Engineering particle size distribution of sintered lightweight aggregates manufactured from waste coal combustion ash

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Abstract. Converting waste coal combustion ash (W-CCA) from power plants into novelty lightweight aggregates (LWA) is a viable and sustainable solution. Utilizing this waste material to produce a useful product for the concrete industry requires that the manufactured LWA adhere to industrial material regulations. This study focuses on engineering laboratory manufactured LWA to achieve aggregate gradation that meets the ASTM C330 standard. A systematic study that manipulates the degree of saturation during W-CCA paste preparation was adopted to understand the effect of moisture on LWA gradation. The degree of saturation was assessed based on the liquid (water) to solid ratio required to manufacture W-CCA paste. The investigation only alters the amount of water and recorded the gradation for fine LWA (FLWA), coarse LWA (CLWA), and combined coarse and fine LWA. L/S ratio of 0.33 achieved ASTM C330 required gradation for FLWA. A combination of L/S ratio of 0.33 and 0.34 achieved ASTM C330 required gradation for combined coarse and fine LWA. Engineering the gradation of LWA to meet ASTM required standard will allow the production of LWA from W-CCA a more attainable and practical product for the construction industry.

1 Introduction

The U.S. Energy Information Administration (EIA) reported in February 2022 that coal was the second largest energy source, generating 22% of the United States' electricity supply [1]. A by-product of burning coal for energy is solid waste, referred to as waste-coal combustion ash (W-CCA) [2]. The American Coal Ash Association (ACAA) declared in 2021 that 90 million tons of W-CCA were produced across the United States and only 60% of the produced W-CCA was utilized [3]. The 40% unutilized CCA is usually disposed of in surface ponds and landfills causing a financial burden on power plants and a hazard to the environment and human health [4]. The negative impact of storing W-CCA is an incentive

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for researchers to utilize this waste material and produce a useful product for the industry [5]. Studies have been focusing on converting W-CCA into a value-added product such as lightweight ceramic referred to as lightweight aggregate (LWA). LWA manufactured from W-CCA has been extensively studied for its beneficial characteristics and high industrial demand [5–27], however, it is associated with many manufacturing challenges that require engineering solutions before it can be available for industrial use. One of the challenges is to find suitable mix proportion between solid and liquid material needed to produce acceptable LWA grading. Furthermore, limited study could be found on the mix proportion optimalization that aims to produce acceptable LWA grading for industrial use.
Thus, this research focuses on manufacturing LWA in accordance with ASTM C330 [28] grading requirements for lightweight aggregates intended for industrial applications. The manufacturing process of W-CCA LWA through the sintering mechanism is investigated. Controlling parameters associated with the manufacturing process, that directly influence the gradation of LWA are analyzed and tailored to manufacture LWA that meet ASTM C330 grading requirement for fine LWA (FLWA), coarse LWA (CLWA), and combined fine and coarse LWA.

2 Materials and Method

2.1 Materials

Three main ingredients were used to manufacture LWA; 1) W-CCA, 2) deionized (DI) water, and 3) a fluxing agent (NaOH). The property of each material was investigated to understand how their composition contributes to the manufacturing process. Raw field W-CCA was tested by Alternative Testing Laboratories, Inc. using an Inductively Coupled Plasma Atomic Emission Spectroscopy (ICP-AES) to analyse its chemical composition. The DI water was supplied through a laboratory tap and the pH value measured was ~ 7. The fluxing agent NaOH was supplied from Macron Fine Chemicals with a Sodium Hydroxide concentration of more than 95% (Macron Fine Chemicals TM). The NaOH properties include molecular weight of 39.997(g/mol), boiling point: 1390ºC, melting point: 323ºC, density: 2.13g/cm3, grade – ACS, category R, and physical form pellets.

2.2 Manufacturing process

The manufacturing process of LWA produced from W-CCA requires both analytical and experimental investigations. The analytical investigation involves a thermochemical analysis guided by a thermodynamic modelling (FactSage software) [29] to predict material formulation and sintering temperature that can generate appropriate slag/solid ratio to produce LWA with required properties. The experimental investigation of the manufacturing process involves three main phases: (1) mixing W-CCA, D.I. water, and a fluxing agent (NaOH) to create W-CCA paste, (2) pelletizing W-CCA paste to create spherical green aggregates, and (3) sintering green pellets through a rotary furnace for particle flow, fusion, and solidification.

2.2.1 W-CCA paste preparation

In phase-1, W-CCA paste was prepared through multiple steps. NaOH-pellets (fluxing agent) were initially mixed with DI water to create a 2 wt% NaOH solution, by mass of W-CCA. The 2%-NaOH solution was then mixed with oven-dry sieved W-CCA to create W-CCA paste (Figure 1). Initial hand mixing was performed, then placed into a mechanical mixer to achieve thorough mixing. Afterward, the W-CCA paste was ready for phase-2 pelletization.

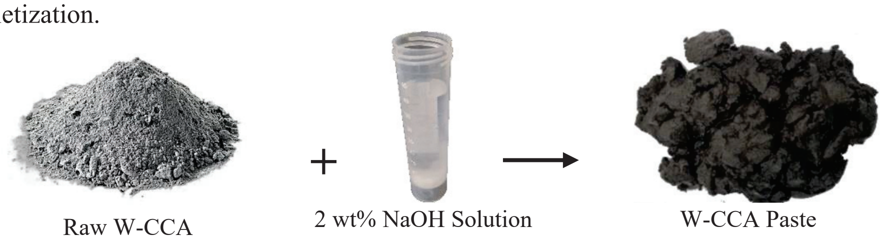

Fig. 1. W-CCA paste preparation by combining raw W-CCA with 2 wt% NaOH solution.

2.2.2 Pelletization

Phase-2 consists of pelletizing W-CCA paste to create spherical pellets. A pelletizer device (Figure 2) with pan that was set to a 45º angle for optimum pelletizing. The rotational rate was set to 10 rpm to ensure sufficient pellet formation and rolling to achieve sphericity. Through testing, spherical pellets were achieved after 6 to 7 minutes of pelletizing. The pelletizing process starting with W-CCA paste placed into the pan to create spherical pellets. During the pelletizing, oven dry (O.D.) W-CCA was added as a coating to prevent agglomeration of spherical pellets. The final spherical pellets were then placed into the stationary oven at 105 °C for 2 hours to remove excess moisture and create green spherical pellets.

Fig. 2. Pelletizer used to convert W-CCA paste into green pellet.

2.2.3 Sintering

In the sintering phase, the rotary furnace (MTI Corporation) and associated apparatus and components were configured to allow a continuous flow process (Figure 3). After green pellets were O.D. for 2 hours and no moisture was left, the dried green pellets were placed into a feeder. The feeder discharged green pellets onto a conveyor belt at a rate of 10g/2.53min. The conveyor belt transported the green pellets to a shooter that fed the green pellets into a rotary furnace. The green pellets travelled through the rotary furnace tube at a defined mean residence time (MRT) at a sintering temperature of 1075 ºC. The sintered green pellets were discharged at the collecting end as LWA. An exhaust hood was placed at the elevated end of the rotary furnace to discharge any gaseous carbon fumes. These fumes are a result of sintering and escape through the feeding end of the rotary furnace due to drag effect.

Fig. 3. Double heat zone rotary furnace used for sintering.

2.3 Parametric investigation

The property of W-CCA pastes was affected by the property and proportion of the materials used. The liquid-to-solid ratio (L/S) of the W-CCA paste affects the paste viscosity and particle size distribution (PSD) of the green pellets. W-CCA paste must contain appropriate moisture content to provide sufficient cohesion to produce green pellets with the desired PSD during pelletization. Three initial L/S ratios at 0.3, 0.35, and 0.4 were tested and the resulting green pellets are shown in Figure 4.

Fig. 4. L/S ratio effect on green pellet particle size distribution.

The coarse-to-fine measured proportions of LWA manufactured using extreme and mid-point L/S ratios were used as a starting point to determine the L/S ratio that may yield a LWA gradation that meets the ASTM C330 PSD range. The two L/S extremes (L/S = 0.3, and 0.4) illustrate either a higher quantity of either fine or coarse aggregate. Green pellets manufactured with L/S of 0.35 yielded 25% coarse and 75% fine aggregate. The PSD of the green pellets manufactured using L/S ratio of 0.3, and 0.4 indicates that their gradation does not fall with ASTM boundary conditions.

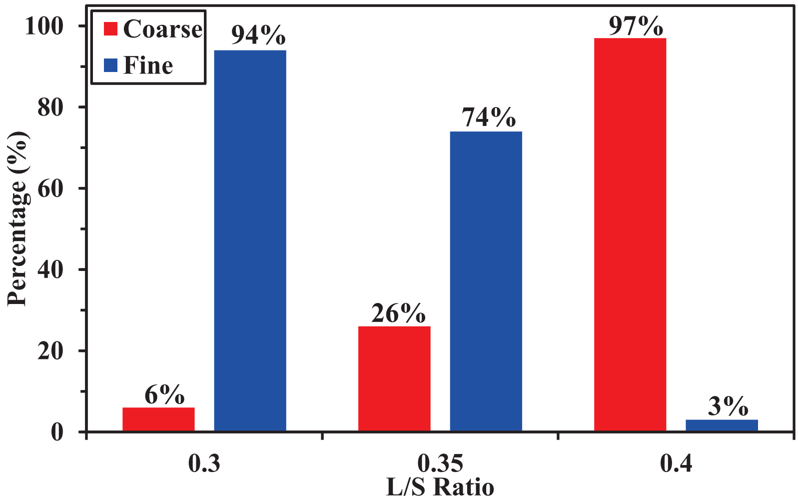

Fig. 5. Coarse-to-fine ratio of LWA manufactured using various L/S ratios.

The ASTM C330 grading for lightweight aggregates intended for structural concrete requires a nominal size designation for fine, coarse, and combined fine and coarse aggregates. The nominal size designation must adhere to mass percentage passing specified sieve sizes (Table 1).

Table 1. ASTM C330 grading requirements for LWA for structural concrete.

Nominal Size Designation	Percentages (Mass) Passing Sieves Having Square Openings								
	19.0 mm (3/4 in.)	12.5 mm (1/2 in.)	9.5 mm (3/8 in.)	4.75 mm (No. 4)	2.36 mm (No. 8)	1.18 mm (No. 16)	300 µm (No. 50)	150 µm (No. 100)	75 µm (No. 200)
Fine aggregates:									
4.75 mm to 0	---	---	100	85-100	---	40-80	10-35	5-25	---
Coarse aggregates:									
12.5 mm to 4.75 mm	100	90-100	40-80	0-20	0-10	---	---	---	0-10
Combined fine and coarse aggregates:									
12.5 mm to 0	100	95-100	---	50-80	---	---	5-20	2-15	0-10

LWA intended for various concrete applications such as lightweight concrete or internal curing of concrete structures must adhere to specific LWA gradation requirements. The concrete mix design of lightweight concrete will require LWA gradation containing a combination of fine and coarse aggregates. Internal curing of concrete requires only fine LWA (FLWA) serving as an internal water reservoir that provides internal water for hydration in the later stages of concrete curing.

3 Results and Conclusion

3.1 Fine aggregate analysis

The initial testing L/S ratio of 0.35 was used to investigate FLWA gradation. Coarse and fine aggregates were separated by sieving the manufactured LWA by sieve No. 4 (Size 4.75 mm). After sieving, the aggregates gradation was fitted along with the ASTM C330 boundary conditions for fine aggregates. The gradation curve for L/S ratio of 0.35 fell beyond the ASTM C330 boundary limits, demonstrating a need for finer aggregate to achieve the required gradation. The L/S ratio was manipulated systematically by reducing the L/S ratio of 0.01 increments until the gradation curve of the manufactured FLWA was within the ASTM C330 boundary limits (Figure 6). The investigation indicates that a L/S ratio of 0.33 was required to achieve a LWA gradation within ASTM C330 grading requirement.

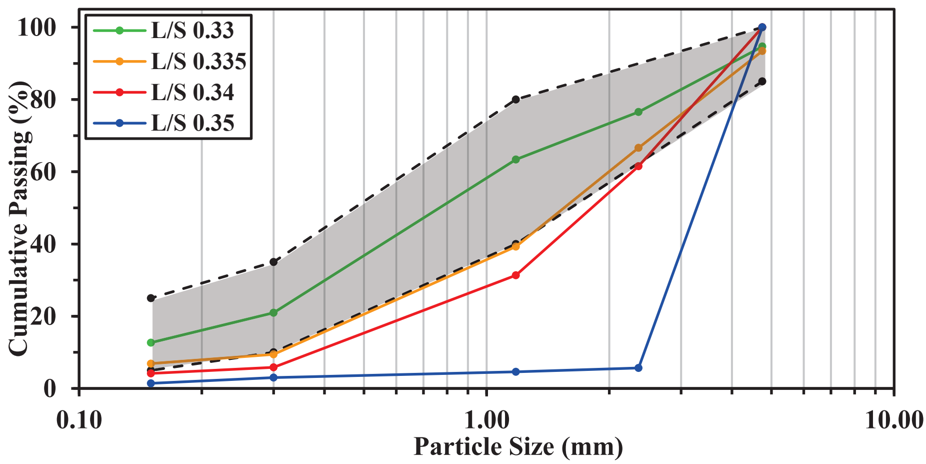

Fig. 6. Gradation of fine LWA manufactured with L/S ratios of 0.35, 0.34, 0.335, and, 0.33.

3.2 Coarse aggregate analysis

The L/S ratio of 0.35 was initially used to assess the LWA gradation in reference to ASTM grading requirement. FLWA were remove by using a sieve No. 4 (size 4.75 mm) and retained coarse aggregates were passed through the required grading assigned by ASTM C330. The LWA manufactured with a L/S ratio of 0.35 demonstrated a gradation within ASTM C330 boundary limits. Furthermore, LWA manufactured with L/S ratios of 0.34 and 0.36 were tested to understand the influence of moisture during paste preparation on their gradation. LWA with L/S 0.34 also demonstrated a gradation within ASTM C330 boundary limits (Figure 7). LWA manufactured with L/S ratio of 0.36 showed a similar distribution trend. However, this gradation failed to fall within the boundary limits at LWA size 12.5 mm.

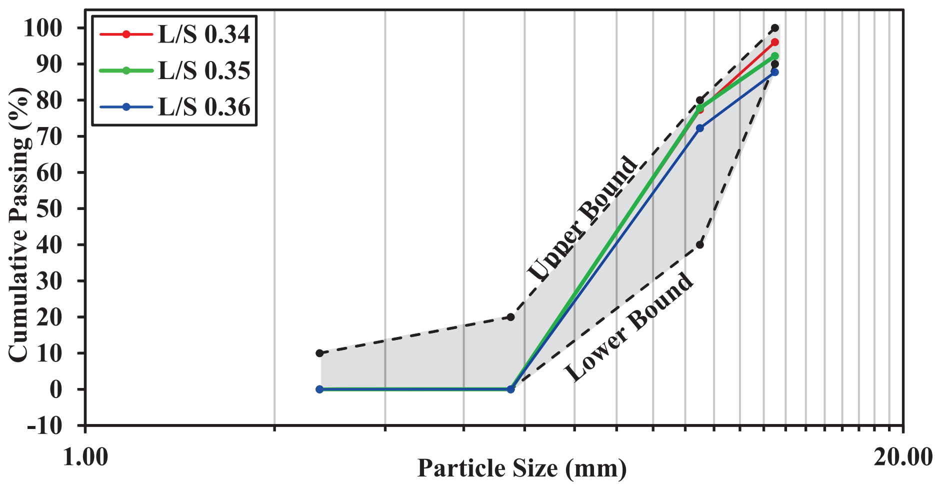

Fig. 7. Gradation of coarse LWA manufactured with L/S ratios of 0.34, 0.35, and, 0.36.

3.3 Combined coarse and fine aggregate analysis

Using the L/S ratio of 0.35 as a starting point for this investigation, its gradation was fitted between the ASTM C330 boundary limits for combined coarse and fine aggregates (Figure 8), to understand the basis for manipulating the degree of saturation in the W-CCA paste to achieve the required LWA distribution. It is understood that lowering the L/S ratio will achieve finer aggregates and increasing the L/S ratio will yield coarser aggregates. L/S ratio of 0.35 and 0.36 did not meet the ASTM C330 grading requirement. As the L/S ratio was lowered to 0.34 the gradation was closer to required ASTM limits, however, there was smaller LWA sizes that were not within the limits. At a L/S ratio of 0.335 the gradation was within the ASTM C330 grading limit. Once the L/S ratio was lowered beyond 0.335, the gradation was not within the ASTM limits.

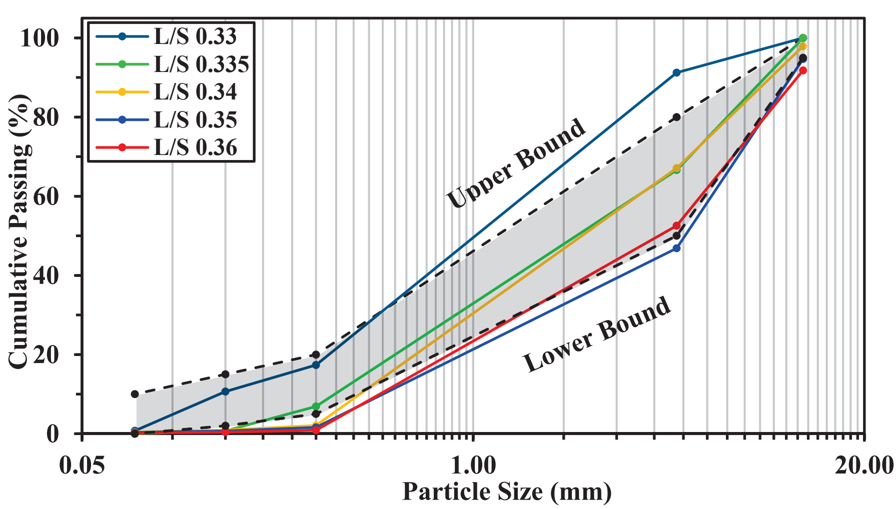

Fig. 8. Gradation of combined coarse and fine LWA manufactured with L/S ratios of 0.33, 0.335, 0.34, 0.35, and, 0.36.

3.4 Conclusion

The study investigated the influence of hydration on the resulting LWA gradation. The gradation for manufactured fine, coarse, and combined fine and coarse LWA were examined to assess their agreement with ASTM C330 grading requirement. FLWA manufactured with a L/S ratio of 0.33 achieved a gradation that agreed with ASTM standard limits. For CLWA a L/S ratio of 0.35 achieved the minimum required gradation for ASTM C330. The required gradation of combine fine and coarse was achieved with a L/S ratio of 0.335. This investigation demonstrates that a reduction in moisture content during W-CCA paste preparation with achieve finer LWA and an increase in moisture level will achieve coarser LWA. This phenomenon is illustrated according to the degree of cohesion between particles at early stage of W-CCA preparation. As moisture level is increased the degree of cohesion and bond between particles is also increased respectively, resulting in coarser LWA. On the contrary the decrease in moisture level will achieve less cohesion and bond between particles in the mixing stage and will consequently achieve finer LWA. This research demonstrates that the manipulation of moisture level to achieve the required gradation is an effective approach. Therefore, this method can be adopted to manufactured LWA from W-CCA, that meet ASTM C330 grading requirement.

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