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Removal of carbon constituents from hospital solid waste incinerator fly ash by column flotation

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\textbf{Abstract}

Hospital solid waste incinerator (HSWI) fly ash contains a large number of carbon constituents including powder activated carbon and unburned carbon, which are the major source of polychlorinated dibenzo-p-dioxins and dibenzofurans (PCDD/Fs) in fly ash. Therefore, the removal of carbon constituents could reduce PCDD/Fs in fly ash greatly. In this study, the effects of the main flotation parameters on the removal of carbon constituents were investigated, and the characteristics of the final product were evaluated. The results showed that loss on ignition (LOI) of fly ash increased from 11.1% to 31.6% during conditioning process. By optimizing the flotation parameters at slurry concentration 0.05 kg/l, kerosene dosage 12 kg/t, frother dosage 3 kg/t and air flow rate 0.06 m\textsuperscript{3}/h, 92.7% of the carbon constituents were removed from the raw fly ash. Under these conditions, the froth product has LOI of 36.53% and calorific values of 12.5 MJ/kg, LOI in the tailings was below 5%, and the total toxic equivalent (TEQ) of PCDD/Fs decreased from 5.61 ng-TEQ/g in the raw fly ash to 1.47 ng-TEQ/g in the tailings. The results show that column flotation is a potential technology for simultaneous separation of carbon constituents and PCDD/Fs from HSWI fly ash.

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1. Introduction

Hospital solid waste is considered dangerous because it may possess infectious, radioactive and toxic substances and can cause undesirable effects on human health and environment (Sabiha et al., 2008). Incineration has become the main method for disposal of hospital solid waste in China since the nation-wide outbreak of severe acute respiratory syndrome (SARS) in 2003 (Zhao et al., 2010). It is estimated that currently there are over 30 centralized incinerators and the number is still increasing (Zhao et al., 2008). Incineration can destroy pathogens and reduce the weight of waste by more than 70%, a large amount of hospital solid waste incinerator (HSWI) fly ash (3% of the original mass) has been generated (Bo et al., 2009). HSWI fly ash contains heavy metals and polychlorinated dibenzo-p-dioxins and dibenzofurans (PCDD/Fs), which is classified as hazardous wastes.

Recent reports have shown that the fly ash from HSWI is quite different from that from municipal solid waste incinerator (Bo et al., 2009; Yan et al., 2011). Firstly, hospital solid waste contain more chlorine-containing scrap plastics like polyvinyl chloride compared with municipal solid waste, therefore the HSWI fly ash usually generally has a higher level of chloride and organic pollutants like PCDD/Fs (Wu et al., 2011). The total toxic equivalent (TEQ) values of PCDD/Fs in some HSWI fly ash exceeded 20 ng I-TEQ/g (Chen et al., 2009). In addition, a lot of powder activated carbon was sprayed into exhaust gas before entering a bag filter for absorption of PCDD/Fs from flue gases to meet much more strictly emission regulations of the hospital solid waste incineration (<0.05 ng I-TEQ/Nm\textsuperscript{3}) (Chen et al., 2009). Yan et al. (2007) found that carbon content in some of HSWI fly ash reached the range of 11.40–91.0% due to activated carbon injection. Both injected powder activated carbon and unburned carbon in solid waste were identified as the main carbon sources of fly ash (Kakuta et al., 2007).

The characteristic of high chloride and carbon content in HSWI fly ash make the tradition processes such as cementation, melting which are effective for municipal solid waste incinerator fly ash be inefficient for HSWI fly ash. Cementation is the most popular and inexpensive method for stabilizing fly ash, but it is difficult to solidify a HSWI fly ash since chlorides and activated carbon hinder the hydration of cement and bring a decrease of compressive strength (Colangelo et al., 2012; Zheng et al., 2011). Melting can also provide an alternative because it can destroy PCDD/Fs at high temperatures and make various heavy metals inert through their incorporation into the glass matrix. This technique is also limited, however, because most chlorides are too volatile at high temperature over 1000 °C to be confined into the vitreous products, which...
causes secondary pollution (Jiang et al., 2009). Meanwhile, high carbon content in fly ash would accelerate the electrode erosion of plasma or arc melting furnace (Liu et al., 2011). Recent reports have found that the water washing pre-treatment for fly ash can reduce undesirable side effect from high chloride in fly ash (Jiang et al., 2009; Zheng et al., 2011; Huang et al., 2011). The appropriate water washing condition is washed twice in distilled water at a liquid-to-solid ratio of 10 or 20 for successful processing (Chiang and Hu, 2010; Liu et al., 2009). However, water washing pre-treatment cannot separate activated carbon from HSWI fly ash.

Researchers also reported that carbon constituent including powdered activated carbon and unburned carbon is indicated as the major source of organic pollutants in fly ash due to the large adsorptive surface area and the role in denovo synthesis (Huang et al., 2003a). Therefore, it is necessary to explore a physical method to separate carbon constituent in HSWI fly ash. The modern flotation technology was introduced to mineral industries in early 18th centuries. At present, the flotation technique has been applied not only in the mineral industry, but also pulp mills, rubber, waste battery, and environment engineers (Naik et al., 2005). Column flotation is a sophisticated froth flotation technique, which has been developed as an alternative to the conventional, mechanically agitated flotation (Finch et al., 1995; Hasan and Hale, 2007). Column flotation is the most effective method of separating the carbonaceous material from coal ash (Altun et al., 2009). Atsushi et al. (2005) found that column flotation can clean up and reduce the PCDD/Fs-contaminated soil by removing selectively unburned carbon including a high PCDD/Fs concentration of incineration fly ash. Huang et al. (2007) successfully used column flotation to remove 64% of the unburned carbon, 41.9% of total PCDD/Fs and 40.8% of coplanar PCBs from MSW incinerator fly ash. These studies mostly pay attention to the removal of unburned carbon from MSW incinerator fly ash, few concern the fate and disposal of the final product after flotation.

HSWI fly ash contains high amount of soluble salts (NaCl, KCl, calcium compounds) which may influence electrostatic interaction between bubbles and particles, the flotation process and this effect should be taken into account (Chin and Somasundaran, 1993). However, the flotation process for treatment of HSWI fly ash with high chloride and carbon content has not been reported so far. The purpose of this paper is to remove carbon constituents of HSWI fly ash which was injected into flue gas duct before the particle control process. The ash sample was collected over a 7-day period. It was homogenized and passed through a sieve of 20 meshes, and then being dried at 105 °C for 24 h for further analyses. The loss on ignition (LOI) was determined for the sample as the weight loss when sub-sample was kept at 600 ± 25 °C for 3 h in accordance with the standard for pollution control (GB18485-2001). Table 1 shows the chemical composition and LOI of the raw fly ash. The raw fly ash and powder activated carbon were divided into five size ranges by sieves. The weight distribution, LOI and carbon distribution in each fraction were analyzed. XRD analysis of the sample was conducted with a Rigaku Ultima IV diffractometer.

2.2. Methods

Column flotation experiments were carried out in a glass column of 30 mm in diameter and 950 mm in height, fitted with a fine porous glass sparger at the bottom. Compressed air was introduced into the column through a rotameter. In every run, a quantitative of fly ash and 600 ml of deionized water was stirred in a hybrid mixer for 5 min. After that, a collector (kerosene) and frother (methyl isobutyl carbinol) were added subsequently and conditioned for 5 min. The slurry was then transferred into the column. The required air flow rate was maintained by rotameter. The experiments were carried out by varying different operating parameters such as slurry concentration, kerosene dosage, frother dosage, and the air flow rate. Slurry concentration, collector dosage, frother dosage and air flow rate in the flotation process were set as range of 0.015–0.1 kg/l, 3–15 kg/t, 0.5–4 kg/t, and 0.04–0.08 m³/h separately with reference to preliminary experiments. One variable at a time was varied while keeping other variables at constant.

The two-stage flotation (rougher–scavenger flotation) process was applied in order to fully and efficiently remove the carbon from the HSWI fly ash, that is to say, the rougher tailing from the first flotation stage were re-fed into the column and the cleaning process was continued under the same experimental conditions. The combined froth from the two stages and tailings remaining in the flotation column were vacuum filtered, dried and weighed and then determining LOI of each product. Determination of calorific values of the froth samples was carried out using an IKA-C5000 calorimeter device. The scanning electron microscopy-energy dispersive spectroscopy (SEM-EDS) was employed to provide imaging information about the morphology and the composition of the raw fly ash and the final product by a FEI NANOSEM 430 apparatus.

In addition, to evaluate the effect of soluble salts on the ash characteristics during the slurry preparation process, the conditioned fly ash were analyzed and the conditioning process are slurry concentration 0.05 kg/l and conditioned time 10 min.

### 2.3. PCDD/F analysis

The sample pretreatment was conducted according to a modified version of US EPA Method 23 (2001). The following 13C12 isotope labeled internal standard solution were purchased from Cambridge Isotope Laboratory. A high-resolution gas chromatograph/
3. Results and discussion

3.1. The particle distribution of fly ash

Using 300 g sample, particle size analysis of the raw fly ash and the powder activated carbon injected in the air pollution control devices of the incinerator was performed from −25 μm (−400 mesh) to +106 μm (+150 mesh) by wet sieving. Each size fraction was analyzed for the carbon content, i.e. LOI. The results are given in Table 2. It indicates that about 98% of the raw fly ash has a particle size less than 106 μm which is most suitable for froth flotation (Uçurum, 2009). LOI is 19.35% of the finest fraction (−25 μm) and LOI decreased with the increasing of particle size, which is opposition with coal fly ash whose carbon substance is enriched in the coarse size fraction (Altun et al., 2009). Most of the carbon constituents of the raw fly ash distribute in particle size below 75 μm, which may be related to the injected powder activated carbon. It can be seen (Table 2) that powder activated carbon has 74% particles with diameters lower than 38 μm and their LOI is above 67%.

3.2. The effect of soluble salts on the ash characteristics

The chemical composition and LOI of the raw fly ash and conditioned fly ash are shown in Table 1. To ensure validity and reliability of data, the results were mean values calculated from five measurements. The results indicate that LOI of the raw fly ash reach 11.1%, owing to the excess of powder activated carbon injected. Cl content of the raw fly ash is remarkably high, being up to 20.43%. X-ray diffractograms of the raw fly ash and conditioned fly ash are shown in Fig. 1. Comparing the two diffractograms, it can be found that large amounts of soluble compounds like NaCl, were removed during the conditioning process. These results are consistent with XRF analysis of raw fly ash and conditioned fly ash. High amount of NaCl which bring on the increasing of electrolyte concentration in the slurry, which will affect zeta potential, the electrical double-layer interaction between bubbles and particles as well as flotation performance (Harvey et al., 2002). The effect of NaCl salt on floatability of carbon constituent needs further study in detail. The weight loss reached about 64% due to solubilization of chloride and at the same time, carbon constituents were concentrated in solid phase during the conditioning process, the two results caused LOI of the conditioned fly ash to increase to 31.6%. The change of weight loss and LOI may also have noteworthy effect on the subsequent flotation.

3.3. Effect of operate parameters on the flotation performance

Fig. 2 shows the impact of slurry concentration on carbon removal and LOI in the tailings. It can be seen that with increase of slurry concentration, the carbon removal increased and LOI in the tailings decreased when the slurry concentration was lower than 0.05 kg/l. But there is no significant change of flotation performance if the slurry concentration was beyond 0.05 kg/l. Therefore, 0.05 kg/l was determined as the slurry concentration, taking the flotation performance and water conservation into consideration. It can be seen that water requirement of flotation is equivalent to water washing pre-treatment for fly ash (Liu et al., 2009).

Fig. 3 represents the variations of carbon removal and LOI in the tailings in response to the kerosene dosage. The result indicates

| Particle size (μm) | Raw fly ash | Powder activated carbon |
|-------------------|-------------|-------------------------|
|                   | Weight (%)  | LOI (% by wt.) | Distribution of carbon constituents (%) | Weight (%)  | LOI (% by wt.) | Distribution of carbon constituents (%) |
| +106              | 2.22        | 11.11          | 1.96                  | 3.46        | 45.45          | 2.42                          |
| +75−106           | 8.48        | 11.36          | 7.64                  | 9.93        | 51.16          | 7.82                          |
| +38−75            | 32.93       | 12.27          | 32.00                 | 12.24       | 62.96          | 11.85                         |
| +25 +38           | 49.70       | 12.24          | 48.19                 | 58.66       | 67.69          | 61.08                         |
| −25               | 6.67        | 19.35          | 10.22                 | 15.70       | 69.70          | 16.84                         |
| Total             | 100 −       | 100 −          | 100 −                 | 100 −       | 100 −          | 100 −                         |
that the flotation response was poor at lower kerosene dosage, hence the carbon removal were very low. With increasing of kerosene dosage from 3 kg/t to 12 kg/t, carbon removal indicated an increase and LOI in the tailings decreased. However, differences in the carbon removal and LOI in the tailings were not observed when the kerosene dosage exceeded 12 kg/t. Accordingly, the optimal kerosene dosage was 12 kg/t. The collector amount is high compared with the coal fly ash and MSW incinerator fly ash (Eisele and Kawatra, 2002; Huang et al., 2003b), there are two reasons for this result, one is that the high-carbon ash required a significantly higher collector and frother dosage than did the low-carbon ash, the other one is related with the extended surface area, microporous structure and high adsorption capacity of the activated carbon particles that soaks up much of the reagents.

The frother dosage directly affects the bubble size (by controlling bubble coalescence), selectivity and recovery (Uçurum, 2009). Fig. 4 represents the influence of the frother dosage on carbon removal and LOI in the tailings. It was observed that the carbon removal was around 80% at lower level of frother. A carbon removal of 93.0% was achieved with 4.8% of LOI in the tailings at a frother dosage of 3 kg/t. There was a slight increase in carbon removal when the frother dosage was increased further. The effect of frother has a similar trend to that of the kerosene. Therefore, around 3 kg/t of frother dosage is sufficient to float this fly ash.

The results of the experiments carried out at different air flow rates are shown in Fig. 5. The air flow rate has important effect compared to slurry concentration, kerosene dosage and frother dosage. With the air flow rate increased, the carbon removal increased linearly, going through a maximum at 0.06 m³/h. Above this air flow rate, carbon removal decreased and LOI in the tailings increased. This trend is similar to the observations reported by Hacifazlioglu and Sutcu (2007). The reason is that there was turbulence through the column axial and the froth balance was disturbed at excessive air flow rate. On the other hand, when the air flow rate was below 0.06 m³/h, the froth layer did not reach the required thickness. Therefore, the optimum air flow rate was 0.06 m³/h.

### 3.4. Removal of carbon constituents under optimum conditions

The best operating conditions of the flotation were determined as follows: slurry concentration 0.05 kg/l, kerosene dosage 12 kg/t, frother dosage 3 kg/t, air flow rate 0.06 m³/h. Under these conditions, a good separation was achieved with 92.7% of the carbon constituents being removed in the combined froth product from the rougher–scavenger process. There is a high carbon removal compared with the removal of unburned carbon from MSW incinerator fly ash (Huang et al., 2003b). Since the surfaces of the unburned carbon particles are commonly oxidized, which tend to reduce their natural hydrophobicity. After weathering of MSWI fly ash, more oxygen-containing functional groups on the unburned carbon surface easily came into being and accordingly made them more difficult to remove by froth flotation (Huang et al., 2003b). In addition, powder activated carbon in HSWI fly ash is naturally hydrophobic due to their hydrocarbon nature and this hydrophobicity increases with an increase in carbon content.

Furthermore, the froth product has the yield of 18.9%, LOI of 56.4% and calorific values of 12.5 MJ/kg which reach the low heat value of 10.5 MJ/kg of typical hospital solid waste (Xie et al., 2009; Yan et al., 2011). LOI of the cleaned tailings is 4.82%, which meets the American Society for Testing Material (ASTM) specification of 6.0% LOI carbon in fly ash. The yield of the tailings is only 17.2% due to dissolution of massive chloride compounds, which provides a cost savings by reducing the amount of material requiring further treatment.

### 3.5. Microstructure of raw fly ash and the final product

Figs. 6–8 illustrates the SEM/EDS observations for the raw fly ash and the final product under optimum conditions. Fig. 6 shows
that the raw fly ash is composed of non-continues, loose particles, some of particles look like an approximate sphere (about 15 μm in diameter), which consists of much of cubic crystal. EDS analysis (Fig. 6c) of cubic crystal indicates the predominant elements are Cl and Na, which are in agreement with the XRF and XRD results. As shown in Fig. 7, the larger porous sponge-like particles with many open pores were found in the froth product. The EDS analysis (Fig. 7c) showed that the predominant constituent for this particle is C, which may be carbonaceous matter such as powder activated carbon. It was also proved that a great lot of powder activated carbon is transferred into the froth product after flotation process. The surface morphology of the tailings (Fig. 8) is different from that of the raw fly ash and the froth product, more fragmental particle appear in the tailings. The complete absence of porous, sponge-like particles shows that such particles consisted of carbonaceous material that was removed by flotation. As determined by EDS (Fig. 8c), the major elements were O, Ca, Si, Na and Al, which may be quartz, silicates and alkali metal salt. Furthermore, the content of Cl in the tailings is significantly lower than those in the raw fly ash.

3.6. Removal of PCDD/Fs under optimum conditions

PCDD/Fs for the 17 specific congeners in the raw fly ash and the tailings product under the optimum flotation condition are shown in Fig. 9. The total PCDD/Fs in the raw fly ash after flotation was decreased from 78.8 ng/g to 16.7 ng/g in the tailings. We extrapolated that the reason is the PCDD/Fs are hydrophobe and easily captured by kerosene and carried upward by gas bubbles during flotation process. In addition, PCDD/Fs may also be removed following to powdered activated carbon because PCDD/Fs have a considerable tendency to adsorb on the surface of porous activated carbon. The TEQ of the raw fly ash was decreased from 5.61 ng-TEQ/g to 1.47 ng-TEQ/g in the tailings, which is less than 3 ng-TEQ/g. In general, the ratios of PCDD/Fs dissolved in the aqueous phase are much lower than those in the froth and residue, because the PCDD/Fs are strongly hydrophobic. Therefore, the PCDD/Fs were enriched into froth products. These results indicate that the flotation process can be successfully applied to reduce substantially the amount of carbon constituents and the PCDD/Fs in HSWI fly ash.

The focus in this work has solely been on the removal of carbon constituents and PCDD/Fs; further work is needed to solve such problem. For instance, the correlation between the removal of carbon constituents and removal of PCDD/Fs during the flotation process is not well understood. After flotation, the subsequent treatment of slurry remaining containing heavy metals should be considered to remove and recover heavy metals from the tailings by the sulfuration pre-treatment (Kuchar et al., 2007) and then second step flotation.

3.7. Application potential of flotation technology of HSWI fly ash

In China, 3 ng-TEQ/g in fly ash has been designated as a PCDD/Fs content standard for entering the solid waste landfill for landfill disposal (GB16889-2008). Generally, HSWI fly ash needs to be detoxified by treatment prior to landfill. By employing column flotation, PCDD/Fs and carbon constituents will be enriched and separated from HSWI fly ash, at the same time chloride will be washed out. After separation, the froth product could be subject to further treatment such as recirculation in the combustion chamber of incinerator, which can serve a dual purpose: almost complete destruction of the toxic organs pollution such as PCDD/Fs and energy recycling by recovery of combustible part (Samwel et al., 2011). The volume and toxicity of the tailings would be decreased greatly, therefore, the tailings could be directly landfill disposed. Additionally, the flotation column is simple and easy to operate, requires only electricity, cheap and commercially available reagents and eventually water, which would greatly reduce the operating costs in an industrial situation. Among them, the total energy consumption of the flotation column system is below 4 kW/ton of fly ash.
ash, and the water consumption can be reduced by recycling some of waste water (Altun et al., 2009). On the contrary, melting technology involves extensive equipment and high energy input. Cementation of HSWI fly ash need above 40% of cement and 20–30% of water added unless dechlorinating (Liu et al., 2010). Therefore, the technological and economic advantages of floatation are over the conventional methods such as melting and cementation.

4. Conclusions

The carbon constituents of the HSWI fly ash are enriched in finer size particle below 75 μm owing to the presence of powder activated carbon. LOI of the fly ash rapidly increase because of solubilization of large amounts of NaCl by conditioning during the slurry preparation process. The optimum flotation conditions were found as follows: slurry concentration 0.05 kg/l, kerosene dosage 12 kg/t, frother dosage 3 kg/t, air flow rate 0.06 m³/h. Under these
conditions, a froth product with 92.7% carbon constituents' removal and a tailings product with less than 5% of LOI carbon were obtained. After flotation, the froth product is enriched with the PCDD/Fs and has calorific values of 12.5 MJ/kg, which make it suitable for recirculation as fuel of the incinerator and realization of the decomposition of PCDD/Fs. At the same time, the TEQ of PCDD/Fs in remaining fly ash could be decreased to lower than the standard of landfill site of municipal solid waste (3 ng-TEQ/g). It was confirmed that applying flotation process can simultaneously remove carbon constituents and PCDD/Fs from HSWI fly ash. Moreover, flotation technology has relatively low operating costs, which make it be one of the most promising alternatives for the treatment of HSWI fly ash.

Acknowledgments

The authors thank Fund of the Key Laboratory of Education Ministry for Solid Waste Management and Environment Safety under the Project Number SWMES-2010-07. The authors also thank the National Natural Science Foundation of China under the Project Number NSFC 20806051.

References

Altun, N.E., Xiao, C.F., Hwang, J.Y., 2009. Separation of unburned carbon from fly ash using a concurrent flotation column. Fuel Process. Technol. 90, 1464–1470.

Cheng, T., Cioffi, R., Montagnaro, F., Santoro, L., 2012. Soluble salt removal from Chin, L., Somasundaran, P., 1993. Role of electrical double layer forces and polychlorinated dibenzo-p-dioxins and polychlorinated dibenzofurans, US.

Finch, J.A., Uribe-Salas, A., Xu, M., 1995. Column Flotation. In: Matis, K.A. (Ed.), Flotation Science and Engineering, Marcel Dekker, New York, pp. 291–310 (Chapter 11).

GB16889-2008. Standard for pollution control on the landfill site of municipal solid waste, China.

GB18485-2001. Standard for pollution control on the municipal solid waste incineration, China.

Hacifazlioglu, H., Sutcu, H., 2007. Optimization of some parameters in column flotation and a comparison of conventional cell and column cell in terms of flotation performance. J. Chin. Inst. Chem. Eng. 38, 287–293.

Harvey, P.A., Nguyen, A.V., Evans, G.M., 2002. Influence of electrical double-layer interaction on coal flotation. J. Colloid Interface Sci. 250, 337–343.

Hasan, H., Hale, S., 2007. Optimization of some parameters in column flotation and a comparison of conventional cell and column cell in terms of flotation performance. J. Chin. Inst. Chem. Eng. 38, 287–293.

Huang, Y., Takaoka, M., Takeda, N., 2003a. Chlorobenzene removal from municipal solid waste incineration fly ash by surfactant – assisted column flotation. Chemosphere 52, 735–743.

Huang, Y., Takaoka, M., Takeda, N., 2003b. Removal of unburned carbon from municipal solid waste fly ash by column flotation. Waste Manage. 23, 307–313.

Huang, Y., Takaoka, M., Takeda, N., Oshita, K., 2007. Partial removal of PCDD/Fs, coplanar PCBs, and PCBs from municipal solid waste incineration fly ash by a column flotation process. Environ. Sci. Technol. 41, 257–262.

Huang, K., Inoue, K., Harada, H., Kawakita, H., Hoku, K., 2012. Leaching of heavy metals by citric acid from fly ash generated in municipal waste incineration plants. J. Mater. Cycles Waste Manage. 13, 118–126.

Jiang, Y.H., Li, B.D., Li, X.J., 2009. Effect of water-extraction on characteristics of melting and solidification of fly ash from municipal solid waste incinerator. J. Hazard. Mater. 161, 871–877.

Kakuta, Y., Matsuo, T., Tojo, Y., Tomikawa, H., 2007. Characterization of residual carbon influencing on de novo synthesis of PCDD/Fs in MSWI fly ash. Chemosphere 68, 880–886.

Kuchar, D., Fukuta, T., Onyogo, M.S., Matsuura, H., 2007. Sulfidation treatment of molten incineration fly ashes with Na2S for zinc, lead and copper resource recovery. Chemosphere 67, 1518–1525.

Liu, Y.S., Zheng, L.T., Li, X.D., Xie, S.D., 2009. SEM/EDS and XRD characterization of raw and washed MSWI fly ash sintered at different temperatures. J. Hazard. Mater. 162, 161–173.

Liu, H.Q., Zhang, S.T., Zhang, Y.F., Wei, G.X., Zhang, S.G., 2010. Experimental study on solidification of hospital waste incineration fly ash using Portland cement. J. Tianjin Univ. 43, 32–36 (in Chinese).

Liu, H.Q., Wei, G.X., Liang, Y., Dong, F.Y., 2011. Glass-ceramics made from arcel-melting slag of waste incineration fly ash. J. Central South Univ. Technol. 18, 1945–1952.

Naik, P.K., Reddy, P.S.R., Misra, V.N., 2005. Interpretation of interaction effects and optimization of reagent dosages for fine coal flotation. Int. J. Miner. Process. 75, 83–90.

Sabiba, J., Tufail, M., Sofia, K., 2008. Heavy metal pollution from medical waste incineration at Islamabad and Rawalpindi, Pakistan. Microchem. J. 90, 77–81.

Sambuw, V.M., Ignatio, S.K., Janmane, M., 2011. Assessment of medical waste incinerator performance based on physical characteristics of ashes. Engineering 3, 1045–1053.

Uçurum, M., 2009. Influence of Jameson flotation operation variables on the kinetics and recovery of unburned carbon. Powder Technol. 191 (3), 240–246.

Wu, H.L., Lu, S.Y., Yan, J.H., Li, X.D., Chen, T., 2011. Thermal removal of PCDD/Fs from medical waste incineration fly ash – effect of temperature and nitrogen flow rate. Chemosphere 84, 361–367.

Xie, R., Li, W.J., Li, J., Wu, B., Yi, J., 2009. Emissions investigation for a novel medical waste incinerator. J. Hazard. Mater. 166, 365–371.

Yan, J.H., Peng, Z., Lu, S.Y., Li, X.D., Ni, M.J., Cen, K.F., Dai, H.F., 2007. Degradation of PCDD/Fs by mecanochemical treatment of fly ash from medical waste incineration. J. Hazard. Mater. 147, 652–657.

Yan, M., Li, X.D., Lu, S.Y., Chen, T., Chi, Y., Yan, J.H., 2011. Persistent organic pollutant emissions from medical waste incinerators in China. J. Mater. Cycles Waste Manage. 13, 213–218.

Zhao, L.J., Zhang, F.S., Chen, M.J., Wang, K.S., Liu, Z.G., 2008. Chemical properties of heavy metals in typical hospital waste incinerator ashes in China. Waste Manage. 29, 1114–1121.

Zhao, L.J., Zhang, F.S., Chen, M.J., Liu, Z.G., Bo, D., Wu, J.Z., 2010. Typical pollutants in bottom ashes from a typical medical waste incinerator. J. Hazard. Mater. 173, 181–185.

Zheng, L., Wang, C.W., Wang, W., Shi, Y.C., Gao, X.B., 2011. Immobilization of MSWI fly ash through geopolymization: effects of water-wash. Waste Manage. 31, 311–317.