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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.

The 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.v

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.