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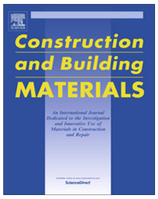

Characterisation and technical feasibility of using biomass bottom ash for civil infrastructures

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HIGHLIGHTS

- Thirty samples of BBA from wood and olive trees were analysed.
- Low density, high absorption and high organic matter content were observed.
- Technical feasibility was proved according to the Spanish specification for roads.
- BBA were classified as subsidiary material feasible as construction material.
- The use of the ashes as a filler material in road embankments was proved.

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ABSTRACT

Biomass is a renewable energy source that is increasingly being used worldwide. However, because of recent increases in production, waste products from biomass combustion are becoming a relevant environmental and economic problem.

In the present research, the technical feasibility of bottom ash from various Andalusian power plants is analysed to evaluate their potential use in civil engineering infrastructures. The physical, chemical and mechanical characteristics of this by-product is evaluated, and these parameters are compared to the technical specifications for roads imposed by Spanish regulation. It was determined that biomass bottom ash possesses acceptable properties to be used as a filler material in the core of road embankments over 5 m in height without additional precautionary measures, such as the construction of road shoulders.

1. Introduction

In Andalusia, the second-largest autonomous community in Spain, energy production by biomass co-combustion is becoming one of the best alternatives to fossil fuels. This use of biomass has been motivated by the threat of global warming, which is caused by the combustion of fossil fuels. The prospect of exhausting natural fossil fuel resources and damaging the natural environment in the process has encouraged the development of alternatives to these fuels (coal, peat, petroleum and natural gas) [1].

Biomass contributes to 6% of global, non-food related energy consumption [2]. Much of this comes from the low efficiency, high emissions combustion of poorly controlled heating and cooking fires, which are used by a majority of the world's population. Biomass is considered to be the most promising source of renewable energy [3], and its by-products are increasingly used worldwide.

European Directive 2009/28/CE defines biomass as the biodegradable fraction of product, industrial and municipal waste and any residues of biological origin from agriculture (including vegetable and animal substances), forestry and related industries, such as fisheries and aquaculture. For that reason, the processing and disposal of ash produced from biofuel combustion has become an environmental and economic issue. The ash is composed of minerals that were either absorbed by the biomass or incorporated into the biomass during harvesting and unburned organic matter. Their potential reuse is determined by their chemical and physical properties. The quantity and quality of ash produced in a biomass power plant are strongly influenced by the characteristics of the biomass and the biomass combustion technology used [4]. Thus, their characterisation facilitates their use in future applications.

The two main types of ash are bottom ash and fly ash. Bottom ash is the portion of non-combustible residue found in the furnace or incinerator, whereas fly ash is the portion of ash that escapes through the chimney and is retained to prevent it from being released into the atmosphere [5].

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The potential reuse of both types of ash has been previously analysed by other authors and organisations. For instance, the recycling of biomass ash in construction materials meets the recommendations of the European Directive on waste 2008/98/CE and has significant environmental benefits. The recycling of biomass ash minimises the extraction of natural aggregates from quarries and reduces the amount of waste that is transported to landfills. According to this regulation, both types of biomass ash can only be recycled in concrete, cement and brick production, and used as a filling material in embankments [6].

In some developed countries, such as Germany, Japan, Denmark and the Netherlands, bottom ash is widely used in roads, concrete, soil amendment and soundproof walls. In these countries, the recycling rate is between 70% and 90% and can be as high as 100% [7–9].

Several authors have recently assessed the possible reuse and recycling of biomass ash as a substitute for aggregates in concrete mixtures [10] and cement production [11]. Previous researchers have demonstrated the satisfactory application of biomass wastes in road pavements because of its pozzolanic and mechanical properties [12–15].

However, the efficiency of biomass combustion, difficulty in delivering and preparing (drying or grinding) a sufficient amount of biomass, cost and the technological limitations of the performance currently hinder the reuse of biomass ash [3,16–19].

Although fly ash has been studied more extensively, many investigations have analysed the reuse of biomass bottom ashes (BBA) in civil applications. This is also the main goal of the present research work. To reach this objective, a large number of BBA samples from three different power plants were analysed. The tested biomass samples were biologically diverse and obtained from distinct sources.

The goal of the present paper is to evaluate the possibility of reusing BBA in civil infrastructures according to the technical specifications for road works imposed by Spanish regulation. The applicable legal regulations for Spain [20] were used for reference. To complete this objective, all samples were mineralogically characterised by X-ray diffraction to detect possible compositional differences based on variations in biomass origin. The organic matter content of BBA was measured, and the combustion systems of each power plant were compared to evaluate system efficiency and determine how efficiency affected organic matter content.

The following parameters were measured to physically and mechanically characterise all samples: granulometric composition, absorption, density, friability, compactability according to the modified Proctor test, bearing capacity by the CBR index, plasticity and swelling.

After measuring these variables, the BBA from the different plants was classified by comparing the results to the limit values/requirements specified by Spanish regulation. This regulation (PG-3) classifies materials into one of the following four categories: subsidiary, tolerable, adequate or selected. Organic matter content is the most restrictive condition/property for this by-product. BBA was classified as a subsidiary construction material that can be used as a filler aggregate in embankments.

Additionally, the present study includes a statistical analysis on the variability of density, absorption and friability in the tested samples.

cThe confirmation of material aptitude in civil infrastructures allows the sale of a by-product that is currently discarded by Andalusian electricity co-generation plants, unlike fly ash. Thus, the results suggest the application of the material (BBA as a valued by-product) as filler in embankments. This application would prevent a large amount of waste from being deposited in landfills and would not provide any economic advantages for the plant managers.

2. Materials

2.1. Sample biomass composition

The geographic location and climate in southern Spain makes Andalusia an ideal area to generate renewable energy from windmills, photovoltaic and solar panels, thermoelectric and hydraulic plants, biomass and bio fuels. The production of energy from biomass combustion is increasingly used in this area because an energy policy developed in the mid-90s offered incentives to encourage renewable energy. Currently, the Renewable Energy Spanish Plan 2011–2020 is being developed with future goals for the 2020 energy map [21].

The diverse and variable amount of biomass that is combusted by the different industrial processes of various plants operating in Andalusia produces heterogeneous ash by-products with distinct characteristics and compositions. The most widespread biomass collected in this community is from the olive tree (which accounts for 80% of the total cultivated area); however, other crops, such as poplar, fruit trees or grapevines, are also able to be converted into biomass fuel [21].

This uncommon material, which has potential applications in construction and engineering sectors, has not been mechanically and physically characterised in Andalusia. Therefore, producers of this area have demanded the development of studies that would determine the value of the ash and whether reducing the disposal of this waste would increase its real commercial value.

To obtain a representative study of the material characteristics, the present work was conducted using 30 samples of BBA obtained from the following biomass power plants: "Puente Genil, PG" (Córdoba), "Villanueva de Algaidas, V" (Malaga) and "Linares, L" (Jaén). The biomass composition of the mixtures is listed in Table 1.

At all the plants that were tested, a large quantity of homogeneous olive cake (commonly named orujillo) was burned during each combustion cycle with relatively constant percentages. Combusting residues, such as oil cake from olives (or colza), generate high calorific power during combustion [1,22]. The combustion efficiency of this fuel increased with higher bed temperature and larger particle size. Combustion efficiency decreased with increasing feed rate and fluidisation velocity [22].

The olive cake used in our study was provided by olive oil manufacturers that stored the olive cake in silos located near the power plants. This oil was extracted from olives that were supplied by various cooperatives during the olive harvesting period from December to March [23]. In addition to olives, biomass from the wood production industry has demonstrated great potential for combustion [1,3]. Therefore, waste from poplar, pine, oak and eucalyptus trees was also included in the biofuel mixtures used in the tested plants.

Based on the data, power plant L burned approximately 40% olive cake and 60% wood biomass (poplar, olive and pine), whereas plant PG combusted 30% olive cake and 70% vegetable waste. Power plant PG had the greatest variability in composition of burned biomass (wood waste from five different trees), whereas plant V, which used the largest amount of olive cake in the combustion mixture (close to 75% of the total biomass), had the most homogeneous composition of burned biomass.

2.2. General characteristics of the power plants and collected bottom ash

Andalusia is able to provide 20% of the electrical energy that is required for regional operation [24]. A brief description of the plant processes is illustrated in Fig. 1. A common flowchart is presented for the three power plants that were analysed. Biomass fuelled steam generators are designed to generate superheated steam through the combustion of biomass and the subsequent recovery of heat from the gases. The automatic fuel feeding system allows biofuel to enter the combustion system from the point of storage. Once the combustion process is finalised, the BBA produced in the combustion chamber is removed by a wet system into the bottom ash bed. Finally, the BBA is deposited in provisional storage. The technical capacity of the analysed plants is summarised in order of power generated and biomass consumed: plant L produced 15 MWe and consumed 110,000 T biomass/year; plant PG produced 9.5 MWe and consumed 70,000 T biomass/year and plant V produced 8.5 MWe and consumed 63,000 T biomass/year.

In all the power plants, the bottom ash was generated from periodic discharges of the bed, which is required to avoid agglomeration and defluidisation and maintain a suitable particle size distribution. These parameters are crucial to guarantee proper hydrodynamic conditions [25,26].

The BBA obtained from each power plant is shown in Fig. 1, all of them affected by weather conditions due to the outdoor storing before their collection.

The samples from plant L were the most disaggregated, whereas the samples from plant PG contained thicker ash particles. The samples from power plant V were large clods that were darker in colour because they contained a high content of organic matter.

3. Experimental methods

3.1. Characterisation of BBA

The particle size distribution, water absorption, density and Atterberg limits of all samples were determined to characterise the BBA. Additionally, the organic matter content and the mineralogical composition were quantified. The methods that were performed are briefly described.

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Table 1
Composition of biomass combustion mixtures.

Composition (volumen)								
	Olive tree	Pine	Olive cake	Poplar	Oak	Eucalyptus	Wood waste	Olive (olive and oil cake)
L1	12	24	64				24	76
L2	–	50	40	10	–	–	60	40
L3	–	50	40	10	–	–	60	40
L4	20	40	40				40	60
L5	20	40	40				40	60
L6	20	40	40				40	60
L7	20	30	40	10	–	–	40	60
L8	12	36	40	12	–	–	48	52
L9	12	36	40	12	–	–	48	52
L10	20	40	40				40	60
Average values							44	56
PG1	50	20	30				20	80
PG2	50	20	30				20	80
PG3	45	19	27	–	9	–	28	72
PG4	50	20	30				20	80
PG5	50	20	30				20	80
PG6	33	17	33	17	–	–	34	66
PG7	35	17	33	15	–	–	32	68
PG8	50	10	30	–	–	10	20	80
PG9	38.4	23.07	23.07	–	–	15.4	38.47	61.47
PG10	45	19	27	–	9	–	28	72
Average values							26.04	73.94
V1	6	30	64				30	70
V2	10	30	60				30	70
V3	5	20	75				20	80
V4	7	18	75				18	82
V5	7	18	75				18	82
V6	5	15	75	–	5	–	50	80
V7	8	17	75				17	83
V8	5	15	75	–	5	–	20	80
V9	5	20	75				20	80
V10	5	15	75	–	5	–	20	80
Average values							24.3	78.7

The distribution of particle sizes was determined following the procedure outlined in UNE-EN 933-1[27]. A representative sample was filtered through a series of sieves, and the percentage of retained sample was analysed. To estimate the sample density and water absorption, the procedure described by the European standard EN 1097-6 [28] was performed. The plasticity indices were determined to establish the limited moisture range in which the material remains in a plastic state. The standards from UNE 103-103 [29] and UNE 103-104 [30] were used. The Atterberg limits reveal and characterise the quality of a material. In civil engineering, the Atterberg limits are used as technical specifications to control the use of a material as embankment filler.

To quantify the oxidisable organic matter, the potassium permanganate method proposed by UNE 103-204 [31] was performed. The test consists of preparing solutions of oxalic acid and potassium permanganate and determining the normality factors. Once they are obtained, a solution is prepared for the test sample. The amount of potassium permanganate used in the assessment is recorded to determine the percentage of organic matter.

The mineralogical composition of BBA was analysed using X-ray diffraction. The peak intensities were compared to estimate and identify the various biomass phases of multiphase samples. X-ray diffraction patterns were collected using a Siemens D5000 diffractometer with monochromatised Co Kα radiation, a step size of 0.05°, a counting time of 20 s and a total sweep of 70°.

3.2. Methods to estimate the mechanical behaviour of BBA

The mechanical behaviour of BBA was studied to estimate the response of the material after it is applied as a sub-grade layer in road pavement.

Friability is an important mechanical factor to investigate. A friable material is easily fragmented into smaller segments from large, undesirable aggregates [32]. This parameter was calculated according to an established standard [33] that measures the change in size of a fine aggregate when subjected to abrasion within a rotating cylinder in water.

The modified Proctor test was performed on various samples. This test is used in geotechnical engineering to evaluate the relationship between the water content and the dry density of a material for a specified compaction energy. Compaction characteristics of the materials were measured and analysed by varying the compaction moisture according to UNE-EN 103-501 [34]. The test was performed using a modified Proctor mould. A cylinder 152.5 mm in diameter and 129.8 mm in length with a tamping foot of 4.53 kg was used to compact all the samples into five layers. The cylinder was dropped a total of 60 times from a vertical distance of 457 mm.

Finally, the bearing capacity of BBA was studied according to the CBR index (California Bearing Ratio), which provides a measurement of the impact resistance of the compacted aggregate. It is determined as the ratio between the impact load causing a given penetration in the samples and a fixed pattern, as stated in the standard UNE 103-502 [35].

4. Results and discussion

4.1. Mineralogical composition: X-ray diffraction data

To detect differences in the mineralogical composition of samples, five samples from each power plant were analysed by X-ray diffraction (XRD). All the biomass combustion plants produced BBA with similar compositions. Only representative samples from each power plant are shown in Fig. 2.

Mineralogical characterisation revealed the composition of BBA to be a series of crystalline phases within a glassy matrix. Logically, it can be affirmed that all BBA presents a similar mineralogical composition. Oxides, such as quartz (SiO_2), are typically produced at high temperatures during the combustion process. Carbonates (calcite) were also detected because biomass fuel contains a naturally high content of wood waste [36].

Previous research [37] has revealed that the detection of these two phases predominately depends on combustion temperature and the type of burned fuel. In addition to these two main phases, traces of the clay mineral chlorite was also detected. However, because BBA has an amorphous structure during combustion at high temperatures, other phases that were detected in low amounts were difficult to identify. The present results obtained for the mineralogical composition are consistent with previous studies [38–40].

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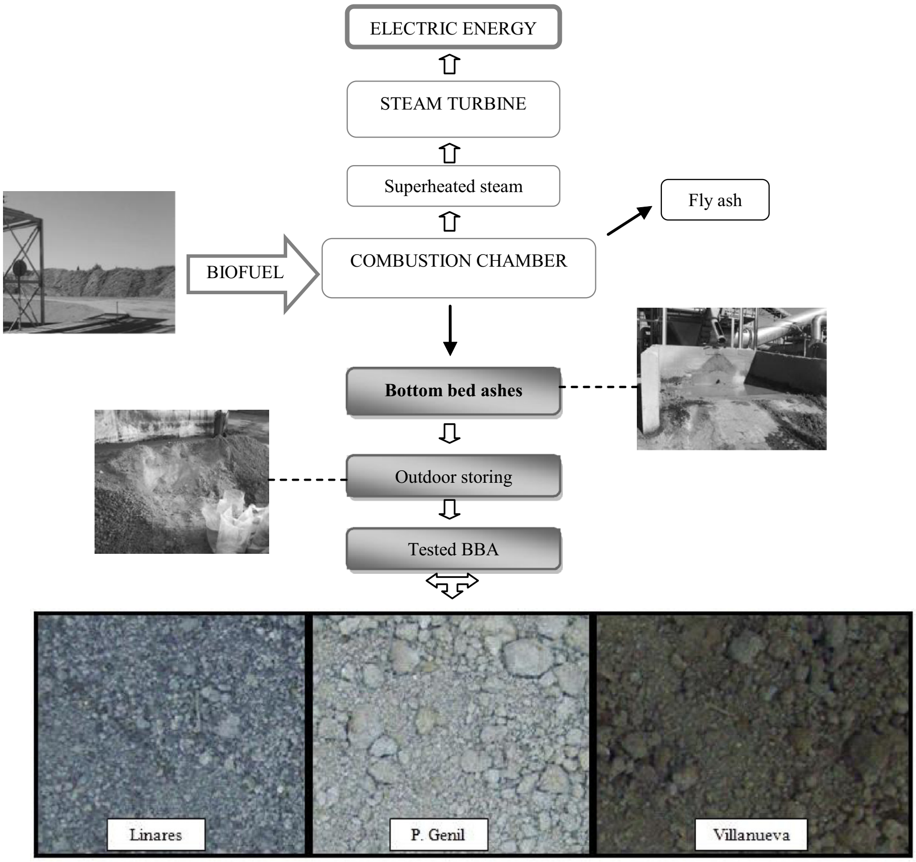

Fig. 1. Flowchart for processing BBA at the tested plants.

4.2. Analysis of organic matter content

Fig. 3 shows the organic matter contents that were obtained using the potassium permanganate method.

A high percentage of organic matter was detected in samples collected from power plant V. The values ranged from 6.52% to 19.97%. Even the lowest percentage of organic matter from power plant V was higher than the percentage measured in the samples from the other two biomass combustion plants. It is important to remark that this factor directly depends on the type of combustion system that is used at each power plant. The amount of organic matter present in BBA is a consequence of biomass combustion efficiency. Previous work by Huang et al. [41,42] affirms that the main reasons for reduced combustion efficiency are feedstocks with low energy densities and biomass with high moisture and/or ash content (e.g., olive pits). Thus, the significant difference in organic matter content between the three plants is attributed to the use of different combustion systems.

Biomass combustion plant L is equipped with an automatic fuel supply, which transports the biomass directly from the storage point to the grate. The grate system has a vibrating movement that uses a double vibrator on each of the two sections to move and distribute the fuel over a large area for efficient combustion and obtain the lowest levels of organic matter (average value of 4.06%). The combustion system from power plant PG uses a hydraulically powered oscillating moving grate and a feeder/pitcher system that propels the biomass fuel in suspension. The combustion of this system is more uniform than the combustion performed by plant L. Plant PG produced the lowest levels of organic matter (average value of 3.64%). In plant PG, the biomass particles are propelled by gravity. Fractions of larger particles contact the grate and are burned first; additionally, coarser fractions burn for longer periods of time than finer fractions. By the same reason, heavier particles with higher water content burn for a longer period of time.

Plant V is equipped with a tilting mobile system, which consists of both fixed and mobile elements that transport the biofuel along the combustion chamber using a swinging movement. The process causes a small portion of the fuel to fall onto the bed without being completely burned, which produces BBA with a higher content of organic matter. Therefore, the highest levels of organic matter were detected in samples collected from plant V (an average value of 12.36%).

4.3. Physical characterisation results

Assessment of the physical behaviour of BBA will determine the possible application of this material as a construction material in civil infrastructures. The average particle size distribution of BBA and the particle size distribution limits of fine aggregates that is imposed by the requirements of the Spanish regulation [43] is presented in Fig. 4.

According to the results, BBA is composed of extremely porous particles with rough surface textures. The size of these particles varies from fine gravel to sand. The curves show that the granulometric distribution of samples from plants PG and V are similar. However, bottom ash from plant L had a lower content of fine particles. Despite the mentioned differences, the particle sizes ranged from 0–10 mm for all samples.

The water absorption and saturated surface-dry (SSD) particle density were measured. Absorption is an important factor to consider because many physical parameters of bottom ash are altered in the presence of excess water [44,6]. Therefore, it is important to study and minimise the direct effect of adsorption on the

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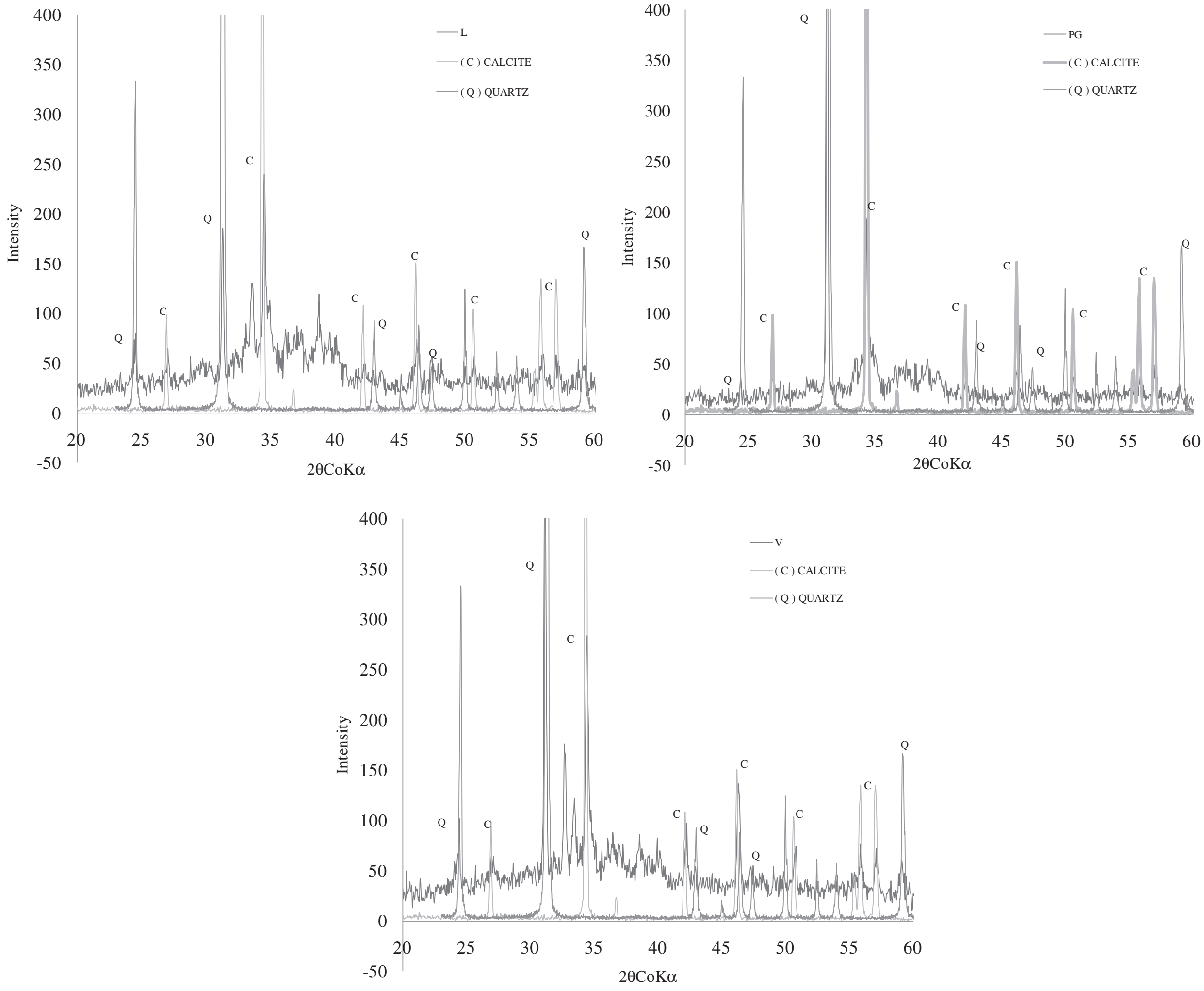
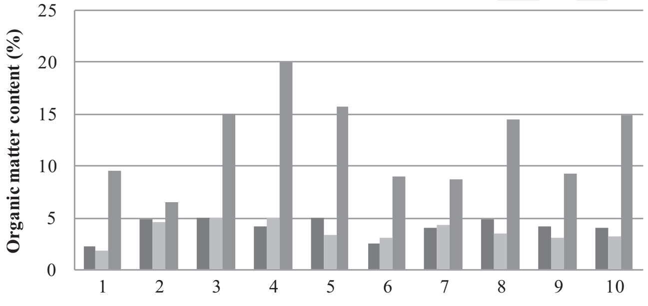


Fig. 2. X-ray diffractograms of BBA (from plants L, PG and V).



	1	2	3	4	5	6	7	8	9	10
■L	2.18	4.77	4.91	4.17	4.92	2.53	4.07	4.89	4.15	3.98
■PG	1.85	4.55	4.98	4.96	3.25	2.99	4.22	3.41	3.05	3.11
■V	9.53	6.52	15.0	19.9	15.7	8.98	8.75	14.4	9.26	14.9

Fig. 3. Organic matter content of all BBA samples.

physical properties of BBA. Significantly altered physical properties could hinder the use of BBA as a building material. Huang et al. [42] analysed the physical properties of asphalt mixtures manufactured using varying amounts of incinerator bottom ash as a fine aggregate substitute and determined that the absorption of the material was 15% higher than natural sand and crushed stone. Previous research has shown that water absorption by bottom ash affects concrete workability. The bottom ash are porous aggregates that act as water reservoirs for the future hydration of the cement [44–46].

The Physical properties of BBA samples are shown in Table 2 and corroborate results obtained by previous research. The results illustrate that two types of moisture were measured. The parameter “moisture at outdoor storing” refers to the moisture content of BBA during its storage before disposal to the landfill, whereas “moisture in bottom ash bed” refers to the moisture content of BBA after combustion (see Fig. 1). The material in the bottom ash bed has an increased moisture content because a wet stream system is used to cool the BBA, which increases the humidity. However, the moisture content of the ashes located in the storage area depends on when they were deposited and the ambient temperature. The lowest water content was measured for BBA under these conditions.

According to the results listed in Table 2, samples from plant PG demonstrated greater absorption (mean value approximately 40%) than samples from plants L and V, which had average values of 20% and 32%, respectively. These values reveal high variability in the data and increased absorption of this material (fact corroborated by previously mentioned works).

Low surface dry (SSD) particle densities were calculated for the BBA samples. Samples from plant V had the lowest SSD density with a mean value of 1.7 g/cm^3, whereas samples from plant L had the highest SSD density with a mean value of 2 g/cm^3. Compared to traditional natural aggregates, low densities were

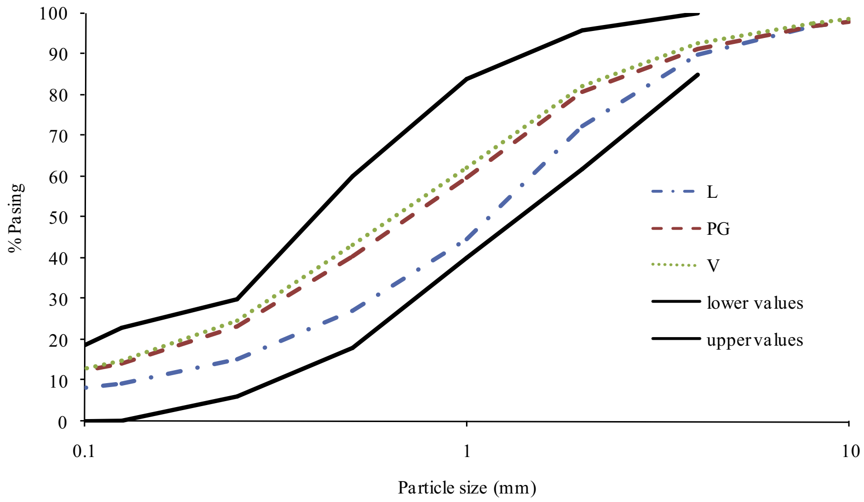


Fig. 4. Particle size distribution curves compared to granulometric limits.

Table 2
Physical properties of BBA samples.

	Moisture (%)		Absorption (%)	SSD density (g/cm^3)
	At outdoor storing	In bottom ash bed		
L1	–	27.92	26.62	1.82
L2	–	45.15	14.00	2.21
L3	–	48.08	13.96	2.14
L4	22.70	36.94	10.41	2.26
L5	19.90	42.60	27.04	1.74
L6	32.63	44.10	17.12	2.04
L7	21.41	76.60	20.15	2.03
L8	47.07	72.69	27.45	1.88
L9	27.36	37.80	19.79	1.93
L10	24.62	41.60	20.31	1.95
Average values	*27.96*	*47.34*	*19.68*	*2.00*
PG1	–	50.12	39.82	1.77
PG2	–	53.87	41.77	1.75
PG3	–	44.02	40.51	1.69
PG4	44.98	65.10	37.00	1.75
PG5	45.70	71.40	25.84	1.67
PG6	43.30	49.96	41.84	1.76
PG7	50.70	53.69	45.69	1.67
PG8	50.82	52.57	44.74	1.65
PG9	40.07	56.10	30.2	1.75
PG10	50.82	71.40	45.9	1.77
Average values	*46.63*	*56.82*	*39.31*	*1.72*
V1	–	64.00	36.04	1.65
V2	–	56.10	26.26	1.98
V3	–	62.21	36.23	1.71
V4	36.88	59.19	32.87	1.69
V5	46.71	71.40	24.35	1.74
V6	35.03	63.01	38.59	1.71
V7	39.70	49.58	27.38	1.70
V8	66.18	74.79	31.96	1.78
V9	57.07	74.93	33.09	1.68
V10	48.78	65.24	33.15	1.42
Average values	47.19	*64.05*	*31.99*	*1.70*

obtained for BBA because it is composed of particles with a low specific weight [42–47]. When used on site, BBA particles exhibited a vesicular texture that was easily degraded under mechanical load, which has previously been shown by Kavussi and Hicks [48]. They found that mastic containing ash was more susceptible to brittle failure because of its high porosity and low density, which was attributed to the formation of small air bubbles during burning. This was also observed in samples analysed in the present study.

4.4. Mechanical behaviour of BBA

One of the goals of this paper is to analyse the possible application of BBA for civil engineering applications, specifically as a material for road embankments. Therefore, it is important to evaluate the mechanical attrition of the material under mechanical loading.

Previous authors [32] have determined that brittle fractures result from the progressive development of cracks, which terminate

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Table 3
Friability coefficients for all BBA samples.

Friability ratio										Medium
L1	L2	L3	L4	L5	L6	L7	L8	L9	L10	29.54
28.2	23.8	25.6	30.6	34	28	29.6	32.6	31	32	
PG1	PG2	PG3	PG4	PG5	PG6	PG7	PG8	PG9	PG10	32.93
33.1	31	29.6	34.9	35.6	33.2	35.4	33.4	31.5	31.6	
V1	V2	V3	V4	V5	V6	V7	V8	V9	V10	28.37
24.5	26.8	25	29	30.6	35	27	26.4	29	30.4	

with a crack opening and cause a sudden loss in strength [49]. The propagation of cracks in unconfined stressed aggregates depends on the density and morphology (connectivity and orientation) of air-filled pores and the strength at the crack tips, as defined by Hallett et al. [50,51]. The occurrence and nature of cracks in the material depends on basic aggregate properties (texture, clay mineralogy), climate (cycles of wetting–drying and frost–thaw), soil biological activity and tillage and traffic.

To evaluate this phenomenon, the value imposed by the Spanish Instruction on Structural Concrete [43] was used as the reference. This regulation indicates that materials with a friability coefficient lower than 40 may be used. To estimate the friability coefficient, the modified Proctor test was performed on all BBA samples. The friability data are listed in Table 3.

The mechanical strength and attrition behaviour of waste products is relevant because it affects the overall mechanical behaviour of BBA. Compared to natural sand [52], significantly higher friability coefficients were measured for BBA, which ranged from 28.37 (V samples) to 32.93 (PG samples). In conclusion, despite the high potential of attrition in tested BBA samples, the data satisfy the levels required by the current regulations.

In soil mechanics, the modified Proctor test is one of the most important procedures in quality control studies. It is used to determine the maximum compaction of an aggregate in relation to its moisture content. The moisture–density curves indicate whether the density of a material is sensitive to variations in moisture content [53].

Because similar behaviour was detected in samples from the same plant, the present analysis includes only one representative data curve for each power plant using the modified Proctor test. The relationship between moisture and dry density is shown in the curves plotted in Fig. 5.

All analysed BBA samples had flat curves, which suggest that these materials can tolerate large variations in moisture content without compromising their density during compaction. None of the tested samples showed sharp curves. Thus, flat curves indicate that the materials are not sensitive to changes in moisture content. This implies that the moisture content is close to the optimum value during compaction.

The California Bearing Ratio (CBR) Test performed is indicative of the ratio of force per unit area required to penetrate a soil mass with standard circular piston at the rate of 1.25 mm/min to that required for the corresponding penetration of a standard material. The CBR test was carried out in both unsoaked and 4-day soaked conditions, and the results are summarised in Fig. 6.

According to the results, under unsoaked conditions, the PG sample presented the highest value of CBR (39%) followed by the L sample (29%). Otherwise, the V sample showed the lowest bearing capacity (24%). The measured values are consistent with the data obtained by previous authors [54] which characterised bottom ashes for be applied in civil infrastructures. From the comparison between CBR data unsoaked and after 4 day soaked it can be concluded that the influence of the soaked period was negligible on the CBR values for all cases.

5. The use of BBA in civil infrastructures

5.1. Statistical analysis on by-product variability

To evaluate the variability in product properties, it is essential to know how the material is produced at each plant. High product variability is not desired if the product is to be reused. Products with more homogeneous properties tend to be easier to reuse and revalorise. Therefore, the present paper includes a statistical study on the response/variability of the main variables that were measured.

The correlation between absorption and SSD density is illustrated in Fig. 7. A significant correlation between these two factors was determined for samples from plant L, which had a R^2 factor of 0.907. However, a lower R^2 factor (0.581) was obtained when specimens from all three plants were considered.

The high R^2 factor indicates that the adsorption and SSD density of samples from plant L were highly variable, which was confirmed by the wide distribution of values for SSD density.

To evaluate the variability of physical and mechanical properties, the SSD density, absorption and friability data are represented by whisker plots. These plots are especially useful for indicating whether a distribution is skewed and determining the presence of any unusual observations (outliers) in the data set. The main statistical data are summarised in Table 4.

The lower and upper whiskers, which represent the minimum and maximum data points, are shown in Fig. 8. The first quartile indicates the lowest 25% of the data set, the median separates the lower and upper 50% of the data set, and the lowest 75% represent the fourth quartile [55].

According to the data set, the friability coefficient showed the greatest variability, which indicates that the BBA could experience variable mechanical attrition under loading. This behaviour is apparent for the samples from plants L and V. Samples from plant PG presented more homogeneous values.

The adsorption and density of samples from plants PG and V were the most consistent. Additionally, samples from plants PG and L also had the lowest densities. From a physical point of view, low density BBA could have decreased wear resistance when it is used as a construction material. A high absorptive capacity is important if BBA will be used in cement-treated materials. The absorptive capacity of a material is an important property when calculating the proportions of concrete mix. Any excess water that is present in cement aggregates will be incorporated into the cement paste and give a higher water/cement ratio than expected (see Fig. 9). Q3

5.2. Feasibility of BBA use in civil infrastructures

The engineering properties of construction materials determine their potential use and application in civil works. The material characteristics must satisfy the engineering functions that contribute to the durability and quality of the entire road structure [56]. Thus, the present work was a thorough study on the potential

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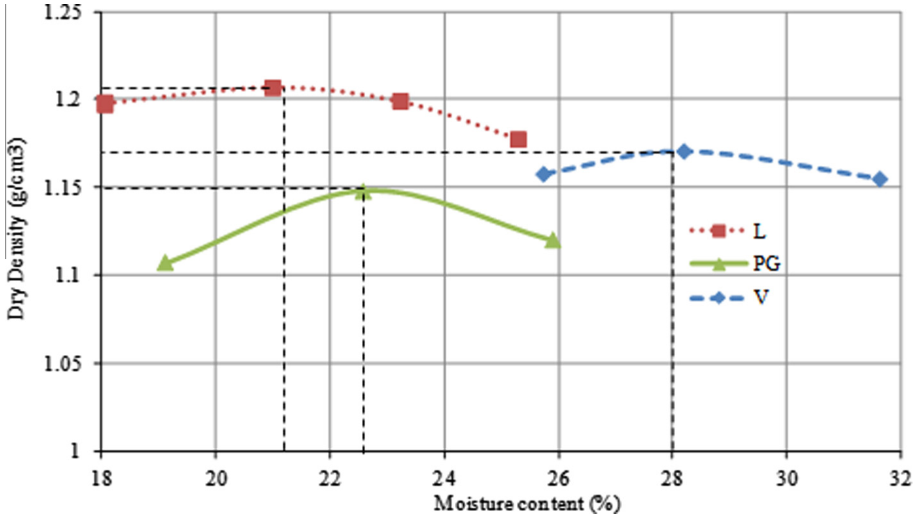

Fig. 5. Moisture–density relationship.

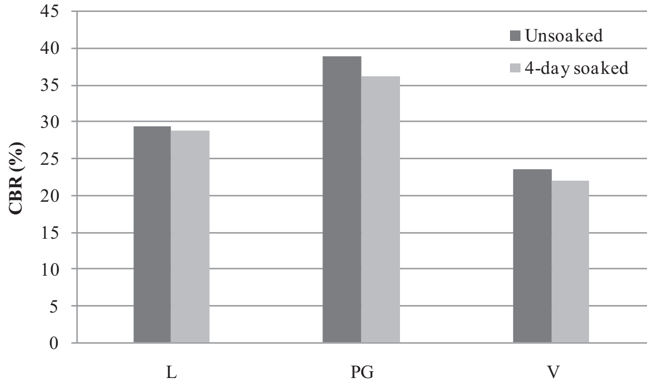

Fig. 6. CBR values.

use of BBA as a civil infrastructure component. Previous works have proved the feasibility of reusing industrial residues from different origin which have been applied in road construction and in hot bituminous mixed manufacturing [57,58]. A construction material must be erosion resistant (measured by friability), compactable (analysed according to the modified Proctor compaction test), dimensionally stable (confirmed by collapse and swelling tests), and demonstrate adequate material drainage (according to granulometric curves), bearing capacity and stability with respect to variations in material volume (analysed with plasticity tests).

The Spanish technical specification for roads [20] was used as a reference for the present work because it provides a set of limit values for the main relevant parameters to ensure proper material function. Thus, the article 330 of the mentioned specification includes the technical requirements (listed in Table 5) for materials that will be used as filler aggregate in embankments.

According to the chemical, physical and mechanical data obtained in the performed tests, all BBA can be classified according to the technical requirements detailed in Table 5. The most limiting factor is organic matter content. As a consequence, BBA samples from combustion plants L and PG were classified as subsidiary materials, whereas the samples from plant V were rejected for use in civil works because the samples contained greater than 5% organic matter. It is important to remark that regardless of the organic matter content, all BBA samples contained an adequate content of soluble salt and possessed proper granulometric properties. The appropriate tests were performed to investigate material plasticity, collapse and swelling.

The liquid limit, plastic limit, and plasticity index of BBA were analysed according to the European standard EN 103-104, which determines whether a material is non-plastic by evaluating the response of the material to variations in moisture content and if it satisfies the conditions described in Table 5. The procedure described by the standard UNE 103-601 [59] (expansiveness test)

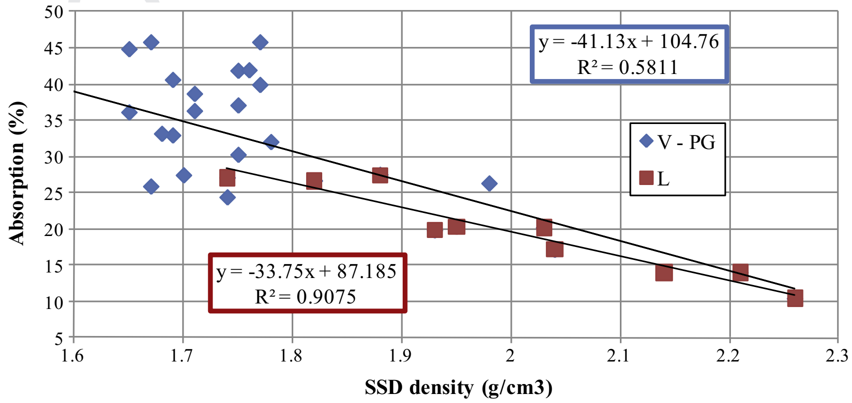

Fig. 7. Correlation between absorption and SSD density.

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Table 4
Summary of statistical data.

		Minimum	Maximum	Average	Variance	Typical deviation
Absorption	L	10.41	27.45	19.68	35.64	5.97
	PG	25.84	45.69	39.31	43.86	6.62
	V	24.35	38.59	31.99	21.52	4.63
Density	L	1.74	2.26	2.00	0.028	0.16
	PG	1.65	1.77	1.72	0.002	0.04
	V	1.42	1.98	1.70	0.018	0.136
Friability	L	25.6	34.0	29.98	6.45	2.54
	PG	29.6	35.6	32.93	4.00	2.00
	V	24.5	35.0	28.33	9.65	3.10

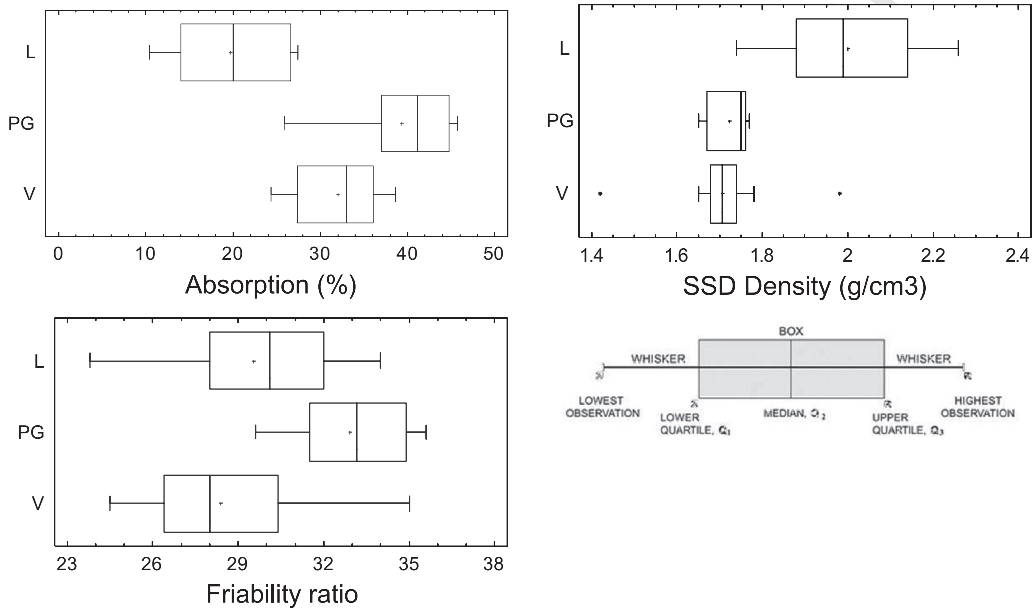

Fig. 8. Whisker plots of measured data (SSD density, absorption and friability).

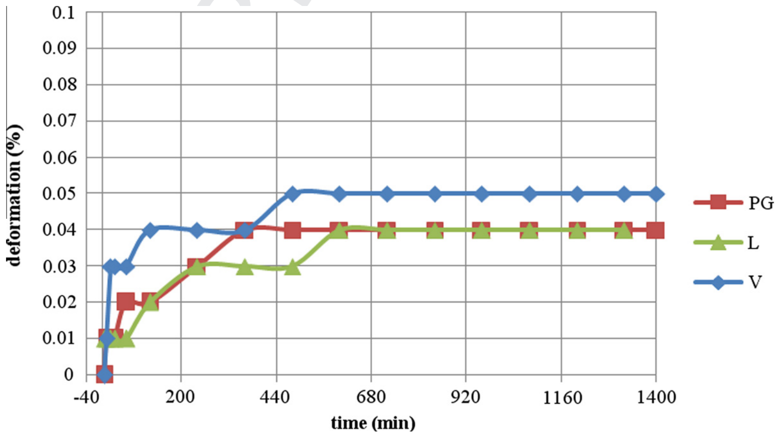

Fig. 9. Swelling behaviour of BBA tested according to UNE 103-601.

was performed to quantify the expansive capacity of the material. Only few, negligible deformations were observed on the BBA samples after testing.

Once the BBA samples from plants L and PG were classified as subsidiary materials, their proper use in construction materials on road work structures was analysed.

Section/article 330.3.2 describes the technical conditions that must be satisfied by subsidiary materials in order for them to be used in embankments. For this type of application, aggregates must filter through a 20 mm sieve opening. Greater than 70% of the materials passed through a 0.08 mm sieve, which exceeds the 35% that was specified. As shown in Fig. 2, 100% of all BBA samples

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Table 5
PG-3 requirements.

	Soil classification according to PG-3 requirements			
	Subsidiary	Tolerable	Appropriate	Selected
Organic matter content	<5%	<2%	<1%	<0.2%
Soluble salt content	–	Gypsum < 5% other salts < 1%	<0.2%	<0.2%
Granulometric	–	–	Dmax < 100 mm Pass # 2 < 80% Pass # 0.08 < 35%	Dmax < 100 mm Pass: # 2 < 80% Pass: # 0.40 < 75% Pass: # 0.08 < 25%
Plasticity	Si LL > 90 → IP < 0.73 (II-20)	LL < 65 Si LL > 40 → IP > 0.73 (II-20)	LL < 40 Si LL > 30 → IP > 4	LL < 30 IP < 10
Collapse	–	Settlement < 1%	–	–
Swelling	<5%	<3%	–	–

Footnote: condition not required.

passed through the 20 mm sieve. Therefore, all BBA samples satisfy the requirement for use as a filler material in the core of road embankments over 5 m in height without additional precautionary measures, such as the construction of road shoulders.

6. Conclusions

In this study, the behaviour of biomass bottom ash was characterised in an effort to implement a sustainable energy strategy for power plants operating in Andalusia and reduce the amount of biomass waste generated by energy production. The potential of using BBA in construction materials was assessed according to the Spanish technical specification PG-3.

The data obtained in this study confirm the potential use of biomass bottom ash from wood combustion and agricultural olive residues as filler material in road embankments.

Despite the continuous grain size distribution of BBA, which facilitates material compaction, the low density and high absorptive capacity of BBA confirms that it is composed of particles with a low specific weight. This composition could cause the material to rapidly degrade under mechanical load, disintegrate when exposed to water, or develop fractures from the formation of ice within its pores.

The flat curves obtained by the modified Proctor test confirm that BBA is little sensitive to changes in moisture; samples with higher water content had increased organic matter content. From an engineering point of view, the organic matter, which predominantly depends on the combustion process of the plant, is the most inconsistent factor. Therefore, BBA that was produced by plant V was discarded. The efficiency of the combustion systems used in plants PG and L produced by-products that could be used in a diverse range of applications. In response to friction, BBA disintegrated. However, the friability results did not exceed the requirements imposed by the cited regulations.

The present study demonstrates that BBA from plants L and PG can be used as filler material in embankments in accordance with Article 330 of the Spanish Technical Specifications for the Construction of Roads. Based on these regulations, BBA was classified as a subsidiary construction material that is suitable for use in embankment cores. By reducing the level of organic matter, BBA could be used in a wider range of civil infrastructures.

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