastes remaining after combustion (Chandler et al., 1997).

6.3.1 Physicochemical properties of municipal solid waste incinerator bottom ashes

The average composition of MSW varies across regions, which influences the chemical composition of MIBA. A previous study showed that the larger fractions typically found in MSW are organic matter, paper and cardboard, plastics, glass, metals and textiles (Dhir et al., 2018). The organic fraction tends to be higher in low-income countries (64%) compared to high-income countries (28%). MSW from East Asia and the Pacific region had the highest organic waste fraction of around 62%, which is significantly higher than the 27% content determined for OECD countries. OECD countries exhibited the highest amount of disposed paper, glass and metals in the MSW stream, with contents of 32%, 7% and 6%, respectively, compared to the corresponding lowest contents of 4%, 1% and 1%, respectively in the South Asia region (Hoornweg and Bhada-Tata, 2012). The factors that influence the composition of MSW are related to the diversity of cultures, waste management policies or specific economic activities in different regions, which result in an increased/decreased disposal of a particular component of the waste (Burnley, 2007).

Concerning the minerology of MIBA, quartz has been identified as the most abundant mineral, followed by calcite, hematite, magnetite and gehlenite. The chemical composition plays a fundamental role in assessing the potential reactivity of MIBA after grinding when using it as a cement component. The oxide composition of MIBA has been determined routinely in most studies providing a wide-ranging worldwide collection of data. The most abundant oxides are SiO_2 (37.4%), CaO (22.2%), Al_2O_3 (10.2%) and Fe_2O_3 (8.3%). Na_2O (2.8%), SO_3 (2.7%), P_2O_5 (2.3%), MgO (2.0%) and K_2O (1.4%) have also been identified in smaller quantities (Dhir et al., 2018). The sum of these three oxides makes up, on average, 70% of the total oxide content of MIBA. **Error! Reference source not found.** presents a ternary diagram of 20 unique compositions of MIBA samples selected from different studies (Zhu et al., 2019, Rożek et al., 2019, Zhu et al., 2018, Giro-Paloma et al., 2017, Chen et al., 2016, Zhu et al., 2016, Song et al., 2015, Kim and Kang, 2014, Lancellotti et al., 2013, Galiano et al., 2011, Krausova et al., 2012, Onori et al., 2011, Qiao et al., 2008, Qiao et al., 2008b, Huang et al., 2019, Huang et al., 2018, Liu et al., 2018, Wongsa et al., 2017, Garcia-Lodeiro et al., 2016, Jing et al., 2007, Penilla et al., 2003, Xuan et al., 2019).

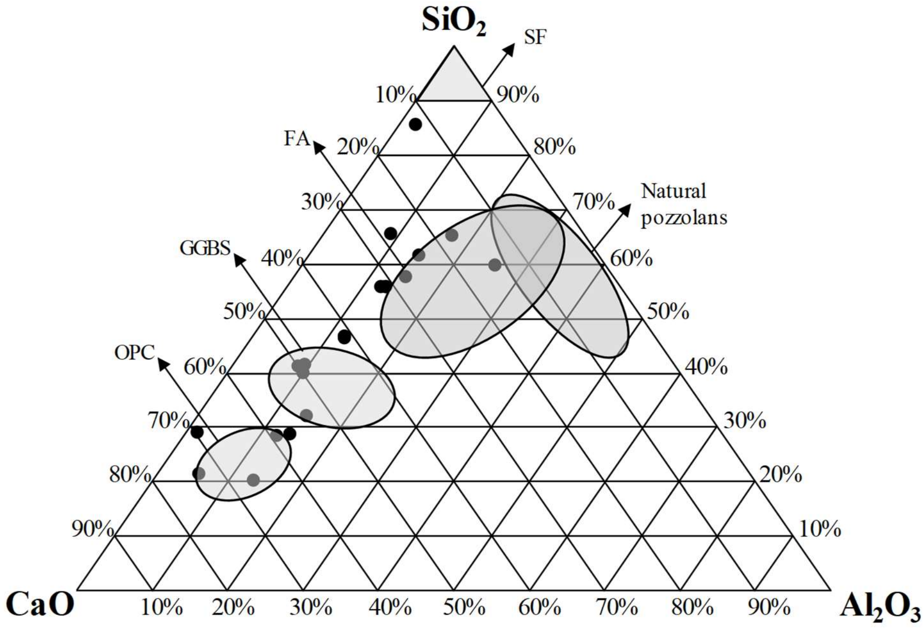

Figure 1 - Ternary diagram SiO_2-CaO-Al_2O_3 of MIBA

It is obvious that there is a considerable scatter in the results, wherein some samples have a composition equivalent to that of ordinary Portland cement (OPC), and others to GGBS and FA. Again, this variability can be attributed to the considerably different MSW fed into the incinerator, which in turn is influenced by cultural and economic issues and waste management policies. Even though the Al_2O_3 content can be relatively high in MIBA, it is most likely present in the form of metallic aluminium, which can lead to damaging expansive reactions in the alkaline conditions of hydrated cement. ASTM-C618 (2019), on the requirements of coal fly ash use in concrete, dictates that the sum of SiO_2 + Al_2O_3 + Fe_2O_3 should be a minimum of 50% for class C and 70% for classes N and F. Most MIBA samples satisfy the former requirement but not the latter. MIBA typically has a specific gravity of 2.35 (Dhir et al., 2018), which places the material around the standard 2.3-2.5 range for normal aggregate, though less dense than the typical 2.65 value for natural sand, but above the 2.15 value for furnace bottom ash (Torii et al., 1986) produced at coal-fired power stations.

6.3.2 Fresh, mechanical and durability-related performance in concrete

The use of MIBA has been studied as replacement of 10%-30% of cement, which is equivalent to the range of FA content typically incorporated in concrete. Before its use, MIBA must be pre-treated in a grinding process to ensure a fine enough state that is equivalent to cement. The option of thermal treatment of MIBA has also been explored despite its obvious environmental impacts (Cheng, 2012, Lo et al., 2020). Regarding the fresh properties of concrete, mixed findings have been reported. In fresh concrete mixes containing 30% MIBA as cement replacement, increases in slump were reported when the MIBA was ground under dry conditions, and the opposite was observed when ground in wet conditions (Bertolini et al., 2004). This was attributed to the increased fineness and associated higher water demands of the latter MIBA. The results of Czop and Lazniewska-Piekarczyk (2020), who have used equivalent contents of MIBA, showed that there was also a slight increase in slump. In the study of Cheng Cheng (2012), the results of concrete containing MIBA ground to two different levels of fineness showed that the finer sample resulted in a slightly lower slump but both comparable to that of the control. Additional thermal treatment up to 1450 ºC, which vitrified the sample, led to further minor improvements in the workability, due to a reduction in the organic content, smoother surfaces and the rounding effect on the particle shape associated with the melting and grinding processing. In the study of Jurič et al. (2006), wherein MIBA was used as partial cement replacement (15% by weight) and mixed recycled aggregates (RA) as NA substitute (up to 23.1% by weight). The use of MIBA led to a reduction of 50% in slump, starting from an initial slump of 105 mm. As the RA content increased, the slump decreased considerably (down to 15 mm), due to its high porosity and water absorption as well as rough and irregular shape. The use of both MIBA and RA led to a combination of effects resulting in zero slump.

The setting time of MIBA-containing concrete is also likely to be affected. Chen and Yang (2017) studied the effects of incorporating 20% MIBA with different particle sizes as partial cement replacement. These ranged from over 6.3 mm to under 0.075 mm. As the replacement level increased, the setting time also increased; the control mix containing only cement showed initial and final setting times of 264 min and 380 min, respectively, whereas the mix with 20% MIBA with size under 0.075 mm showed 867 min and 989 min, respectively. Others also noted increased setting times (Yang et al., 2018), though not as prominent (initial and final setting times of control vs. 50% MIBA of 190 min and 236 min vs. 246 min and 302 min, respectively). The authors also noticed a different hydration behaviour (Chen and Yang, 2017). There was a significant delay of onset of acceleration reaction of C_3S hydration and reduced maximum heat hydration, also observed by others (Tang et al., 2020). It was explained that the presence of heavy metals in MIBA, such as chromium, zinc, and lead, can lead to the formation of metal hydroxides precipitated in the pore solution or surface of unhydrated cement particles, thereby hindering their dissolution.

Concerning the mechanical performance of concrete containing MIBA as partial cement replacement, overall, the results in the literature either show a decline in performance (Czop and Lazniewska-Piekarczyk, 2020, Yang et al., 2018) or the presence of some pozzolanicity evidenced by greater strength development over time. **Error! Reference source not found.** presents the results of Jurič et al. (2006), wherein 15% MIBA were used as cement replacement and up to ~23% RA as NA replacement. The use of either component separately led to slight strength increases at both 7 and 28 days when compared with the control concrete. When combined, the compressive strength started to decrease. The initial improved performance can be attributed to the absorption of the mixing water, thereby leading to lower overall effective water to cement ratio. However, the excessive absorption when both materials were used, not only may have led to lack of water to adequately hydrate the cement, but there also may have been deficient compaction due to the increasingly unworkable mix.

Bertolini et al. (2004) compared the effect of using 30% by weight of dry or wet ground MIBA on the mechanical performance of concrete. The wet grinding process, which involved the addition of water to MIBA to form a slurry with a 1:1 solid/liquid ratio, led to a considerably finer material with an average size of 3 μm, whereas that of the dry ground material was of 15 μm. The 28-day compressive strength of the former was of 64.5 MPa vs. 20.1 MPa of the latter (control of 63.5 MPa). Additionally, after 180 days, the compressive strength of wet-ground MIBA was of ~95MPa and that of the control was under 80 MPa. This demonstrates a considerable strength development by using the waste (better that the mixes with 30% coal FA), prompted by a combination of strong pozzolanic activity and filler effect with the very fine particles. The performance loss in specimens containing 30% dry-ground MIBA can be explained by the expansion that occurred while in the fresh state due to the reaction of aluminium with the alkaline pore solution of concrete. Tang et al. (2020) also assessed the effect of using MIBA milled to different particle sizes and concluded that greater milling times led to improved strength development; after 90 days, the compressive strength of specimens with finer MIBA was equivalent to that of the control, but lower for those with coarser MIBA.

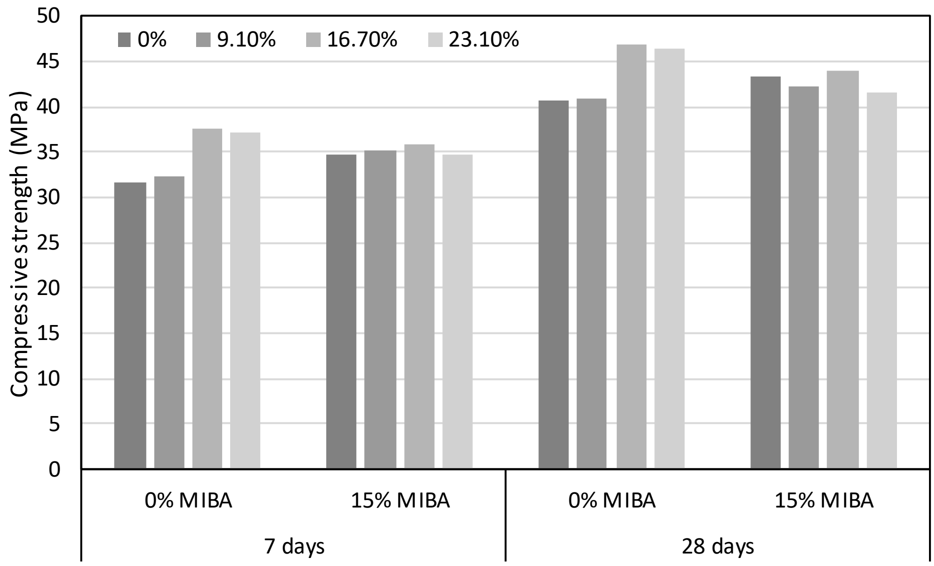

Figure 2 - Compressive strength of concrete mixes with MIBA and mixed RA (Jurič et al., 2006)

Apart from the grinding process, MIBA may also be treated with a $Ca(OH)_2$-containing solution to react with aluminium thereby eliminating expansion in the fresh state (Sharifikolouei et al., 2020). After 28 days, the compressive strength of specimens containing MIBA using this approach showed improved mechanical performance when compared to those with untreated MIBA (~42 MPa vs. ~38 MPa, respectively). However, both still showed performances well below that of the control (~54 MPa).

Figure 3 presents the results of Cheng (2012), in which cement was replaced with MIBA up to 40% by weight. Replacing up to 40% led to a decline in compressive strength of almost 50%. The authors explained this strength loss to be a result of the weaker bond developed at the interfacial transition zone between the cement's hydrated products and aggregates. Although it was not pointed out by the authors, it is possible that, apart from the ashes' lower pozzolanicity, the presence of metallic aluminium may have resulted in an expansive reaction leading to higher porosity in the hardened specimens. Still, mixes containing MIBA showed a greater increase in strength over time when compared to the control specimens suggesting some pozzolanicity. Similar results were reported by others (Jaturapitakkul and Cheerarot, 2003).

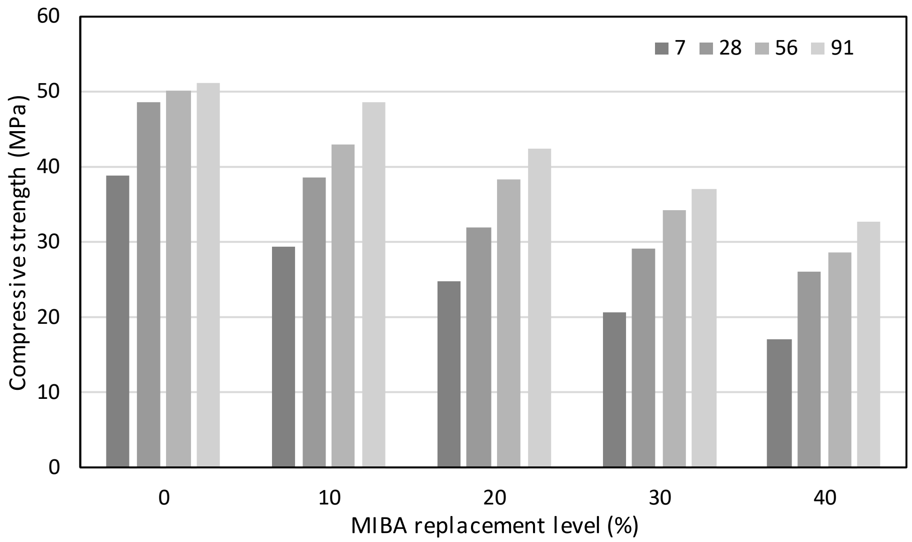

Figure 3 - Compressive strength over time of mixes with increasing MIBA content

The work undertaken on the durability-related performance of concrete with MIBA has progressed little, mostly examining aspects related to permeation properties. Cheng (2012) used the initial surface absorption test to measure the concrete's permeability and reported that the absorption decreased from 0.55 $mL/m^2{\cdot}s$ (control) to 0.30-0.39 $mL/m^2{\cdot}s$ for ground MIBA mixes and to 0.34-0.37 $mL/m^2{\cdot}s$ for the thermally treated MIBA mixes. This decreased absorption was explained as a result of the denser microstructure formed due to the pozzolanic reactions. However, the same authors also reported increased drying shrinkage with progressively higher contents of MIBA (~45% higher shrinkage strain for mixes with 40% MIBA after 91 days).

Regarding the corrosion resistance of concrete, evaluation of the chloride ion penetration was carried out on concrete containing 30% wet/dry ground MIBA by means of indirect electrical resistivity and direct chloride apparent diffusion coefficients (Bertolini et al., 2004). There was an enhanced performance, which was consistent with the strength development, when wet ground MIBA was used (~250 Ω·m vs. ~110 Ω·m of the control) and performed better that FA-containing mixes (~150 Ω·m). The opposite was observed for dry ground MIBA-containing mixes. Based on the overall results, MIBA mixes appear to deliver a level of resistance to chloride attack that is comparable with that of the control mixes at equivalent strengths.

6.4 Biomass bottom ash

Biomass bottom ash (BBA) is produced in power plants that use wood chips or other typologies of wood waste as main combustion fuel as an energy source. Burning waste biomass is one of the main sources of renewable energy. Biomass boilers represent one of the most efficient means of obtaining energy by burning biomass wastes. It is expected that this type of direct combustion of residues obtained from biomass may, in the near future, represent one of the main forms of electricity generation mainly in industrialized countries (Lamers et al., 2018, James et al., 2012). Even though burning biomass waste can be considered as an "environmentally friendly" approach for the production of heat and electricity, the waste generated in the process (BFA and BBA) is likely to represent an environmental problem that must be addressed to avoid jeopardizing the countless environmental benefits of using the waste. For every 483 TWh of electricity produced using the biomass wastes burning, approximately 10 million tonnes of ashes are generated (Lamers et al., 2018).

The combustion of wood waste produces two types of ashes: the BFA and BBA, with a ratio that largely depends on the type of wood waste burnt, but the latter typically comprises 60 to 90% of the total ash produced (James et al., 2013). In general, these ashes are the non-combustible and inorganic part of fuel that remains after complete combustion of the original biomass waste (James et al., 2012, Khan et al., 2009). Table 4 presents an overview of the quantities of ashes as well as the types of biomass used in the largest producing countries. The space occupied by these ashes is significant and the expectations of an increase in their production exerts an increasing pressure on the various operators in the sector to find new solutions for their use. However, the numerous types of biomass combustion fuel sources with distinct properties between them complicates the process of achieving a unique application for all types of biomass ashes. There are already some uses for these ashes with some potential for consumption of significant quantities, namely: cement raw meal addition, cement and concrete filler, use in forestry, soil amendment/fertilizer, asphaltic filler, underground mining, among others.

Table 4 - Total ash quantities produced and types of biomass used in some countries (adapted from (James et al., 2012, Lamers et al., 2018))

Countries	Quantities produced (ktons)	Notes	Type of biomass combustion fuel source

Austria	133	Industry quantities only	Forestry wood; grown biomass
Canada	1000	-	Forestry wood; demolition wood; paper sludge
Denmark	91	-	Forestry wood; demolition wood; straw
Germany	1000	-	Forestry wood; demolition wood; grown biomass; sewage sludge; paper sludge; manure; liquid biomass
Italy	855	Only of ashes from wood combustion	Forestry wood; demolition wood
Netherlands	724	234 ktonnes involves specific biomass combustion	Forestry wood; demolition wood; sewage sludge; paper sludge; manure
		490 ktonnes ashes from co-combustion in coal fired power plants	
Sweden	642	528 ktonnes involves pure biomass combustion	Forestry wood; demolition wood; paper sludge; liquid biomass
		114 ktonnes is based on multifuel wastes	
China	1610	Estimated values	180 ktonnes = ash from wood residue combustion
			1 430 ktonnes = ash from wood fuel combustion
Brazil	370	Estimated values	165 ktonnes = ash from wood residue combustion
			205 ktonnes = ash from wood fuel combustion
USA	307	Estimated values	157 ktonnes = ash from wood residue combustion
			150 ktonnes = ash from wood fuel combustion
Russia	397	Estimated values	97 ktonnes = ash from wood residue combustion
			300 ktonnes = ash from wood fuel combustion
France	134	Estimated values	91 ktonnes = ash from wood residue combustion
			43 ktonnes = ash from wood fuel combustion

6.4.1 Physicochemical properties of biomass bottom ash

BBA are essentially formed by very porous particles, generally below 4 mm (Agrela et al., 2018, James et al., 2013), with heterogenous shape (spherical, rectangular and, in general, very irregular particles), and, depending on their origin, may include unburned residues of wood (Maschowski et al., 2019, Herman et al., 2016). As mentioned, the physical and chemical properties of BBA can vary significantly depending on several factors such as: the type of fuel used as starter or the combustion temperature to which biomass wastes are subjected. Despite these differences, it is generally found that the main components of BBA are: silicone oxide (SiO_2), aluminium oxide (Al_2O_3), iron oxide (Fe_2O_3), calcium oxide (CaO) and carbon (C). BBA also contain other minority components, such as: magnesium (Mg), aluminium (Al), potassium (K) and phosphorus (P) oxides (Table 5). The two main oxides present in greater quantity are, on average, SiO_2 (≈ 35.7%) and CaO (≈ 29.5%), followed by Al_2O_3, Fe_2O_3 and K_2O. Other minor elements are MgO, TiO_2, P_2O_5 and Na_2O.

Table 5 - Oxide composition of BBA from different studies

Publication	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	K_2O	TiO_2	MnO	Mn_2O_5	KO	C	CuO	P_2O_5	Na_2O	ZrO_2	SO_3	LOI
Meawad et al. (2010)	53.7	18.9	7.71	1.21	0.48	0.23	-	-	-	-	-	-	-	0.05	-	-	-
Maschio et al. (2011)	14.8	3.20	3.30	48.4	9.90	11.1	<0.1	0.40	-	-	1.10	2.70	1.00	1.00	-	-	2.4
Arenas et al. (2013)	52.3	25.2	9.23	2.37	1.84	3.72	-	-	-	-	-	-	-	0.66	-	-	-
Maschowski et al. (2019)[a]	25.1	4.51	2.28	44.6	4.73	-	0.19	0.83	-	10.2	-	-	4.96	0.58	-	-	5.4

Maschowski et al. (2019)[b]	33.1	5.80	2.53	38.1	4.76	-	0.22	0.95	-	8.90	-	-	3.56	0.96	-	-	9.41
Maschowski et al. (2019)[c]	35.8	0.98	0.79	51.1	1.48	-	0.07	0.35	-	7.31	-	-	3.51	0.43	-	-	3.51
del Valle-Zermeño et al. (2014)	43.31	5.81	14.1	16.9	2.22	1.11	-	-	-	-	-	-	-	7.58	-	-	-
Carrasco et al. (2014)	27.9	4.34	3.59	29.9	4.05	23.2	-	-	-	-	-	-	-	0.35	-	-	-
Herman et al. (2016)	44.0	9.31	25.0	13.0	1.88	1.25	-	-	-	-	-	-	-	-	-	-	-
Nunes et al. (2016)[d]	4.30	1.30	1.50	55.9	8.50	16.8	0.10	-	-	-	-	-	3.90	0.60	-	1.30	-
Nunes et al. (2016)[e]	32.7	8.40	6.30	14.5	4.20	4.30	0.30	-	-	-	-	-	2.50	26.2	-	0.60	-
Nunes et al. (2016)[f]	48.0	3.50	0.50	3.70	1.80	20.0	-	-	-	-	-	-	3.50	14.5	-	1.90	-
Nunes et al. (2016)[g]	67.7	20.3	0.05	0.5	0.05	0.15	0.05	-	-	-	-	-		11.2	-	-	-
Nunes et al. (2016)[h]	45.8	4.60	2.90	25.7	3.60	8.20	0.30	-	-	-	-	-	3.40	0.60	-	4.20	-
Rosales et al. (2017)	55.4	5.39	2.25	16.6	2.64	7.67	-	-	-	-	-	-	-	-	-	0.24	-
Nasr et al. (2018)	1.38	<0.01	0.44	35.2	7.78	7.91	-	-	-	-	-	-	3.80	-	0.43	12.2	29.0
Kępys (2018)	-	3.85	1.21	84.1	1.52	0.71	-	-	0.18	-	-	-	2	0.09	-	0.71	3
Vaičiukynienė et al. (2020)	22.4	2.51	2.18	49.0	8.29	8.69	0.33	0.35	-	-	-	-	5.05	0.28	-	0.58	-

Notes: [a] St. Peter; [b] Freiburg; [c] Ammertzwiller; [d] Wood pellets; [e] Olive husk; [f] Wheat straw; [g] Olive kernel; [h] Pine woodchips.

Regarding the elements present in BBA (Table 6), the most common on average are Si, Ca e K, with 24.4%, 15.2% e 14.1%, respectively, followed by Fe, Mg, Al, Ti e Na, with 1.5%, 2.5%, 0.8%, 0.1% and 0.3%, respectively. The relatively high heavy metal content can and the presence of organic pollutants and high amounts of organic carbon, possibly resulting from an incomplete combustion of biomass waste (Maschowski et al., 2019), can compromise the use of the ash in some applications and even the process of landfilling it, due to possible environmental pollution of adjacent water bodies. For this reason, BBA are often classified as hazardous materials (Herman et al., 2016).

Table 6 - Elemental composition of BBA from different studies

Publication	Fe	Si	Ca	K	Mg	Al	Ti	P	Na
Herman et al. (2016)	36.1	30.9	16.4	1.92	1.62	-	1.53	1.04	0.61
Rosales et al. (2017)	1.03	24.3	17.1	15.6	2.27	0.98	0.09	-	0.15
Cabrera et al. (2016a) (Málaga)	1.30	24.7	11.0	11.1	2.1	0.53	0.16	-	0.43
Cabrera et al. (2016a) (Jaén)	1.86	25.1	15.5	15.2	3.16	0.59	0.20	-	0.42
Cabrera et al. (2016a) (Cordoba)	1.39	24.2	13.9	11.6	2.22	0.51	0.17	-	0.46
Cabrera et al. (2016b)	1.85	21.9	16.4	14.7	2.52	0.81	0.12	-	0.27
Beltrán et al. (2016)	-	24.5	14.1	13.1	2.38	0.75	0.14	-	0.38
Rosales et al. (2017)	1.20	25.1	17.2	16.9	2.59	1.16	0.09	-	0.21
Cabrera et al. (2018)	1.64	25.1	16.9	14.3	3.09	0.76	0.12	1.96	0.35

Error! Reference source not found. presents the specific gravity, water absorption and organic matter content of BBA from different studies. The specific gravity varied between 1.67 and 2.53, with an average value of 1.98, whereas the water absorption varied between 19% and 38.7%, with an average value of 24.9%. The average values of both fall well outside the range typically observed for other supplementary cementitious materials. The variability of these values is associated with the origin and type of biomass burnt, as well as the treatment conditions for BBA that vary from job to job. The organic matter content values, on the other hand, are more uniform (~3-5% with an average of 4.15%) if the value obtained by Cabrera et al. (2016a) from the Malaga area (Spain) with a 12.3% value, much higher than the rest, is excluded.

Table 7 - Physical properties of BBA from different studies

Publication	Specific gravity	Water absorption (%)	Organic matter content (%)
Beltrán et al. (2014)	2.02	19.9	3.06
Rosales et al. (2016)	1.97	26.6	4.12
Herman et al. (2016)	2.53	-	-
Cabrera et al. (2016a) (Málaga)	1.70	29.4	12.3
Cabrera et al. (2016a) (Jaén)	2.00	21.8	4.05
Cabrera et al. (2016a) (Cordoba)	1.72	38.7	3.67
Cabrera et al. (2016b)	1.82	32.0	4.85
Beltrán et al. (2016)	1.67	19.0	5.26
Rosales et al. (2017)	1.86	21.8	4.34
Cabrera et al. (2018)	2.46	20.1	4.89
Agrela et al. (2018)	2.01	20.0	3.15

6.4.2 Fresh, mechanical and durability-related performance in concrete

As mentioned in the previous section, BBA exhibits a particle size distribution similar to that of natural sand. For this reason, it has been typically used in the substitution of fine aggregates for the production of mortars and concrete. Regarding the use of BBA as partial replacement of cement, most of the consulted works reported a significant loss of mechanical performance with increasing in BBA content. However, there are numerous types of BBA with very distinct compositions and, depending on their chemical composition (amount of CaO, SiO_2, Al_2O_3 and Fe_2O_3), there is some potential for their incorporation into blended cements. In addition to the quantities of organic matter content and the high percentage of lightweight particles, one of the limitations for their application is associated with the fact that the inclusion of biomass ash in blended cements is not regulated. The European standard for cement EN-197-1 (2011) does not allow this type of ash to be used as compound.

Regarding the use of BBA in RAC, few studies were carried out. Agrela et al. (2018) conducted a study on the use of coarse RA to replace coarse NA and BBA to replace fine NA. In order to reduce the amounts of organic matter content and high percentage of lightweight particles (two common problems in BBA), the authors also used processed BBA (Pr-BBA). The BBA used by the authors were generated from the combustion of olive pruning. The results of the compressive and flexural strengths tests showed that the performance declined with the presence of BBA and Pr-BBA as fine FNA replacement, probably as a result of the higher porosity and lower density of BBA particles. The authors pointed out that mixes with Pr-BBA show more favourable results when compared with mixes with unprocessed BBA. Agrela et al. (2018) also studied the drying shrinkage and reported an increase of 45% to 76% with the use of RA together 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 RA as the main reason for the significant increase in shrinkage.

Beltrán et al. (2014) studied several mixes containing different types of coarse RA and for which they replaced the FNA with 0%, 3% and 6% of BBA. BBA was produced in the combustion of several biomass compounds residues composed mainly of olive mash, olive orchard prunings as well as other energy crops. For mixes with BBA without coarse RA, the reduction in compressive strength observed by the authors was 15% to 20%, when compared to the control concrete. The authors observed that, in mixes with only coarse RA and without BBA, the compressive strength decreased approximately between 15% and 25%, when compared to the control concrete. The combination of both BBA and RA led to reductions in the compressive strength of 30-40%. Naturally, the adhered mortar in the RA, which increased the porosity of the mixes, was the main reason for this decline in performance. In the drying shrinkage test, the incorporation of both RA and BBA increased shrinkage strains by over 130%.

The use of BBA already has some implementation in civil infrastructures as soil-cement. In the study of Cabrera et al. (2016a), BBA was used as aggregate replacement alongside NA or RA (0%, 15% and 30%, by volume). The BBA came from the combustion of biomass with approximately 40% of olive cake and 60% of wood biomass (poplar, olive and pine). Cabrera et al. (2016a) observed that, in all mixes produced, the presence of 15% BBA contributed to an improvement in compressive and splitting tensile strengths as well as modulus of elasticity, when compared to the control concrete, though a decline was observed for 30% BBA.

Rosales et al. (2016) studied the replacement of NA by BBA and recycled mixed aggregates (RMA) in the production of lightweight RAC with the addition of expanded clay. The authors carried out a series of mixes using either only RMA or RMA and BBA (with constant expanded clay content). The results showed that there was a gradual decline in the compressive strength with increasing BBA and RMA contents, in comparison with the control concrete. Despite this reduction, the authors pointed out that the compressive strength of all mixes was within the range of 15 to 20 MPa, which corresponds to the limit established for structural and non-structural lightweight concrete. The authors emphasized the importance of the density of both RA and BBA on the variation of the concrete's mechanical performance. Some of the same authors analysed the environmental impact of BBA in mixes with RMA in structural layers of roads, essentially through leaching assessment (Cabrera et al., 2016b). The authors used the BBA generated in three biomass power plants. Two types of mixes of BBA and aggregates were made, one with NA and the other with RMA. The results showed that 37% of the BBA samples could be classified as inert, whereas 13% were non-hazardous and 50% hazardous. The main heavy metals released, in order of relevance, were: As, Hg, Cr, Ni, Cu, Se and Mo. Subsequently, the authors analysed the most contaminated BBA in mixes with the two types of mentioned aggregates. It was observed that, even for the most dangerous BBA sample mixed with NA or with RMA, the leached hazardous compounds were reduced, proving the feasibility of using these mixes.

Nasr et al. (2018) studied the incorporation of BBA and sanitary ceramic waste (SCW) as partial replacements of cement. The authors produced three series of mixes in which the first corresponds to the addition of BBA in 5%, 10%, 15% and 20% of cement replacement, the second to the use of 5%, 10%, 15% and 20% of SCW in substitution of cement and the third to a combined mixture of BBA/SCW with 5% + 5%, 10% + 10%, 5% + 10% and 10% + 5% instead of cement. The results showed that there was a reduction in compressive strength in all mixes, except for the 20% SCW mix, which exhibited approximately 94% of the control concrete's compressive strength. Although the same trend was observed in the flexural strength for BBA mixes, those with SCW exhibited slightly higher values (2-9%) than those of the control mixes. In the remaining mixes, the compressive strength values corresponded to values between 24% and 67%. Mixes with BBA alone showed the worst results (variation between 24% and 43% when compared with the control concrete). The authors stated the main cause for this decline was the low pozzolanic activity of BBA and SCW, though more prominent in the former. This improvement was attributed to the filler effect of SCW.

6.5 Conclusions

The construction industry is one of the economic sectors with the greatest environmental impact, in terms of extracted natural resources, energy consumption and emissions released into the biosphere. For these reasons, it is essential to promote sustainability in construction to reduce the ecological footprint during the construction, maintenance and end of life phases of structures.

Since concrete is the most widely used building material in the world, one way to promote sustainability in construction is by improving the environmental performance of this material. Currently, due to the aforementioned emphasis placed on sustainable development requirements, a new approach to concrete technology is essential: looking for production methods and placing concrete on site with less energy consumption; improving the durability of structures; and increasing the use of industrial by-products and recycled construction and demolition waste in the construction process. Of the three vectors considered, the incorporation of by-products from other industries in the production of concrete and mortar is considered as the one with the greatest potential for improvement.

The use of additions as partial replacement of cement is an option capable of reducing the ecological footprint of concrete. Among the existing additions that have shown promising results in the performance of the concrete produced with them, it was decided to study, in conjunction with the use of RA in the production of concrete, bottom ash from coal burning (CBA), bottom ash from the incineration of municipal solid waste (MIBA), and bottom ashes from biomass combustion (BBA). Any of the by-products mentioned pose an environmental issue given the quantities produced worldwide and the volume of material that still goes to landfill.

Concerning the effects of using CBA, MIBA or BBA on the performance of concrete in combination with RA, the literature largely suggests an overall decline in performance. Not only do the ashes present a lower level of pozzolanicity and higher porosity, in comparison with conventional coal FA, which leads to a diminished strength development when used as cement replacement, but the RA are also widely known to have a lower quality than NA, essentially due to the presence of adhered mortar, which increases overall porosity. The combined incorporation of either of the bottom ashes with RA is likely to increase the water requirement of concrete due to the higher porosity of both components. The use of MIBA as cement replacement was found to decrease the heat of hydration, as one would expect, and it also extends the setting time of concrete, though within manageable levels. When adequately processed, CBA and MIBA were found to present some pozzolanicity, becoming more relevant in the process of concrete hardening over time, through the formation of additional pore-filling C-S-H, resulting in a denser microstructure and thus improved mechanical performance for older ages. Some MIBA have been found to comply with the pozzolanic activity requirements of mineral additions and performed comparable to other established materials, such as FA and natural pozzolana. Naturally, thermal treatment can be effective in increasing the amorphous phases and therefore the reactivity of the material, but at the cost of increasing their environmental impact. The chemical activation with $CaCl_2$ and $CaSO_4$ was also found to be successful in further promoting the development of pozzolanic reactions. One noteworthy positive influence of CBA when used as sand replacement, was the significant decrease in drying shrinkage strain due to the internal curing provided by the water stored in the porous microstructure of CBA particles. In the production of concrete with RA, this fact can represent a significant added value as it is precisely the finer fraction of RA that presents the greatest problems in the performance of concrete with RA. In the case of BBA, however, a generalized decline in performance has been recognized, partly due to the presence of lightweight particles. The type of wood combustion, the boiler size and type, and the subsequent treatments also have considerable influence on the final properties of the ashes and thus on the resulting concrete, which can hinder the process of regulation and specification of the material. Nevertheless, in spite of the performance losses with increasing incorporation level of the bottom ashes, it is possible to establish some potential in the use of these by-products within an optimal incorporation interval in high-end applications, including those in structural concrete.

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