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Strength activity and microstructure of blended ultra-fine coal bottom ash-cement mortar

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HIGHLIGHTS

- Pulverized BA increases the setting time and workability of mortar.
- Pulverized BA strength activity can be retained above 100% at high replacements.
- C-S-H in the fine pulverized bottom ash has lower Ca/Si ratio.
- CH consumption depends on pulverized BA fineness levels.

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ABSTRACT

Replacing Portland cement with reutilized coal combustion products can have substantial benefits to the environment as well as infrastructure. In this study, a sub-bituminous coal bottom ash is re-utilized as a cement replacement. The bottom ash was pulverized using a high energy vibratory ball mill at two different milling times to achieve a particle fineness approximately two and three-times finer, respectively, than type I cement. The workability and final setting time were found to increase by 21% and 14%, respectively, and the highest strength activity was observed to be 120% at 90 days. After normalization for particle fineness, age, and binder replacement using a general linear regression model, the data suggested the bottom ash blended cement mortar had 6.8% less strength activity than a comparative fly ash blended cement mortar. Blended bottom ash-cement paste samples were observed to have densely packed CSH product composed of relatively lower Ca/Si ratio (1.37) compared to that of fly ash blended cement paste (1.43) and the control (2.27). The CH content was also observed to be significantly lower in the bottom ash blended cement paste (19.1%) when compared against the control (27.2%) and fly ash blended paste (23.3%). Within the range of experimental conditions considered here, the results suggest that a coal bottom ash can be pulverized with a high energy ball mill to produce a re-utilizable pozzolan that, depending on the powder fineness, can significantly increase the strength activity, improve the microstructure of cement mortar, and increase the cement replacement tolerances without significant reduction to compressive strength activity.

1. Introduction

In 2015 approximately 117 million tons of coal combustion products (CCPs) were produced in the United States, while only 61 million tons were re-utilized beneficially (52%) [1]. Fly ash (FA), is one of the most common reutilized CCPs (24 million reutilized tons in the U.S. at a 55% reutilization rate), which is used beneficially as a supplementary cement replacement. Coal bottom ash (BA), the incombustible granular and porous residue found in the bottom of the combustion furnace [2], is not reutilized in the U.S at the same rate as FA (4 million tons reutilized beneficially at a 33% reutilization rate). BA is mostly limited to road base substitution or cement feed stock applications [1]. Additional pathways for BA applications are needed to increase the reutilization rate and decrease the amount of landfilled ash.

Reutilizing BA as fine or coarse aggregate has been studied and shown to significantly decrease the concrete unit-weight and yield adequate compressive strength [3–5]. Coal bottom ash has also been used as an internal curing source due to its high porosity and steep desorption; essentially allowing fluid to permeate from the internal porous reservoirs to the surrounding matrix without

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requiring significant changes to internal capillary pressure to generate the fluid displacement [6]. The porous BA also has been shown to increase capillary water absorption which tends to extend drying time [7], lower drying shrinkage [8,9], decrease unit weight, and increase air content [10].

As a cement replacement, pulverized BA can increase the compressive [11] and flexural strength [12], strength activity, and pozzolan reactivity. The mechanical properties of the concrete or mortar, will however, depend largely on the pulverization and particle fineness [13]. Additional thermal treatments can also be applied to the BA to decrease the Loss on Ignition (LOI), decompose the calcium carbonate [14], and increase pozzolan reactivity [15]. Although BA has been reutilized in both cement and aggregate concrete applications, it has been done with varying success. Most of the studies have focused on low cement replacement dosages (<30%) or utilized bottom ash at moderate fineness (~400 m^2/kg). The performance of the coal bottom ash blended cement mortars can be potentially improved, however, by increasing powder fineness through pulverization with high energy ball milling. Improved performance and higher cement replacement dosage tolerances can provide industry with a stronger justification to use coal bottom ash for cementing applications and ultimately serve to increase the ash product reutilization rate.

In this study, a high fineness BA (~1000 m^2/kg), achieved by means of high energy vibratory ball milling, is reutilized in cement mortar applications. At high fineness levels, the particles approach the nanometer range which can alter the microstructure of the blended mortar and increase strength activity, even at high volume replacement dosages. The high fineness BA powders are studied here under a wide range of replacement dosages. The data reported in this study is then combined with data reported from the literature and a general linear model is derived using ANOVA to robustly quantify the experimental variance associated with strength activity using fineness, cement replacement dosage, age, and type of supplemental cementitious material (bottom ash or fly ash) as predictors.

2. Materials and methods

2.1. Bottom ash pulverization

The raw BA was ground into fine powder using a high-energy vibratory ball mill (V80, Columbia International Inc., USA) using a ball-to-particle ratio of 3-to-1 (by mass) under ambient conditions at two different pulverization time periods: 0.5 and 3 h. Fig. 1 shows a photograph of the vibratory ball mill. The hardened stainless-steel milling chamber was loaded with 25 g of raw bottom ash and 75 g of SS316 hardened stainless-steel balls: 12.5 g of 4 mm diameter steel balls and 62.5 g of 9 mm diameter steel balls. The chamber volume was 80 ml and rotated at a rate of 1200 rpm. The chamber was supported by a radial pin that was connected to the external base by a flexible spring; allowing the chamber to move in three-dimensions during operation: 1) rotational displacement along the longitudinal axis, and 2) translational vibratory displacement oscillation in both the vertical and lateral directions. During the ball milling process, the particles were trapped between the balls and chamber walls, and undergo continuous impact fracturing which results in the refinement of particle size. The powder particle size can be further reduced by increasing the milling time. In the present study, the milling times of 0.5 and 3 h produced bottom ash powders with fineness approximately twice (~800 m^2/kg) and three times (~1100 m^2/kg) the fineness of standard cement and class F fly ash powder, respectively. Hereafter, the two respective pulverized powders are denoted as PBA(I) (0.5-h mill time) and PBA(II) (3-h mill time).

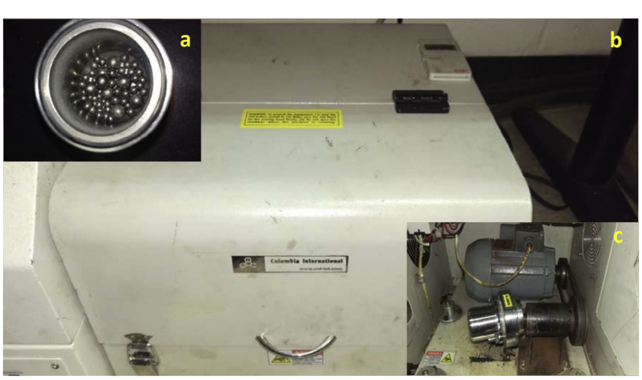

Fig. 1. (a) Stainless steel ball distribution within milling chamber, (b) External view of high energy vibratory ball mill (Model: CIT-VBM- V80), (c) Internal view of high energy vibratory ball mill motor and supporting pin and flexible spring.

2.2. Materials

The cement mortar was casted using ASTM C778 sand [16], ASTM C150 type I Portland cement (PC) [17], class F FA (for the FA binary blended mortar mixes), and pulverized sub-bituminous bottom ash (for the PBA binary blended mortar mixes). The raw BA was obtained from the Coleto Creek Power Plant near Fannin, Texas, U.S.A. The raw BA material was granular and dark gray. The gradation of the ASTM C778 sand, and raw BA is provided in Fig. 2. The chemical composition of the PC, FA, and BA are provided in Table 1.

The particle size distributions of each cementing powder (PC, FA, PBA(I) and PBA(II)) are shown in Fig. 3, determined by particle size counting using images obtained from a scanning electron microscope (SEM, Hitachi 3400N) at two different magnifications (500X and 3000X). Fig. 4 shows the images at 500X magnification for the PC, FA, PBA(I), and PBA(II).

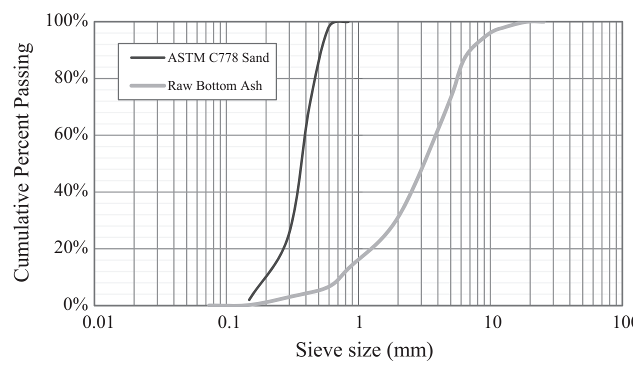

Fig. 2. Cumulative size distribution of the ASTM C778 graded mortar sand and as-received BA.

Table 1
Chemical composition of PC, FA, and BA.

Chemical composition (wt%)	PC (I)	FA	BA
Silicon Dioxide (SiO_2)	20.6	52.0	58.7
Aluminum Oxide (Al_2O_3)	4.4	23.0	20.1
Iron Oxide (Fe_2O_3)	3.3	11.0	6.2
Calcium Oxide (CaO)	62.9	5.0	9.5
Magnesium Oxide (MgO)	2.2	–	1.6
Sulfur Trioxide (SO_3)	2.7	0.8	0.4
Sodium Oxide (Na_2O)	0.2	1.0	0.1
Potassium Oxide (K_2O)	0.5	2.0	1.0
Loss on ignition (LOI)	1.3	0.8	0.8

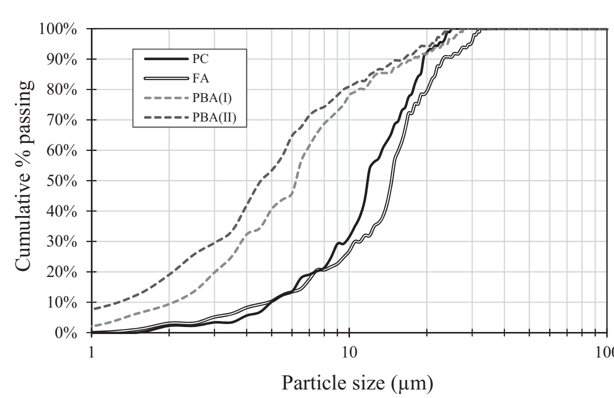

Fig. 3. Particle size distribution of PC, FA, PBA(I), and PBA(II).