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Zinc immobilization in simulated aluminum-rich waterworks sludge systems

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Abstract

All processing systems of waterworks produce a substantial amount of sludge with the residues of treatment chemicals used as coagulants (commonly aluminum-based). Landfill is usually considered as a common disposal strategy for sludge and the incineration residues in most metropolitan areas worldwide. However, the aluminum and/iron contained in the sludge will be largely wasted in landfills, and the metal ions might also be leached out and cause further pollution to the surrounding areas. Therefore, the need for "waste-to-resource" makes the increasing incentive to develop economically viable reuse and recycling options. The major elements in the incinerated ash of municipal wastewater sludge are aluminum and silicon detected from XRF results, which are major components for glass-ceramics. Therefore, in this study, the incineration ash of waterworks sludge was reused as raw materials to produce the glass-ceramics, and the metal transformation mechanisms were further explicated via the combination of advanced techniques. The $ZnAl_2O_4$ spinels were produced with large quantity when sintering zinc oxide with ashes of waterworks sludge. The simulated system with clay and zinc oxide was also studied to investigate the incorporation mechanism of zinc in the glass-ceramics products. Both zinc aluminate spinel ($ZnAl_2O_4$) and willemite (Zn_2SiO_4) phases were formed during the sintering process. Furthermore, the efficiency of zinc transformation was determined through Rietveld refinement analyses of X-ray diffraction (XRD) data. The results show a competitive formation between $ZnAl_2O_4$ and Zn_2SiO_4, and the $ZnAl_2O_4$ spinel is predominant at high temperatures. This study used a prolonged leaching test modified from the U.S. Environmental Protection Agency's toxicity characteristic leaching procedure (TCLP) to evaluate ZnO, $ZnAl_2O_4$, and Zn_2SiO_4 product phases. The zinc concentrations in ZnO and Zn_2SiO_4 leachates were about two orders of magnitude higher than that of $ZnAl_2O_4$ leachate at the end of the experiment, indicating that $ZnAl_2O_4$ formation is the preferred stabilization mechanism for incorporating zinc in ceramic products.

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1. Introduction

Sludge management strategy often receives widespread attention in public media and attracts intensive technical and political debates. Usually, waterworks sludge typically contains mineral and humic matters removed and precipitated from the raw water, together with the residues of any treatment chemicals used as coagulants (commonly aluminum or iron salts) and coagulant aids (mostly organic polymers). In the practical context, alum sludge and ferric sludge refer respectively to the waterworks sludge generated when aluminum or iron salt is used as the coagulant. As a waste-to-resource technology, the use of sludge residue resulting from water treatment process and incineration treatment has attracted much attention (1). During the drinking water (waterworks) treatment, all processing systems generate a substantial amount of sludge with the treatment chemicals used for coagulants (commonly aluminum-based) (2). The metal resources contained in the sludge/residues will be largely wasted if they are disposed of in landfills. Furthermore, the metal ions might also be leached out and cause further pollution to the surrounding areas. Therefore, potential reuse and recycling strategies for aluminum and iron in the incineration residues should be taken into account to be part of a sustainable waste management plan.

Zinc is a typical heavy metal which is not biodegradable and could be accumulated in nature, causing various diseases and disorders when exceeding specific limits (3). Many investigators attempted to immobilize metals via adding amendments (4). However, researches on the solidification/stabilization technologies talked above failed to investigate the transformations of compounds within the system and recognize the mechanisms of reactions occurring. It has been demonstrated in our previous work that nickel and copper can be stabilized with well-controlled thermal treatment schemes via the formation of the spinel structure (5-7). In addition, the product was proposed to be beneficially used as a part of the raw materials for marketable ceramic products.

Recently, use of Al-rich sludge as raw material for ceramic products was also reported by Vicenzi et al. (2). Therefore, based on the stabilization effect caused by the formation of spinel structure, it is expected that such type of sludge rich in aluminum content and its dried and heated forms may serve as a potential ceramic resource to stabilize hazardous metals.

2. Materials and Methods

2.1. Sludge characterization

Samples of waterworks sludge collected in Hong Kong were heated at 900 ºC for 30 min. Results from X-ray fluorescence spectroscopy (XRF) show aluminum and silicon to be the predominant constituents (Table 1). The X-ray diffraction (XRD) pattern in Fig. 1a indicates that the aluminum component may exist in mullite ($3Al_2O_3{\cdot}2SiO_2$) and poor-crystalline phase(s) in the calcined waterworks sludge. A strong quartz signal was also found, which is consistent with the second-largest component (silicon) detected by XRF.

Table 1. Major compositions of waterworks sludge residues (wt. %)

Waterworks Sludge Residue								
Al_2O_3	SiO_2	Fe_2O_3	P_2O_5	K_2O	SO_3	MnO	CaO	others
56.5	30.2	6.2	3.8	1.3	0.5	0.7	0.5	0.3