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Evaluating the manufacturability and combustion behaviors of sludge-derived fuel briquettes

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ABSTRACT

Based on the physical and chemical properties as well as calorific values of pulp sludge and textile sludge, this study investigates the differences between manufacturability, relationship between extrusion pressure and formability, as well as stability and combustion behaviors of extruded sludge-derived fuel briquettes (ESBB) and cemented sludge-derived fuel blocks (CSBB). The optimum proportion and relevant usage ESBB policies are proposed as well. Experimental results indicate that a large amount of water can be saved during the ESBB manufacturing process. Additionally, energy consumption decreases during the drying process. ESBB also has a more compact structure than that of CSBB, and its mean penetration loading is approximately 18.7 times higher as well. Moreover, the flame temperature of ESBB (624–968 °C) is significantly higher than that of CSBB (393–517 °C). Also, the dry bulk density and moisture regain of ESBB is significantly related to the penetration loading. Furthermore, the optimum mix proportion of ESBB is co-determined by the formability of pulp sludge and the calorific values of textile sludge. While considering the specific conditions (including formability, stability and calorific values), the recommended mix proportion for ESBB is PS50TS50.

1. Introduction

While importing more than 99.5% of its energy needs, Taiwan is unlikely to achieve energy independence, explaining why major science and technology projects nationwide highly prioritize the development of green energy and biomass energy. According to Ministry of Economic Affairs (MOEA) statistics, in 2012, the average annual quantity of sludge reached approximately 226,661 metric tons/year and 44,012 metric tons/year from the pulp sludge and textile industry, respectively. Whereas the sludge produced from the pulp and paper industry was approximately 5.15 times more than that of the textile industry. It was announced in the "Industrial Waste Reuse Management Regulation", released by the Industrial Development Bureau, MOEA, Taiwan, that pulp sludge and textile sludge as highly promising for use as fuel. The biofuel emitted from waste, such as municipal solid waste (MSW) (Wan et al., 2008; Piao et al., 2000; Rada and Andreottola, 2012; Velis and Cooper, 2013), industrial sludge (Yaman et al., 2000; Chen et al., 2011), and agricultural waste (Bak et al., 2009; Huang et al., 2009; Binod et al., 2010; Wang et al., 2012; Jung et al., 2012) was used mainly as an auxiliary fuel for brick kilns (Chang et al., 2001), cement kilns (Madlool et al., 2011) or boilers (Harrison et al., 1981). Agricultural residues have been actively developed and extensively used worldwide, including rice stalks (Bak et al., 2009; Huang et al., 2009; Binod et al., 2010), wheat straw (Wang et al., 2012), corn stalks, sugarcane bagasse (Jung et al., 2012); industrial sludge (Yaman et al., 2000; Chen et al., 2011) or sewage sludge (Kargbo, 2010; Manara and Zabaniotou, 2012; Liu et al., 2013), sawdust (Rada et al., 2009; Chen et al., 2011; Ren et al., 2012; Uzun and Kanmaz, 2012; Virmond et al., 2012; Vitali et al., 2013) as biofuels. For instance, some countries have even used the waste of pruned street trees to produce biofuels. However, the pulp sludge can be mixed with tires, bituminous coal and RDF-5 for use as an auxiliary fuel (Wan et al., 2008). Moreover, biomass co-firing can be done (Chyang et al., 2010; Lee et al., 2010), together with bio-crude products (Zhang et al., 2011; Upadhyaya et al., 2013), bioethanol (Sjöde et al., 2007; Phillips et al., 2013) or biogas (Zhang et al., 2010; Hagelqvist, 2013) to produce H_2 (Fiori et al., 2012). Additionally, while textile sludge briquettes are made from textile sludge mixing with cow dung and soils, these briquettes can be used as compost (Rosa et al., 2007a,b) or non-structural building materials (Balasubramanian et al., 2006; Raut et al., 2011).

While performed at temperatures of ranging from 350 to 400 °C, the conventional drying process used in Taiwan for industrial

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sludge can reduce the moisture content of industrial sludge from 70% to roughly 30% (Chiou et al., 2011). Some industrial sludge is used as an auxiliary material added to bricks or used for culture soils. However, owing to its strong odor during storage and processing, organic sludge is a potential environmental hazard. Pulp sludge and textile sludge are organic–rich sludge (Combustible content: 40–50%) with high moisture (70–85% for dewatered sludge) and strong odors (Rosa et al., 2007a, 2007b; Manara and Zabaniotou, 2012). Therefore, obtaining adequate landfill sites for storing industrial organic sludge appears to be extremely difficult. Additionally, the demand for bricks has significantly reduced, making it rather difficult to manage a large quantity of industrial organic sludge. Given these circumstances, some manufacturers request governmental assistance in helping them to transform industrial sludge into sludge-derived fuel briquettes for use in boilers to replace coal. Correspondingly, the Taiwan government has cited pulp sludge and textile sludge as having strong development potential for use as fuel. Moreover, owing to that textile sludge and pulp sludge have acceptable calorific values (8.73–11.99 MJ/kg) (Chiou et al., 2011), in this study, derived-fuel was fully developed from sludge. This not only can resolve sludge treatment problem, but also is economic, and can be widely adopted everywhere. This study examines the differences between manufacturability, relationship between extrusion pressure and formability. Stability and combustion behaviors of ESBB and CSBB, based on the physical and chemical properties and calorific values of pulp sludge and textile sludge, are examined as well. Furthermore, this study proposes the optimum proportion and relevant use of ESBB policies.

2. Methodology

2.1. Experimental materials

Experimental materials used in this study were the pulp sludge (PS), which is the sludge generated from the factory producing pulp, paper and paper products, and the textile sludge (TS), which is the sludge generated from the textile company. From which, textile sludge and pulp sludge could be obtained after pre-treatment processes, including drying and shredding. This study then assessed their basic physical and chemical properties, as well as calorific value analysis results. The pulp sludge powders were considered as the primary material, which required mixing with various proportions of textile sludge powders and water. The aqueous slurries were first stirred thoroughly and then extruded with self-designed extrusion blow molding equipment. Various extrusion pressures were generated using extruded steel plates with three thicknesses (i.e. 7.5 mm, 15 mm, and 35 mm). Owing to the limited output power of a relevant device, unsuccessful extrusion of mixtures may occur when using a steel plate with a thickness of 50 mm. Therefore, ESBB products with a diameter of 10 mm and length of 10–50 mm were obtained under a range of operating conditions, including optimum extrusion pressure and mixtures with an ideal moisture content. The pulp sludge powder was used as a base, to which various proportions of textile sludge powders were added. Following premixing, the recommended water content in each sample was determined, and subsequently added to each sample of the sludge mix. Samples were extruded in a 50 mm cubic mold in a fastening process to form CSBB. Thereafter, ESBB must be kept in a moderately dry atmosphere.

2.2. Experimental design

With long-fiber pulp sludge, this study could thus provide ESBB with an improved cementing property. Owing to the inability to extrude the textile sludge separately, this study examined ESBB using dried pulp sludge powders with variable weight ratios, including 100%, 70%, 50%, 30%, which were partially mixed with textile sludge powders with variable proportions of 0%, 30%, 50%, 70%, respectively. Whereas, the proportion codes of ESBB were PS100TS0, PS70TS30, PS50TS50, and PS30TS70, respectively.

The procedures for pulp sludge and textile sludge analysis included approximate analysis (NIEA R213, NIEA R205; "NIEA" stands for "National Inspection and Environmental Analysis Laboratory, Environmental Protection Administration, Taiwan"), pH, calorific values (by the adiabatic bomb calorimeter method, NIEA R214.01C), elemental analysis (by Heraeus vario III-NCSH), analysis of the leaching concentrations of the heavy metals (using the toxicity characteristic leaching procedure, TCLP, as described in the Taiwan EPA-SW 846–1311 method) and appearances. Based on the combustion bomb calorimeter, this study also performed heat equivalent analysis to evaluate the standard sample of benzoic acid. Experimental results indicated that the temperature rose to 2.69 °C, and the calorific value of benzoic acid was 28.17 MJ/kg.

Moreover, the analysis items for ESBB included formability (referring to the weight percentage of ESBB longer than 10 mm over total incoming weight), calorific values, moisture regain, dry bulk density (ASTM C29), penetration loading (by a penetrometer), thermo-gravimetric loss (by a differential thermal thermo-gravimetric/thermo-gravimetric analysis, Perkin Elmer, TGA 7), transition temperature (using a differential scanning calorimeter, Perkin Elmer, DSC 7), and (using an infrared thermal camera in the spectral range 8–14 μm).

3. Results and discussion

3.1. Characteristics of pulp sludge and textile sludge

The moisture content of pulp sludge was 65%; ash content (in wet basis) was 19.0%; fixed carbon (in wet basis) was 8.06%; volatile substance (in wet basis) was 7.94%; combustible constituent (in dry basis) was 45.71%; and pH value was 6.58. However, the moisture content of textile sludge was up to 80%; ash content (in wet basis) was 10.72%; fixed carbon (in wet basis) was 4.16%; volatile substance (in wet basis) was 5.12%; combustible constituent (in dry basis) was 46.40%; and pH value was 6.58 (Table 2). According to elemental analysis results of pulp sludge and textile sludge, carbon and hydrogen were the main source of calorific values. Additionally, carbon, hydrogen, oxygen, and chlorine elements in the pulp sludge were 18.48%, 1.78%, 78.82%, and 0.09%, respectively, and its calorific value was 8.73 MJ/kg. Nevertheless, carbon, hydrogen, oxygen, and chlorine elements in the textile sludge were 32.15%, 5.73%, 59.04%, and 0.07%, respectively, and its calorific value was 11.99 MJ/kg. Due to the calorific value of the textile sludge was significantly higher than that of pulp sludge, it demonstrated that textile sludge can improve the calorific values of ESBB.

Furthermore, the TCLP leaching concentration (including copper (Cu), lead (Pb), cadmium (Cd) and chromium (Cr)) in both pulp sludge and textile sludge were well within the Taiwan EPA criteria as established in the "Standards for Defining Hazardous Industrial Waste", where the concentration of Cu, Pb, Cd and Cr is lower than 15.0 mg/L, 5.0 mg/L, 1.0 mg/L, 5.0 mg/L respectively.

3.2. Manufacturability of sludge-derived fuel briquettes

The fineness modulus of these four composite mixtures was 2.50, 2.71, 2.23, and 2.28, respectively (Table 1). Moreover, the fineness modulus and grain size distribution curve revealed that the four composite mixtures had a similar grain size. Under certain specific conditions, four ESBB (i.e. mix proportions of PS100TS0, PS70TS30, PS50TS50, and PS30TS70 respectively) were produced