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Properties of sintered low calcium bottom ash aggregate with clay binders

S. Geetha, K. Ramamurthy *

Building Technology and Construction Management Division, Department of Civil Engineering, Indian Institute of Technology Madras, Chennai 600 036, India

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ABSTRACT

This paper focuses on the properties of sintered aggregates with low calcium bottom ash from coal fired thermal power plants using a wide range of clay binders through pelletization process. The experimental runs were designed using central composite design of response surface methodology. The aggregate was produced using a disc pelletizer. The pelletized aggregate was sintered at 800–1100 °C for 30–120 min. Sintered aggregates were tested for bulk density, 10% fines value and water absorption. The factors involved in the process are moisture content, binder, $Ca(OH)_2$ dosage, sintering temperature and duration. It was observed that an increase in binder dosage and sintering temperature resulted in aggregates with higher 10% fines value and low water absorption. The properties of aggregates depended on the type of binder used. Aggregate with kaolinite and metakaolin binders resulted in high 10% fines value. The results indicate the potential for manufacturing high quality lightweight aggregate from bottom ash using clay binders.

1. Introduction

Artificial lightweight aggregates (LWA) are produced either using natural materials such as clay, shale, slate, diatomite and perlite or industrial by-products viz., blast furnace slag, fly ash, sewage sludge ash [1]. LWA are produced from naturally occurring materials by agglomerating the raw materials and heating them to high temperature inside a rotary kiln to expand or bloat [2]. Binders like cement, lime, bentonite, silicon carbide, dextrin, waste liquor and marine clays were used to improve the properties of LWA [3–7]. Addition of binders have been reported to improve the efficiency of the production, enhance mechanical properties such as strength, water absorption, density and alters the chemical composition [8,9]. Pelletization includes cohesive and tumbling forces which bridges moistured particles. The green pellets after being air-dried attain sufficient strength for handling but not to the extent for its use in concrete. Hence hardening mechanisms have to be adopted to make the pellets hard enough to be used in concrete. Sintering is the most commonly used hardening method for the production of light weight aggregate with clay binders, at a temperature range of 1000–1300 °C. During sintering, depending on the type of raw materials used, the fusion of particles at higher temperature causes physical and chemical changes in the aggregate.

In India over 75% of the total installed power generation is coal-based. High ash contents varying from 30% to 50% are generated during the power generation. More than 110 million tonne of ash is generated every year. Presently 65,000 acres of land are occupied by ash ponds. It has been observed that disposal of ash may lead to arsenic and lead pollution [10]. Though extensive studies have been reported on the use of fly ash, limited studies have been reported on the use of bottom ash. A systematic pelletization study carried out by the authors revealed that (i) raw bottom ash resulted in lower pelletization efficiency, (ii) though pulverized bottom ash could be pelletized they disintegrated upon sintering, (iii) addition of binders enhanced pelletization efficiency, (iv) the duration of pelletization process was influenced by the addition of $Ca(OH)_2$ and binder dosage and (v) for aggregate with clay binders binder dosage and moisture content had significant effect on the pelletization efficiency [11]. Though factor levels and their interaction effects have been identified for achieving maximum pelletization efficiency in the above investigation, this paper discusses the relative influence of type of binder and its dosage, sintering temperature and duration on bulk density, strength and water absorption of bottom ash aggregate using statistically designed experiments.

* Corresponding author. Tel.: +91 44 22574265; fax: +91 44 22574250.
E-mail address: vivek@iitm.ac.in (K. Ramamurthy).

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Table 1
Physical and chemical characteristics of clay binders and bottom ash.

Physical properties	Pulverized bottom ash	Kaolinite	Metakaolin	Clay (PI: 78)	LSB	MSB	HSB
Specific gravity	1.6	2.59	2.57	2.51	2.53	2.52	2.65
Fineness (m^2/kg)	212	480,00	160,00	176,789	164,345	136,885	200,420
Plasticity index (%)	–	32	35	78	108	208	370
SiO_2	53.68	46.67	45	44.56	45.3	46.67	41.84
CaO	1.24	1.37	0.06	1.12	1.53	1.37	0.83
Al_2O_3	18.91	22.72	38	20.86	22.01	22.72	20.94
Fe_2O_3	7.7	11.94	0.60	13.4	11.54	11.94	11.09
MgO	0.48	1.47	0.07	2.34	1.16	1.47	1.39
TiO_2	–	0.086	0.55	0.15	0.19	0.086	0.077
Na_2O	0.7	1.20	0.15	1.02	1.23	1.20	2.97
K_2O	–	0.14	0.10	0.23	0.42	0.14	0.09
SO_3	0.19	–	–	0.23	0.86	–	–
MnO	–	–	–	0.34	0.67	–	–
Carbon	5.51	–	–	–	–	–	–
LOI (%)	8.35	14.75	14.5	15.67	14.67	14.75	19.73

2. Materials and methodology

2.1. Materials

Bottom ash (BA) collected from a local coal-based thermal power station, having chemical composition similar to class-F fly ash [12] was used. Its physical and chemical properties are presented in Table 1. Clay binders viz., kaolinite, metakaolin, clay with a plasticity index of 78, low, medium and high swelling bentonites (LSB, MSB, HSB) have been used to facilitate pelletization. The physical and chemical properties of these binders are also presented in Table 1.

2.2. Methodology

To study the relative influence of various factors on the properties of aggregate and to determine the optimum value of factors response surface methodology (RSM) of central composite design, with 32 sets of experiment was designed. A five-factor, five-level central composite design with a quadratic model was used. The factors considered for pelletization are moisture content, $Ca(OH)_2$ dosage, binder dosage, sintering temperature and time. The parameters were carefully selected to carry out composite factorial design, where the effect of each factor was evaluated at five different levels, in coded values of $-\alpha$, -1, 0, 1, $+\alpha$. The value of α was chosen so that the variance of the response predicted by the model would depend only on the distance from the centre of the modeled region. The value of α was taken as ±2. Each independent variable had five levels which were -2, -1, 0, +1 and +2. A total of 32 different combinations (including six replicates of centre point with the coded value 0) were chosen in random order according to a central composite design configuration for five factors. The factors and their levels which were identified from the first phase of experiments are presented in Table 2. The pelletization of bottom ash was carried out in a disc pelletizer of size 56 cm diameter and 25 cm depth. The angle of tilt of the pelletizer was fixed at 55° and the speed of the disc was maintained at 50 rpm. The pelletized aggregates were air-dried and then sintered in a muffle furnace. The sintering temperature was varied between 800 °C and 1100 °C and the sintering duration between 30 and 120 min. The percentage of each size fraction was determined through sieve analysis. Bulk density was determined as per ASTM C 29/C 29M-07 [13]. The strength of the aggregate, determined through 10% fines value by BS 812-111 (1990) [14]. Twenty-four hour water absorption was determined on aggregate size fraction 12.5–10 mm based on ASTM C 127-07 [15] and open porosity was determined by vacuum saturation method [16]. Regression analysis was made using Statistical Analysis Software (SAS Release 8.02) [17] for estimating the coefficients in the second order quadratic response surface model.

Table 2
Factors in uncoded values for the coded values.

Notation	Factor	Coded values				
		+2	+1	0	−1	−2
		Uncoded values for factors				
Moisture content (%)						
A						
A1	Kaolinite and metakaolin	26	26.58	27	27.42	28
A2	Other clay binders	30	30.87	31.5	32.13	33
B	$Ca(OH)_2$	0	0.58	1	1.42	2
Binder content (%)						
C						
C1	Other clay binders	5	9.35	12.5	15.65	20
C2	Bentonite (HS)	5	7.69	9.5	11.39	14
C3	Bentonite (MS)	5	6.45	7.5	8.55	10
D	Sintering temperature (°C)	800	957.56	1000	1042.4	1100
E	Sintering duration (min)	30	56.8	75	93.92	120

3. Results and discussion

3.1. Factors influencing bulk density

The aggregates produced by the pelletization process were spherical. For the same grading and particle shape, it has been reported that the bulk density of an aggregate is proportional to particle relative density [18]. Hence the variation in bulk density is discussed for the influence of different factors through response surface in Fig. 1a–f. The loose bulk density of the aggregate size fraction between 4.75 mm and 16 mm ranged from 720 to 980 kg/m^3 which fall under the category of LWA as per ASTM C 125-07 [19]. For a constant sintering temperature, the bulk density of aggregate increased with binder dosage, i.e., finer binder makes aggregate denser. At 900 °C the bulk density for aggregates with 6% of binder content was 600 kg/m^3 and it increased to 950 kg/m^3 when binder content was increased to 20%. At low binder content bulk density was low (i) as voids present in coarser bottom ash did not get filled up completely and (ii) as loss on ignition (LOI) was relatively higher in binders than in bottom ash. Voids created by LOI also adds to the porosity. When the binder dosage increases, higher fines content of the binder fills the voids in coarser bottom ash which compensates the higher LOI leading to increase in density. At constant binder dosage, the bulk density increased with sintering temperature. For aggregates with 6% of swelling clay binders sintered at 800 °C the bulk density was 600 kg/m^3; (i) when the sintering temperature was increased to 1100 °C the bulk density increased to 950 kg/m^3. At a constant sintering temperature of 1100 °C, an increase in binder dosage from 6% to 20% enhanced the bulk density to 1050 kg/m^3. This could be attributed to the densification caused by elevated temperature as well as reduction in open pore volume resulting in higher bulk density [20]. During the sintering process, fluxes like sodium, potassium and calcium oxides, together with silica has been reported to begin melting into pockets of glassy phase (quartz) within the pores of the aggregate. The ANOVA results in Table 3 show that the