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Construction material properties of slag from the high temperature arc gasification of municipal solid waste

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ABSTRACT

Slag from the high temperature arc gasification (HTAG) of municipal solid waste (MSW) was tested to evaluate its material properties with respect to use as a construction aggregate. These data were compared to previously compiled values for waste to energy bottom ash, the most commonly produced and beneficially used thermal treatment residue. The slag was tested using gradations representative of a base course and a course aggregate. Los Angeles (LA) abrasion testing demonstrated that the HTAG slag had a high resistance to fracture with a measured LA loss of 24%. Soundness testing indicated a low potential for reactivity and good weathering resistance with a mean soundness loss of 3.14%. The modified Proctor compaction testing found the slag to possess a maximum dry density (24.04 kN/m^3) greater than conventionally used aggregates and WTE BA. The LBR tests demonstrated a substantial bearing capacity (>200). Mineralogical analysis of the HTAG suggested the potential for self cementing character which supports the elevated LBR results. Preliminary material characterization of the HTAG slag establishes potential for beneficial use; larger and longer term studies focusing on the material's possibility for swelling and performance at the field scale level are needed.

1. Introduction

The management of municipal solid waste (MSW) through thermal treatment processes represents a proven approach for waste volume reduction and power generation (Psomopoulos et al., 2009). Thermal treatment of MSW reduces the amount of waste destined for disposal while recovering energy (most commonly in the form of electricity). The current state of the practice with respect to thermal treatment of MSW is combustion in a waste to energy (WTE) facility. In a WTE facility, the MSW is combusted in a boiler under an oxic atmosphere with the heat energy recovered in the form of steam used to produce electricity (Psomopoulos et al., 2009; Wiles, 1996).

High temperature arc gasification (HTAG) (also referred to as plasma arc gasification) is an alternative (and emerging) technology for the thermal treatment of MSW. In a HTAG system, the MSW is heated in an anoxic or low oxygen environment through the use of plasma, electric arc, or other means to create a syngas. This syngas is then combusted to produce electricity or passed through a catalyst to generate biofuels (Arena, 2012; Zhang et al., 2012). Numerous benefits of HTAG have been cited, including a higher energy recovery efficiency, the production of a vitreous residual reported to be more inert that typical WTE combustion residues, and the ability to produce liquid fuels which can be transported and stored prior to use (Arena, 2011, 2012; Consonni and Viganò, 2012; Roessler et al., 2014).

An important element when assessing the feasibility of any thermal treatment process for MSW is how the generated residuals must be managed. Traditional WTE produces two residuals: a fly ash [the particulate matter that exits with the flue gas during combustion and is subsequently captured by the facilities air pollution controls (APC)] and a bottom ash (the combustion residues which drop from the rotating grate following combustion). In many European and Asian nations, a fraction of the WTE bottom ash is beneficially used, most commonly as an aggregate replacement in construction applications (Chimenos et al., 1999; Oehmig et al., 2015; Psomopoulos et al., 2009; Shih and Ma, 2011; Wiles, 1996).

Determination of a waste's potential for beneficial use must consider both the material's potential to adversely affect human or environmental health and the ability of the waste product to

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meet the necessary structural and material specifications for its intended engineering application. An assessment of the environmental risk of pollutants leaching from HTAG slag has been shown to be similar or less in comparison to conventional WTE bottom ashes (Jung et al., 2005; Moustakas et al., 2012; Roessler et al., 2014; Saffarzadeh et al., 2009).

Much less information is available regarding the fundamental material properties of MSW HTAG slag. Material characterization has been conducted on WTE bottom ash and data are available with respect to WTE bottom ashes maximum dry density, California bearing ratio (CBR), and resistance to fracture through Los Angeles (LA) abrasion, as well as published data on a number of other material tests (Forteza et al., 2004; Izquierdo et al., 2002; Lin et al., 2012; Pandeline et al., 1997; Toraldo et al., 2013). Similar data for MSW HTAG slag are needed to better assess its potential for reuse as an infrastructure material. Specifically, the objective of this study was to conduct a material characterization of MSW HTAG slag to evaluate its properties for use as a roadway base course or as an aggregate [either in hot mix asphalt (HMA) or Portland cement concrete (PCC)].

Samples of MSW HTAG slag were collected from a pilot scale HTAG unit which operated for a short time in Florida, US and used the MSW from the surrounding military base as a feedstock. This sampling event provided the researchers with a unique opportunity to sample an HTAG unit, as there are very few operational HTAG facilities (at full or pilot scale) located in North America. While HTAG systems do exist in Europe and Asia the majority of the published studies have focused on evaluating slag produced from the vitrification of WTE ashes or other combustion residues (e.g. sewage sludge ash), and not from the vitrification of MSW directly (Lin and Chang, 2006; Cheeseman et al., 2005; Roether et al., 2010). The data generated as a result of this study will also allow for the comparison of the differences in the material properties of HTAG slag produced from MSW, with that of slag produced from WTE ashes (where the initial feedstock was MSW).

The HTAG slag samples were graded into two different particle size fractions to assess the slags viability for use as a roadway base and as a course aggregate. To evaluate the HTAG slag's potential as a soil amendment, the aggregate fraction of the slag was blended with limerock (a typical material used for roadway base courses) and the density and strength properties were quantified. While additional data would likely be required if a full scale project were to be conducted, this research was designed as a guide to aid interested parties looking to evaluate management options for MSW HTAG slag. Furthermore as it is the first of its kind it will serve as a starting point for further research on the beneficial use of this emerging thermal treatment residue.

2. Materials and methods

2.1. Sample collection and material processing

HTAG slag samples were collected from an 11 ton per day HTAG gasification system at the Hurlburt Field Air Force Base in Florida, US. The HTAG system used the municipal waste from the surrounding military base as a feedstock and operated with a ferrous and non-ferrous metals recovery system prior to gasification. An exact determination of the composition of the MSW entering the HTAG unit was not obtained, and the authors do acknowledge that the composition of the MSW used at the site could have differed from conventional MSW due to the nature of the activities conducted at a military installation (and the subsequent wastes produced). A process flow diagram of the HTAG system is provided in Fig. 1; the HTAG slag was air cooled following vitrification and represents the residual slag that remained after gasification and not the APC residues collected during the flue gas treatment. Slag samples were collected during two separate sampling events, which were conducted approximately three months apart in an attempt to reduce sampling bias (due to MSW heterogeneity). At each event approximately 100 kg of slag was collected. The recovered slag was observed to be predominately in in large pieces (>10 cm in width) as shown in Fig. 2. All the material sampled was subsequently combined and broken with a sledge hammer until the material could be size reduced using a jaw crusher. A full scale crushing operation would likely employ a series of crushers (most typically jaw and cone) to size reduce the material to a desired gradation.

2.2. Particle size distribution and material characterization

Once processed, the slag was graded into two different particle size distributions (PSDs). The first PSD was a more poorly graded (uniform), larger size fraction, representative of a material used as a course aggregate (referred to as *Agg).* The second was a gap graded material representative of a coarse roadway base material (referred to as *Base*). Both of the slag PSDs are shown in Fig. 3. The PSD was determined for each material in triplicate, in accordance with the procedures outlined in ASTM C136 (ASTM C136, 1995). Table 1 provides a list of the names and method numbers for all of the ASTM materials tests conducted. The gradation was similarly measured for a limerock source, and this was used to produce a 1:1 (by mass) limerock-HTAG slag blend (referred to as *Blend*) by adding each material to a concrete mixer and mixing for 15 min. The limerock used in the study met the Florida Department of Transportation (FDOT) specifications for use as a limerock base course which include: minimum density and LBR values, particle size requirements, and percentage of deleterious materials (FDOT, 2015b). The diameter corresponding to 10% (D_{10}), 30% (D_{30}), and 60% (D_{60}) finer in the particle size distribution was reported for all of the aggregates (slag, limerock, blend) and used to calculate the uniformity coefficient (C_u) and the coefficient of gradation (C_c).

Specific gravity and absorption of the *Agg* fraction were determined in accordance with ASTM C127 (ASTM C127, 2015). The *Base* fraction contained a substantial fraction of particles smaller than the US #4 sieve (4.75 mm), the specific gravity was determined by taking a weighted average of the specific gravity measured for the coarser particles (>4.75 mm) (using ASTM C127) and the finer particles (<4.75 mm) in accordance ASTM C128 (ASTM C128, 2013). To evaluate the *Agg* fractions resistance to weathering, soundness testing was conducted in accordance with ASTM C88 (ASTM C88, 2013). This test was conduced in duplicate, the reported values represent the average loss value of the two tests. Los Angeles (LA) abrasion testing was conducted on the HTAG *Agg* fraction to evaluate its durability and resistance to fracture; the test was run in accordance with ASTM C131 (ASTM C131, 2014). LA abrasion grade B (2500 g – 19.0 to 12.5 mm aggregate, 2500 g - 12.5 mm to 9.5 mm aggregate) was used for the HTAG *Agg* fraction.

2.3. Modified proctor compaction, maximum index density and Limerock Bearing Ratio (LBR)

A modified Proctor compaction test was conducted on the *Agg* and *Base* fractions in accordance with ASTM D1557 (ASTM D1557, 2012). After testing it became evident that the *Agg* fraction did not contain enough fines for a compaction curve to be developed (with the modified Proctor effort) therefore, a vibratory compaction test was done in accordance with ASTM D4253 (ASTM D4253, 2014) at the "as-is" moisture content of the material (<1%). Following the compaction of the *Base* fraction (using the