Life Cycle Assessment of Lightweight Aggregates from Coal Ashes: A Cradle-to-Gate Analysis

Kelsey J. O'Hare[1], Giuseppe Pizzulli[2], Michelle Torelli[1], Mohammad Balapour[1], Yaghoob Farnam[1], Y. Grace Hsuan[1], Pieter Billen[3], Sabrina Spatari[1,4]

[1] *Civil, Architectural and Environmental Engineering, Drexel University 3141 Chestnut St., Philadelphia, PA, 19104, United States*
[2] *Mechanical Engineering, University of Bologna, Bologna*
[3] *Italy University of Antwerp, Biogem, Salesianenlaan 90, 2660, Hoboken, Belgium*
[4] *Faculty of Civil and Environmental Engineering, Technion – Israel Institute of Technology*

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INTRODUCTION

Power plant coal combustion residues (CCR) that consist of bottom ash and off-spec fly ash may be beneficially converted to value-added construction materials thereby reducing disposal costs and landfilled waste. Coal ashes have been investigated as sources of raw material for lightweight aggregates owing to their mineral properties, using well-known processes for agglomeration of fine particles (e.g., via sintering or autoclaving processes). Recent literature by Billen et al. [1]. proposed converting coal bottom ash to spherical porous reactive aggregates (SPoRA) using a sintering process and fluxing agents that allow lowering the operating temperature of the rotary furnace used to produce the lightweight aggregates (LWAs). The authors used constitutive modeling to optimize the operating temperature needed to produce slag where viscosity was maximized in order to retain a spherical shape during melt formation. At the same time the authors tested converting CCR materials experimentally at different NaOH additions and modeled the thermodynamic conditions for producing slag with optimal spherical properties.

In addition, Balapour et al. [2] recently tested the same SPoRA materials as possible candidates for internal curing of concrete owing to the porous structure of the manufactured aggregate. The authors prepared samples of LWAs made from low- and high-calcium waste coal bottom ash and evaluated the total porosity using x-ray computed tomography (XCT), which was measured to fall within the range between 39.6% to 57.8%. This showed that theoretically, the LWAs possessed a great capacity for storing water in their pore structure. The sphericity of LWAs, which is an influential factor on the workability if used in concrete, was measured ranging from 1 (meaning perfect sphere) to 0.75. Generally, the sphericity reduced when increasing the fluxing agent for preparation of the LWAs. Low-calcium LWAs passed the perfect spherical shape beyond 10% incorporation of NaOH, while high-calcium LWAs passed this point beyond 5.85% incorporation of NaOH [2].

Our objective in this paper is to understand the life cycle environmental impacts and costs of SPoRA LWAs for select environmental metrics, namely, the 100-year global warming potential (GWP), ozone depletion potential (ODP), eutrophication potential (EP) and acidification potential (AP). We use life cycle impact assessment (LCIA) characterization factors from the CML 2015 database developed at Leiden University. We examine the use of NaOH as a fluxing agent and discuss the possibility of using waste glass (soda lime glass or fluorescent lamp glass) as alternative fluxing agents as investigated by Torelli [3].

We evaluate the conversion of CCR to LWA using a sintering process that uses NaOH as fluxing agent, which lowers the temperature needed to form slag, and based on the properties of CCR collected from two power plants located in the U.S. Experiments together with thermodynamic and viscosity models described in Billen et al. [1] identified optimal additions of fluxing agent to attain desired characteristics in the final lightweight aggregate. Thermodynamic calculations were used to approximate the change in enthalpy and thermal input requirements for the sintering process based on the heat capacity of ash constituents using equations 1 and 2, where t is temperature in K/1000 and A through E are constants for each material at a certain temperature and phase. A cradle-to-gate life cycle inventory (LCI) model (Figure 1) that treats the ash as a waste material, and therefore accounts for transportation steps to haul the ash to a LWA processing facility that is assumed to be close to concrete end-use markets (e.g., within a 150 km radius of a city) was built using GaBi 6.0 LCA software [4]. Table 1 summarizes the properties of the ash samples modeled and Table 2 summarizes the reference flows (material and energy inputs) needed to process 1 metric tonne of ash.

$$Q = mC_p\Delta T \qquad \textit{Equation 1.}$$

$$C_p\left[\frac{J}{mol} * K\right] = A + Bt + Ct^2 + Dt^3 + \frac{E}{t^2} \qquad \textit{Equation 2.}$$

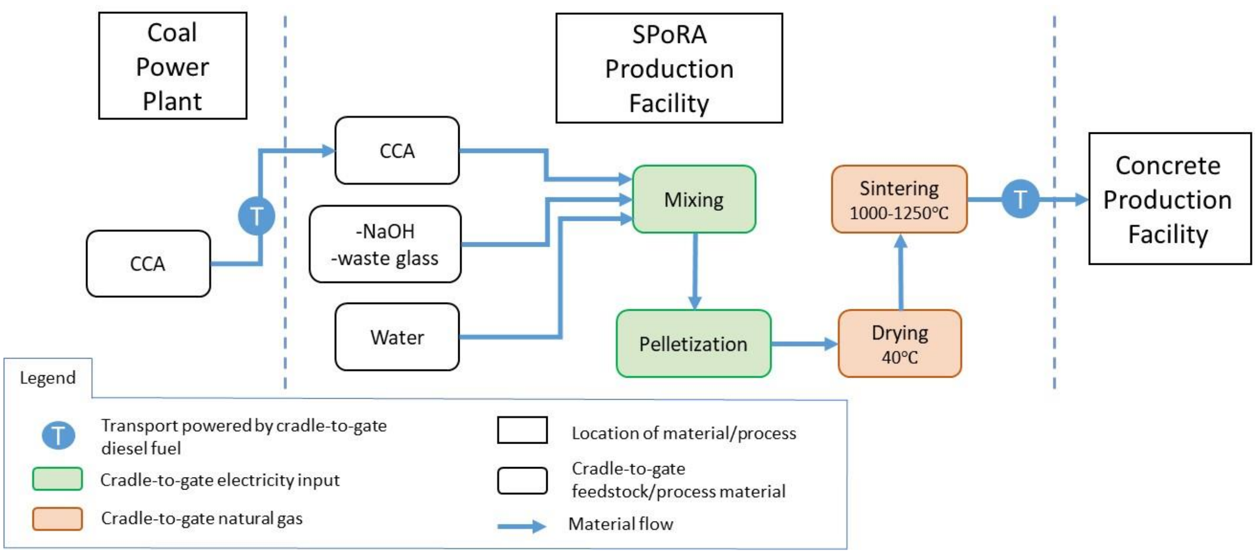

Figure 1. Process flow diagram for industrial-scale SPoRA production using coal combustion ash (CCA) and either NaOH or waste glass as fluxing agents. Water would be added to the case with NaOH but may not be necessary for waste glass, which may enter "wet" to the manufacturing facility. The system boundary shows processes expected to use electrical or thermal (natural gas) energy inputs into the system.

Table 1. Chemical Composition by weight percent from Billen et al. 2018 [1].

Chemical Composition (% wt)	**WP**	**NV**
SiO_2	43.1	63.2
Al_2O_3	17.1	20.1
Fe_2O_3	7.29	6.66
SO_3	0.64	0.39
CaO	22.5	3.51
Na_2O	1.19	1.43
MgO	4.10	0.97
K2O	0.41	1.13
P_2O_5	0.91	0.09
TiO_2	1.25	1.03

Table 2. Inputs of energy, utilities, and chemicals needed to transport raw materials and process them to LWA (SPoRA).

Energy input	**WP**	**NV**
Diesel	119.42 kg	90.51 kg
Electric	.18 MJ	.18 MJ
NaOH	16 kg	20 kg
Water	384 kg	380 kg
Thermal Energy	1934 MJ	1937 MJ

RESULTS

Life cycle assessment results were carried for two ash samples for four life cycle impact assessment (LCIA) metrics (Table 3). Results in Table 3 assume 4% and 5% NaOH addition to the WP and NV samples presented, respectively, based on experimental observations found to achieve spherical properties in the LWA. The NV ash sample, which is lower in Ca concentration, was found to have slightly better environmental performance (lower LCIA metrics) compared to WP, and additionally, according to research by Balapour et al. [2], it also possessed better sphericity, which aids the workability of concrete, and small uniform pore structure, which is desired for internal curing of concrete. While NV ash needed slightly more thermal energy input for the drying and sintering steps owing to its composition, the increment did not have an impact on the environmental indicators studied. Rather, a lower upstream transportation distance to move the ash feed from the coal plant to the assumed location of the SPoRA facility resulted in lower input of diesel. Napolano et al. [5] evaluated select LCIA metrics for recycled and natural clay-based lightweight aggregates using high temperature processing conditions (1200-1380°C) and reports a GWP between 39 and 339 kg CO_2e/metric ton LWA, which are lower than our results (Table 3) owing to co-product credits, different operating conditions, including thermal processing only without use of a fluxing agent. As a reference, cradle-to-gate crushed stone aggregate, which is minimally processes, has a GWP of approximately 12 kg CO_2e/metric ton, but this does not include the transportation steps that would be required to ship lightweight natural aggregates to concrete mixing sites.

Table 3. Cradle-to-gate LCIA metrics for two ash samples converted to LWA using NaOH as fluxing agent. Basis of analysis is 1 metric ton ash treated.

Indicator	WP Ash (4% NaOH)	NV Ash (5% NaOH)
GWP (kg CO_2-eq)	896	625.5
AP (kg SO_2-eq)	1.2	0.926
EP (kg Phosphate-eq)	0.291	0.228
ODP (kg R11-eq)	$5.24E^{-9}$	$4.57E^{-9}$

CONCLUSIONS

Findings from this research suggest that CCR can be a beneficial raw material for producing SPoRA. Additional benefits of using waste material beneficially should be further explored by investigating the possible benefits of avoiding the treatment or empoundment of CCR generated from the many coal power plants around the U.S. Furthermore, exploring substitution of waste glass for NaOH can further reduce environmental burden owing to use of waste material.

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