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Properties of water-soluble and insoluble particulate matter emitted from dewatered sewage sludge incineration in a pilot-scale ash melting furnace

Lian Zhang [a,1], Megumi Masui [b], Hiroharu Mizukoshi [b], Yoshihiko Ninomiya [a,*], Jugo Koketsu [a], Chikao Kanaoka [c]

[a] *Department of Applied Chemistry, Chubu University, 1200, Matsumoto-cho, Kasugai, Aichi, Japan*
[b] *Actree Cooperation, Mishumi-cho, Hakusan, Ishikawa, Japan*
[c] *Ishikawa National College of Technology, Kitacyujo, Tsubata, Kahoku-gun, Ishikawa, Japan*

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Abstract

Emission of inorganic particulate matter (PM) from the incineration of dewatered sewage sludge has been investigated in a novel ash melting furnace. The sludge containing 79 wt% water was incinerated in an oxygen-enriched atmosphere at the primary temperature of 1400 °C, and its unburned volatile was combusted at 1100 °C in a secondary combustion chamber. A 13-stage low-pressure-impactor and the conventional impinger methods were employed for PM sampling at the outlet of the secondary combustion chamber. The results indicate that, PM is dominated by volatile and semi-volatile elements including Br, Cl, P, S, Na, K, Zn, As, Cu, Mn and Ni. Less refractory elements were found. PM has two major fractions: <0.22 and $\geqslant 0.22$ μm. Their chemical forms as well as water solubility are different between two fractions. The majority of Br, nearly half of Cl, and 40% of S and P are present in the small fraction. They are mostly water-soluble due to the association with alkali elements and heavy metals. The water-insoluble calcium sulfate and calcium/iron phosphate were, however, found in the large fraction of PM. Regarding the cations, the water solubilities of Na, K, Mn and Ni are close to their proportions partitioned into the small fraction of PM, since their water-soluble species were preferentially formed in this fraction. A relatively weak correlation for Al, Ca and As, while no such a correlation were found for Cu, Zn and Fe, due to the complex compounds formed for them.

Keywords: Dewatered sewage sludge; Oxygen-enriched incineration; Particulate matter; Water solubility

1. Introduction

Inorganic particulate matter (PM) can be formed during the incineration of sewage sludge [1,2]. Its emission is much severe compared to that released from coal or even other biomasses, because of the specific properties of inorganic elements within sewage sludge. Generally, sewage sludge has a high ash content, *e.g.*, 15–40 wt% in the dried sewage sludge [3], which includes a large quantity of toxic metals and halides derived from wastewater treatment [4–7]. These species tend to vaporize and condense into submicron particles at high temperatures [8,9].

The properties of PM formed by vaporization–condensation pathway can affect its collection as well as its environmental impacts greatly. The submicron particles have a higher potential of escaping the conventional air pollution control devices [2,10]. Once released into air, they

* Corresponding author. Tel.: +81 568 51 9178; fax: 81 568 51 1499.
E-mail addresses: l.zhang@aist.go.jp (L. Zhang), ninomiya@isc.chubu.ac.jp (Y. Ninomiya).
[1] Present address: Energy Technology Research Institute, National Institute of Advanced Industrial Science and Technology (AIST), Tsukuba 305-8569, Japan. Tel.: +81 298 61 8437; fax: +81 298 61 8408.

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exhibit a lengthy residence and are capable of deep pulmonary ingestion as well. The chemical properties of PM are also significant [11]. For example, the trivalent arsenicals are more toxic than the pentavalent ones. The hexavalent chromium can cause genetic damage, whereas its trivalent state is one essential nutrient for glucose metabolism. Moreover, the particle solubility is one principal criterion for the bioavailability of PM as well as its ecological impacts [12]. The water-soluble species can pollute the groundwater and even the surface water if it is landfilled or used as a soil ameliorant [13]. All highlight the importance of identification on the properties of PM.

This paper aims at elucidating the properties of water-soluble and insoluble PM mainly formed by vaporization–condensation pathway from an incineration of dewatered sewage sludge (DSS). In order to collect such PM efficiently, a reverberating ash melting furnace was adopted; fewer the inherent minerals were spurted out and no soot was formed [14]. DSS fed into the incinerator was dried and burned sluggishly through receiving radiation heat from the combustion of auxiliary fuel with enriched oxygen generated from pressure swing adsorption. PM was mainly formed by condensation of the vaporized metals, which was collected by a wet analysis method for investigating the water solubility of different species and by a 13-stage low-pressure-impactor (LPI) for size-segregation.

The individual sizes of PM were characterized by several techniques: X-ray fluorescence (XRF) for elemental composition, transmission electron microscopy (TEM) for morphology observation, and X-ray photoelectron spectroscopy (XPS) for speciation. The impingers containing 10% (v/v) nitric acid was used to trap the total species; meanwhile those having pure water were used to trap the water-soluble substances.

2. Experimental

2.1. Properties of DSS and incineration plant description

DSS tested has water: 79.3, volatile matter: 15.6, fixed carbon: 0.9 and ash: 4.2 wt% (see Table 1). The ash content is high, constituting 20.1 wt% of the dried sewage sludge. There are also P 1.7, S 0.2, Cl 0.2 and Br 0.04 wt%. The contents of P and halogens are noticeably higher than them in coal [15]. P is caused by precipitation of its organic precursors in wastewater, having a major form of phosphates like apatite [16]. Halogens are mostly of halides added during wastewater treatment. Br was also detected in DSS, which however has not been reported in other sewage sludges [1,17–19]. The contents of alkali elements and heavy metals are also high (see Table 2).

A schematic diagram of the pilot-scale incineration plant is illustrated in Fig. 1. The ash melting furnace was heated by radiation heat from the combustion of propane in oxygen enriched air. DSS with a feeding rate of 70 kg/h was fed by a snake pump into the melting furnace and stacked in pile on the slag pot. The oxygen above 95% purity with a flow rate of $\sim 10\ m^3_N/h$ was also fed into the furnace. The outer surface of the DSS pile was dried and burned inwards sluggishly through receiving radiation heat from the combustion of propane. Consequently, fewer the mineral particles were spurted out. The averaged temperature in the furnace was kept at ~1400 °C. The unburnt carbon further entered the secondary combustion chamber and combusted to completion there. The chamber was operated under the conditions: temperature, ~1100 °C; gas residence time, ~2 s; exhaust gas, $\sim 175\ m^2_N/h$.

Table 1
Properties of DSS tested in this study

Proximate analysis, wt% as received	
Moisture	79.3
Volatile matter	15.6
Fixed carbon	0.9
Ash	4.2
Dried sewage sludge (wt%)	
Volatile matter	75.7
Fixed carbon	4.2
Ash	20.1
Ultimate analysis, wt%, dry and ash free	
C	42.0
H	6.0
O	43.2
N	6.0
P	1.7
S	0.9
Cl	0.16
Br	0.04

Note: P, Br and Cl were quantified by XRF, amount of O was calculated by difference.

Table 2
Elemental composition of DSS ash, wt%

SiO_2	8.68	MnO	2.45
Al_2O_3	3.74	ZnO	0.71
CaO	12.80	TiO_2	0.64
Fe_2O_3	39.50	SrO	0.64
SO_3	7.50	BaO	0.38
P_2O_5	19.20	CuO	0.33
Na_2O	0.47	As_2O_3	0.13
K_2O	1.37	NiO	0.03
MgO	0.39	PbO	0.03
Cl	0.82	Co_2O_3	0.00
Br	0.21		

2.2. PM sampling

PM in the exhaust gas was isokinetically collected at the duct connecting the secondary combustion chamber and the ceramic filter (numbered 4 in Fig. 1), where the particle distribution was assumed to be uniform and representative of the overall PM. A quartz-made sampling probe, 1 m in length and 0.6 cm in inner-diameter, was employed. Its tip, being perpendicular to the whole body, was inserted horizontally till the centerline of the duct, which was also