Construction and Building Materials 124 (2016) 582–588

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Novel coal bottom ash waste composites for sustainable construction

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HIGHLIGHTS

- Novel materials can be manufactured from coal bottom ash wastes.
- Sustainable construction is possible for cement paste composites.
- Alternative materials can be produced for control low-strength applications.
- Developing sustainability strategies in building construction to reduce CO_2 emissions is mandatory.
- Comprehensive literature review on the topic is provided.

ARTICLE INFO

Article history:
Received 22 March 2016
Received in revised form 27 July 2016
Accepted 29 July 2016

Keywords:
Bottom ash
Paste
Sustainable construction
Composite
Sulfate
Lightweight

ABSTRACT

The construction industry generates large amounts of greenhouse gases, which negatively impact the environment and society. International actions have increased to reduce the carbon footprint of this industry. A way to achieve this target is by promoting a sustainable construction industry e.g., by recycling bottom ash waste for producing ecological products. This paper examines the potential use of coal bottom ash residue, obtained from a brick-producing factory, in cement pastes. The physical, mechanical, and sodium sulfate test results revealed the lightweight nature of the prepared composites, which are suitable for use in brick, tile, paving stone, and controlled low-strength applications.

1. Introduction

Portland cement (PC) is widely used in the construction industry. Specifically, PC is the most widely used component in concrete [1], and its use accounts for ~90% of the world's carbon dioxide (CO_2) emissions [2], which are known to have detrimental impacts on the environment and society. In most parts of the world, the replacement of clinker with supplementary cementitious materials (SCMs) is the conventional way to reduce CO_2 emissions, provided the SCM is a low-carbon material (e.g., fly ash or bottom ash) [3,4].

There is a growing interest in a sustainably built environment, and green technologies are gaining worldwide attention. However, such non-traditional technologies typically require more investment to achieve high efficiencies when compared with established traditional technologies [5–8]. To this effect, Wu et al. suggested introducing a carbon-labeling scheme to encourage benchmarking and to develop sustainable building construction [6].

Sustainability is popular in the construction industry when metropolitan areas are considered. Building sustainability became popular in the 1990s and its assessment criteria have been used to incorporate sustainability into the building industry worldwide [9]. As the construction industry is developing, so is the demand for sustainable materials. Thus, considering the need for changes in performance, building designers are working toward including new procedures in design processes by considering environmental issues [10]. The global need for construction materials is estimated to be 13,000 ton/year for a sustainable construction industry; and 80% of those materials constitutes of limestone, clay-based materials, and sand [11].

The American Coal Ash Association has supported the use of coal combustion products (CCPs) to help achieve environmental friendly, technically sound, commercial, and sustainable building construction since 1968 [12]. CCPs have been used in diverse applications for over 2000 years. The Resource Conservation and Recovery Act is the principal governing statute for the management and use of CCPs. Furthermore, the use of CCPs has been assessed by the U.S. Environmental Protection Agency; the evaluations revealed that CCPs do not present a significant risk to the environment [13].

As an example of a CCP, bottom ash (BA) consists of coarse granular particles, which can be collected at the base of boilers. BA is

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http://dx.doi.org/10.1016/j.conbuildmat.2016.07.142
0950-0618/

typically ground before use to accelerate pozzolanic reactions and thus can be used to replace PC [14]. BA is widely used as an aggregate to replace fine and coarse aggregates (ingredients used in manufacturing concrete blocks) to control low-strength applications [15–19]. BA is additionally used in embankments, waste stabilization, municipal solid waste (MSW) management, and road base/sub-base, and as an ingredient in cement manufacturing [12,13,20–23]. However, BA is primarily used in road construction and structural fills [13,24–26]. Additionally, some high-strength concrete (HSC), fiber-reinforced, and self-compacting BA applications have been reported [27–29].

BA is an alternative construction material to cement and can be used as a replacement for sand in bituminous mixtures and as a fine aggregate replacement in the production of concrete. Its porous nature makes it unsuitable for hot-mix asphalt applications. However, there are many other applications in cold-bonded asphalt systems where grain size distribution and durability requirements are not as critical as in hot mixtures [13,30–32]. Lightweight cement-based composites offer many advantages such as reduced weight, strength, durability, low expansibility, good thermal and sound insulation, and ease of use in construction. Moreover, the final product is inexpensive. Therefore, the use of lightweight cement-based composites in many applications has enabled reduction in CO_2 emissions and improved energy conservation. Many countries have studied the use of waste materials in concrete to improve the engineering properties of cement such as density, strength, and thermal and acoustical properties [33,34]. A review on the use of BA-based waste materials in concrete is provided below.

Keulen et al. [35] investigated the performance of treated and MSW for the incineration of BA in specifically designed dry and wet treatment processes to realize the sustainability strategies set by the European Union (EU) Construction Products Regulation (CPR 305/2011/EU, http://ec.europa.eu/growth/sectors/construction/product-regulation_en). The authors reported that the fresh and hardened properties were superior to those of the reference concrete mixtures [35]. Jang et al. studied the resistance of BA mortar against carbonation and chloride diffusion. The authors found that the attack of BA mortar by chloride was less pronounced than that of mortars using blend cements [36]. Garcia-Lodeiro et al. proposed the combination of fly ash and BA as an alternative raw material in alkali-activated hybrid cements. The leaching test results showed that the proposed hybrid cement could neutralize potentially hazardous metals present in BA [37]. Singh and Siddique investigated coal bottom ash (CBA) as a replacement for sand by evaluating the workability and strength properties of concrete. The results showed that the later age strength of the BA concrete mixtures was similar to that of reference concrete mixtures [38]. However, the concrete mixture comprising BA showed a lower resistance to abrasion than the reference mixtures examined [39]. Additionally, the pulse velocity through BA concrete mixtures indicated that a better-quality concrete could be prepared using CBA as a replacement for fine aggregates [38]. Tang et al. studied the characteristics and application potential of MSW BAs from two plants. The authors observed that the use of fine BA had detrimental effects on cement hardening and mortar strength [40]. Xie and Ozbakkaloglu investigated the behavior of low-calcium fly and BA-based geopolymer concrete cured at ambient temperature. The density and homogeneity of the geopolymer concrete increased with increasing fly ash-to-BA mass ratios [41]. Song et al. studied the effect of BA as an aerating agent in the production of autoclaved concrete. The results showed that the loss of water to aeration was more rapid and that the resistance to chemical attack was adversely affected in pastes composed of larger contents of BA aerating agent [42]. Kim et al. studied the chloride resistance of HSC composed of BA aggregates. Based on the laboratory results, BA in HSC could considerably reduce chloride dispersion [43].

Menéndez et al. investigated the mechanical behavior of cement mortars containing either fly ash or BA as a cement replacement. Their results showed that mortars manufactured with either ordinary PC or BA had similar or even better mechanical behavior than mortars manufactured with fly ash. The authors concluded that partially replacing cement with BA might be as suitable as, if not better than, replacing it with fly ash [44]. Aggarwal and Siddique studied the incorporation of foundry sand and BA. The results showed that incorporating foundry sand and BA, as sand replacement, had no adverse effects on the strength properties as long as the replacement level was maintained to below 60% [45]. Carrasco et al. assessed the use of blocks containing BA as a replacement for cement. The results showed that BA increased the porosity and decreased the thermal conductivity and strength of the final product. However, the authors reported that a 1:1 Si/Ca mixture showed superior strength properties, which are suitable for use in the manufacturing of building blocks [46].

Singh and Siddique studied the strength and microstructural properties of concrete composed of various amounts of CBA as a replacement for fine aggregates. The results indicated that, at a given water-to-cement ratio, the consistency and loss of water from bleeding could be reduced in the presence of CBA [47].

Cabrera et al. assessed the potential of biomass BA in civil infrastructures and showed that biomass BA possesses desirable properties for use as a filler material in road embankments [48]. Singh and Siddique studied the compressive strength and chemical stability of concrete by incorporating CBA as a partial or total replacement for fine aggregates. BA concrete exhibited better dimensional stability and slightly better resistance to sulfuric acid attack than normal concrete [49]. Kuo et al. investigated washed MSW incinerator BA as a replacement for aggregates in porous concrete [50]. Arenas et al. studied CBA for designing sound-absorbent materials for highway noise barriers. The sound properties of the final composites were similar to, or even better than, those displayed by porous concrete used in the same applications [51]. Zhen et al. investigated the use of low load-bearing materials obtained from sludge and refuse-incinerated BA. The results revealed that BA could be used [52]. Vu et al. examined the manufacturing of a ceramic composed of BA and fly ash. The results showed that fabrication involving sintering consumed more energy than conventional production methods [53].

Siddique et al. examined the effect of the water-to-cement ratio on the mechanical properties of self-compacting concrete composed of fly ash and BA. The best result performance was achieved at BA contents of less than 20% [54]. Qiao et al. studied the fine fraction of incinerator bottom ash treated at 800 °C for manufacturing cementitious materials. The final composites had compressive strengths of $\sim$15 MPa following curing for 28 days [55]. Maschio et al. studied the rheological behavior of pastes composed of fly ash and BA. Both types of ashes altered the rheological behavior of the mortar. However, the samples displayed a significant reduction in compressive strength and an increased content of both types of ashes after 180 days of testing [56].

There is now increasing recognition in the scientific society that conventional PC composites are unsustainable and that it is necessary to recycle large volumes of wastes produced by industries. In light of the discussion above, the fabrication of environmental friendly low-cost building products from industrial wastes are being examined at the laboratory scale toward developing sustainability strategies in building construction to reduce CO_2 emissions.

The present study thus examines the use of bottom ash waste as a cement replacement to produce ecological building materials. The performance and suitability of bottom ash waste were