Journal of Hazardous Materials 141 (2007) 106–114

Journal of Hazardous Materials

www.elsevier.com/locate/jhazmat

Study on use of MSWI fly ash in ceramic tile

Zhang Haiying [a,b,*], Zhao Youcai [b], Qi Jingyu [c]

[a] *Department of Environmental and Energy Engineering, Shanghai Institute of Technology, Shanghai, China*
[b] *The State Key Laboratory of Pollution Control and Resource Reuse, Tongji University, Shanghai, China*
[c] *School of Marine Geology and Geophysics, Tongji University, Shanghai, China*

Received 6 December 2005; received in revised form 25 June 2006; accepted 26 June 2006

Abstract

In this work, MSWI (municipal solid waste incineration) fly ash is used as a blending in production of ceramic tile by taking advantage of its high contents of SiO_2, Al_2O_3 and CaO. Besides, macro-performance and microstructure of the product as well as its leaching toxicity in practical application were studied by means of XRD, IR and SEM analysis, and leaching toxicity and sequential chemical extraction analysis of the product. It is found that when 20% fly ash is added, the product registers a high compressive strength of 18.6 MPa/cm^2 and a low water absorption of 7.4% after being sintered at 960 °C. It is found that the glazed tile shows excellent resistance against leaching, in accordance with HVEP stand, of heavy metals with $Cd < 0.0002$ ppm, $Pb < 0.0113$ ppm and $Zn < 0.0749$ ppm, and Hg below the low detection limit. These results show that heavy metals are cemented among the solid lattice in the product and can hardly be extracted. Leaching toxicity of heavy metals in the product, especially Hg, Pb, Zn and Cd, is substantially reduced to less than one-tenth of that in fly ash. In addition, specifications of Hg, Pb, Zn and Cd are largely changed and only a small portion of these heavy metals exists in soluble phases. These results as a whole suggest that the use of MSWI fly ash in ceramic tile constitutes a potential means of adding value.

Keywords: MSWI fly ash; Ceramic tile; Macro-performance; Microstructure; Leaching toxicity

---

1. Introduction

Fly ash is a must by-product of MSW incineration process. It has been classified as a hazardous waste all over the world. Its management is becoming a challenge for the incineration. Treatment methods of fly ash include solidification with cement-based materials, chemical stabilization with EDTA, sodium sulfide and thiourea [1], hydrometallurgical extraction by dissolution in acidic or alkaline medium, and sintering or vitrification for reuse as a construction material. Except the last thermal method, it is difficult to remove dioxins from MSWI fly ash. Hence, the last method is among the most promising methods to handle fly ash safely.

Papers from Korea demonstrated that MSWI fly ash can be vitrified by melting at 1500 °C for 30 min with the addition of >5 wt.% of SiO_2 [2]. A recent work in China reduced the vitrification temperature to below 1000 °C, by adding B_2O_3, borax and CaF_2 [3]. However, leaching toxicity and specification of heavy metals have not been tested thoroughly. And performance of the vitrification product has not been analyzed, resulting to its limited use.

There was also a study on sintering of washed MSWI fly ash at 1140 °C for 60 min for reuse as a concrete aggregate [4]. However, in the preliminary washing process, some heavy metals are extracted by water, resulting to a problem of water treatment. Practically, it is non-feasible, especially in engineering, as it may cause secondary pollution through the pretreatment process of fly ash washing. In addition, the sintering temperature of 1140 °C is so high that most heavy metals evaporate, resulting in a poor capability in stabilization of heavy metals. Moreover, sintering of fly ash for further use in construction materials, is an indirect way of fly ash reuse, which costs so much that only a few rich countries can afford. Consequently, how to use fly ash directly without pretreatment to reduce the cost is also a challenge facing countries across the world.

In addition, there is a shortage of clay in production of ceramic tile across the world and thus finding another material to replace clay is necessary. Fly ash, featuring a high content of

---

[*] Corresponding author. Tel.: +86 21 64945005; fax: +86 21 67625727.
E-mail address: haiying86@sohu.com (Z. Haiying).

0304-3894/$ – see front matter © 2006 Elsevier B.V. All rights reserved.
doi:10.1016/j.jhazmat.2006.06.100

SiO_2, Al_2O_3 and CaO, can replace part clay as one kind of raw materials of ceramic tile.

With this in mind, this work was done to find a way of direct use of fly ash, to reduce the cost of fly ash treatment and ceramic tile production. In stead of only emphasizing treatment of fly ash like the above two thermal methods, this work attaches great importance on use of fly ash which is a raw material in the work, rather than a hazardous waste.

In this work, use of untreated fly ash to make ceramic tile, aiming to reduce the treatment cost of fly ash and production cost of ceramic tile, was studied in detail. Firstly, characterization of MSWI fly ash sampled from Shanghai Pudong MSW Incineration Plant was analyzed. Secondly, macro-performance and microstructure of ceramic tile and their relationship were described by means of XRD, IR and SEM. Thirdly, the leachability and specification of heavy metals in the ceramic tile were tested.

Through the above analysis, this work proves that it is possible to use fly ash in making ceramic tile of sound macro-performance on the one hand and stabilize heavy metals and decompose dioxins on the other hand.

2. Materials and methods

2.1. Characterization of MSWI fly ash

The ash used in this study was sampled from Pudong MSW Incineration Plant, Shanghai, China, which handles 1000 t/day. Mineral and chemical compositions of fly ash, leaching toxicity and specification of heavy metals were performed.

XRF analysis was conducted on a SRS 3400 fluorescent X-ray spectrometer to detect chemical composition of MSWI fly ash, and XRD analysis was performed on a Philips powder diffractometer employing Cu Kα radiation (40 kV, 20 mA) in the range $2\theta = 3°–70°$ at a goniometer rate of $2\theta = 3°/\text{min}$ to detect its mineral composition.

The leaching toxicity analysis was performed in accordance with HVEP [5] (horizontal vibration extraction procedure) and ALT [6] (available leaching toxicity) standards, in which deionized water is used as the agent and the liquid to solid ratio registers 10:1 for the former and 100:1 for the latter.

Sequential chemical extraction has long been used as a method to analyze specification of heavy metals. In this study, sequential chemical extraction was performed on 10 g fly ash, with a liquid to solid ratio of 10:1 in each step. Specific description of each step is shown in Table 1 [7–9]. Heavy metals of the last two specifications are hardly soluble. In the last step, the contents of Cd, Pb and Zn in the residue from Step 5 were analyzed by digestion with $HCl/HNO_3/HF/HClO_4$ and that of Hg by digestion with $HCl/H_2O_2/HNO_3$.

Table 2
Chemical composition of cream-colored clay

Chemical composition	Content (%)
SiO_2	72.3
Al_2O_3	16.4
Fe_2O_3	1.6
K_2O	3.7
Na_2O	0.8
CaO	0.3
MgO	0.6
TiO_2	0.8

2.2. Raw materials for making ceramic tile

To make ceramic tile, MSWI fly ash, cream-colored clay, fired clay and limestone are used.

- *MSWI fly ash*. MSWI fly ash used in making ceramic tile came from Pudong MSW Incineration Plant, Shanghai China, and its characteristics are shown in Section 2.1 characterization of MSWI fly ash.
- *Cream-colored clay*. Cream-colored clay is a kind of natural clay output in surrounding area of Yixing, Jiangsu Province of China. Table 2 shows that its major chemical constitutions are SiO_2 and Al_2O_3, which can react at high temperature to form a large amount of mullite and silicates, the backbone of ceramic tile.

  Fig. 1 indicates that major mineral constitutions of cream-colored clay are quartz, illite and kaolinite, which can change into mullite at temperature over 900 °C, thus facilitating formation of framework of ceramic tile.
- *Fired clay*. Fired clay is a kind of fired material produced by grinding waste terracotta. Table 3 implies that fired clay has a high content of Al_2O_3, which is a major constitution of ceramic body. It can react with SiO_2, forming mullite and thus improving physical performance of the product.

  Being a fired material, its mineral compositions include quartz, mullite and cordierite (Fig. 2), which help strengthen framework of the product.
- *Limestone*. Limestone used in the experiment came from Yixing, Jiangsu Province China. It is conducive to reduction of sintering temperature of ceramic tile.

Table 1
Sequential chemical extraction procedure

Step	Reagent	Conditions
(1) Water soluble	Deionized water	3 h Continuous agitation
(2) Exchangeable	$MgCl_2$	3 h Continuous agitation
(3) Acid soluble	0.5 M CH_3COOH + 0.1 M $Ca(NO_3)_2$	3 h Continuous agitation
(4) Organically bound	0.1 M $Na_4P_2O_7$	3 h Intermittent agitation
(5) Iron oxide occluded	0.175 M $(NH_3)_2C_2O_4$ + 0.1 M $H_2C_2O_4$	3 h Intermittent agitation
(6) Residual	$HCl/HNO_3/HF/HClO_4$, $HCl/H_2O_2/HNO_3$	Digestion on electric hot plate

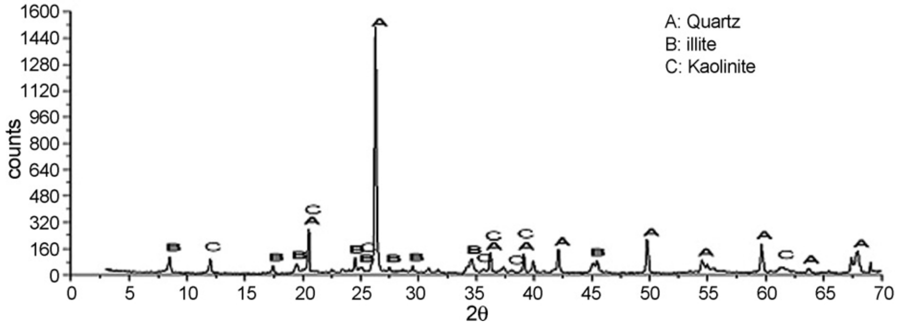

Fig. 1. XRD analysis of cream-colored clay.

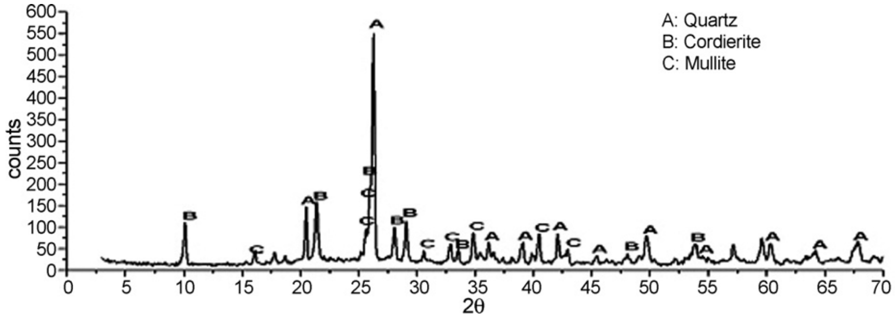

Fig. 2. XRD analysis of fired clay.

Table 3
Chemical composition of fired clay

Chemical composition	Content (%)
SiO_2	61.3
Al_2O_3	29.4
Fe_2O_3	2.2
K_2O	1.9
Na_2O	0.2
CaO	0.7
MgO	2.9
TiO_2	1.0

2.3. Ratios of raw materials for making ceramic tile

Table 4 shows the ratios of raw materials for making ceramic tile. Six samples of varied ratios without the addition of limestone were tested, and the sintering temperature exceeded 1000 °C, which inflicts an adverse effect on stabilization of heavy metals. And then limestone was added to reduce sintering temperature (Table 5). The sintering temperature was reduced to 960 °C in the work. Y7, Y8, Y9 and Y10 all feature good appearances and macro-performances. In order to increase the uses of fly ash, Y10 was chosen as the ideal ratio of raw materials.

Table 4
Ratios of raw materials (%) (without limestone)

	Number					
	Y1	Y2	Y3	Y4	Y5	Y6
Cream-colored clay	55	50	45	40	35	30
Fired clay	40	40	40	40	40	40
MSWI fly ash	5	10	15	20	25	30

Table 5
Ratios of raw materials (%) (with limestone)

	Number					
	Y7	Y8	Y9	Y10	Y11	Y12
Cream-colored clay	55	50	45	40	35	30
Fired clay	30	30	30	30	30	30
Limestone	10	10	10	10	10	10
MSWI fly ash	5	10	15	20	25	30

2.4. Method of making ceramic tile

Method of making ceramic tile is shown in Fig. 3. First, raw materials should be grinded and then mixed with water. The mixed material should be placed for 18 h before screening, and then molded using machine. Prior to the sintering process, the molded body should be dried at around 60 °C.

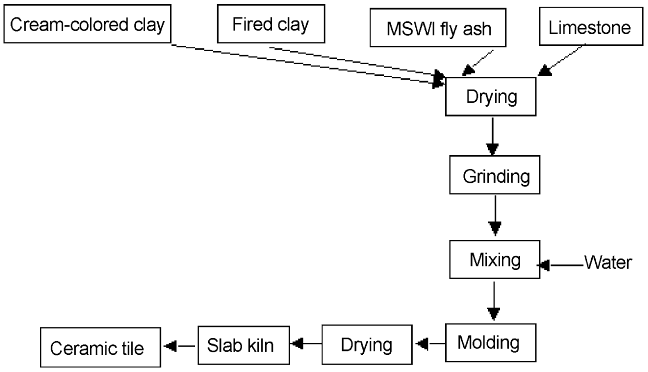

Fig. 3. Method for making ceramic tile.

Table 6
Major chemical constitution of sampled fly ash

Chemical constitution	Content (%)
CaO	35.8
SiO_2	20.5
Al_2O_3	5.8
K_2O	4.0
Na_2O	3.7
Fe_2O_3	3.2
MgO	2.1

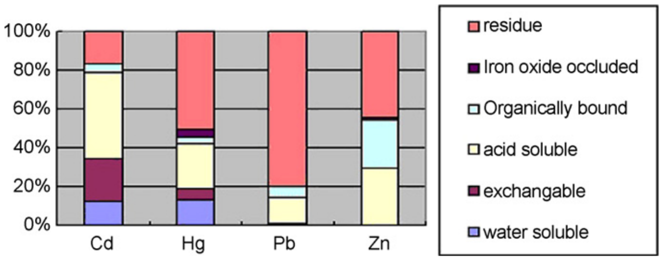

Fig. 5. Sequential chemical extraction results of sampled fly ash.

3. Results and discussion

3.1. Characterization of MSWI fly ash

Major chemical constitutions of fly ash are CaO, SiO_2 and Al_2O_3, registering a $CaO–SiO_2–Al_2O_3$ system, which are shown in Table 6. Hence, the fly ash can be used as a blending of ceramic tile whose raw materials feature a $SiO_2–Al_2O_3–CaO–Fe_2O_3$ system.

Fig. 4 is the XRD analysis of sampled fly ash. From Fig. 4, it can be seen that major mineral constitutions of fly ash should be SiO_2, $K_2Al_2Si_2O_8·3.8H_2O$, $AlCl_3·4Al(OH)_3·4H_2O$, $Ca_3Si_2O_7$, $Ca_9Si_6O_{21}·H_2O$ and $Ca_2SiO_4·0.35H_2O$. Based on calculation of peak and background intensity, its glass phases account for around 59%. High constitution of glass phases indicates high activity of fly ash, which is conducive to energy-saving in the recycling.

From the above analysis, it is clear that the fly ash mainly includes silicates, aluminum silicates and quartz in terms of mineral constitution. Being a product of incineration at high temperature, it features a high content of glass phases, as observed in Fig. 4. These glass phases play a key role in activity of fly ash. In terms of particle size of fly ash, smaller particle size means larger reaction area per unit volume and higher surface energy per area, thus resulting to a higher activity [10]. Hence, fly ash, whose average particle diameter is below 19 μm according to laser particle size analysis, registers a high activity. This is conducive to its reaction with other raw materials of ceramic tile

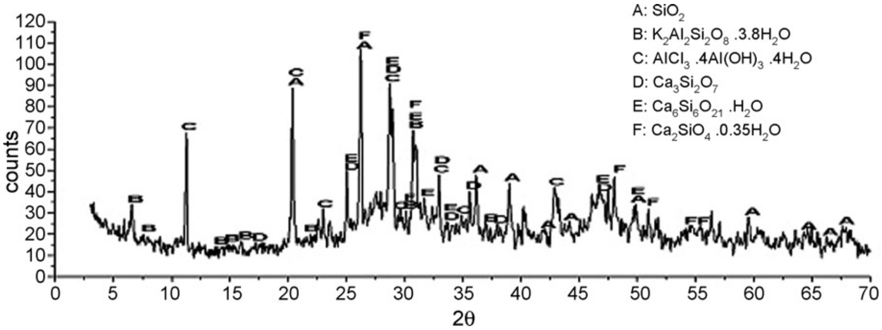

Fig. 4. XRD analysis of sampled fly ash (3°–70°).

Table 7
Leaching results of heavy metals in accordance with HVEP standard (mg/l)

Number	As	Cd	Cr	Cu	Hg*	Ni	Pb*	Zn
1	0.037	0.120	0.930	0.068	0.512*	0.004	38.09*	7.42
2	0.002	0.075	0.938	0.067	0.510*	0.007	38.28*	7.46
3	0.030	0.048	0.922	0.077	0.610*	0.006	38.83*	7.55
Limit [11]	1.5	0.3	10	50	0.05*	10	3	50

* Leaching toxicity exceeds the standard.

Table 8
Leaching results of heavy metals in accordance with ALT standard (mg/kg)

Number	As	Cd*	Cr	Cu	Hg*	Ni	Pb*	Zn*
1	7.28	29.13*	38.40	59.75	1.45*	19.03	797.5*	1656.3*
2	8.28	29.33*	37.58	59.53	0.76*	18.38	625.3*	1682.0*
3	7.79	29.17*	37.98	59.63	1.73*	18.71	597.1*	1569.5*
Limit [11]	15.00	3.00	100	500	0.5	100	30	500

* Leaching toxicity exceeds the standard.

to form new silicates so that heavy metals can be stabilized in these new silicates.

The results of leaching test are shown, respectively, in Tables 7 and 8.

From Tables 7 and 8, it can be seen that leaching concentrations of Cd, Hg, Pb and Zn in two tests considerably exceed the limit described in "Identification Standard of Hazardous Waste—Identification of Leaching Toxicity" [11], indicating that Hg, Cd, Zn and Pb are potentially harmful to the environment by HVEP and ALT standards. It is indicated that major hazardous heavy metals of the sampled fly ash are Cd, Hg, Pb and Zn.

Fig. 5 shows that soluble Cd mainly exists in the acid soluble, exchangeable and water soluble phases, soluble Hg mainly in acid soluble and water soluble phases, while soluble Pb mainly appears in acid soluble and soluble Zn mainly in organically bound and acid soluble. Hence, it is relatively difficult for Pb and Zn to be leached out in environment without the existence of acids. However, in natural environment exposing to acid rain, acids always exist and the above four heavy metals tend to be extracted by acidic liquid after years. The aim of stabilization and sintering of the fly ash is to minimize leaching toxicity of these heavy metals by reducing their existence in water soluble, exchangeable, acid soluble and organically bound phases, as done in this work.

3.2. *Major macro-performance analysis of ceramic tile*

Performances of the product based on the Y10 ratio, at different sintering temperature, were studied in detail.

3.2.1. *Compressive strength*

Compressive strengths were measured in accordance with China GB4100-83. Fig. 6 shows compressive strength of the products at different sintering temperature. It is indicated that when ratio of fly ash is no more than 25%, MSWI fly ash is conducive to improvement of compressive strength of the product sintered at temperatures between 920 and 1060 °C. However, when 25–30% fly ash is added, the compressive strength decreases when the sintering temperature exceeds 1000 °C. Besides, compressive strength of Y10 increases considerably as temperature rises from 920 to 940 °C. While after 1000 °C, it increases slightly with the increase of temperature. Strengths of Y10 meet the requirements on ceramic tile described in China GB4100-83.

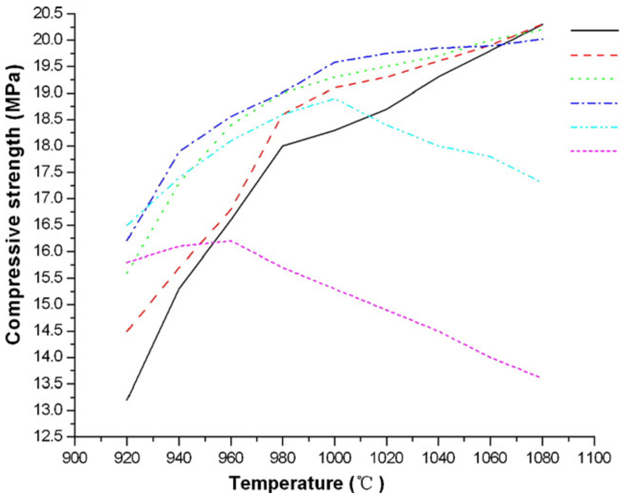

Fig. 6. Compressive strength at different sintering temperature.

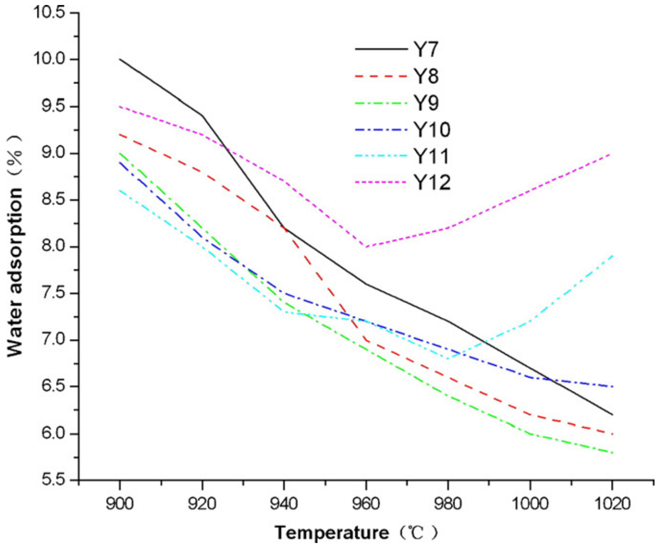

Fig. 7. Water absorption of product sintered at different temperatures.

3.2.2. *Water absorption*

Water absorptions were measured following China GB2579-81 and China GB4100-83. Specific water absorptions of the product at different sintering temperature are shown in Fig. 7. From Fig. 7, it can be seen that water adsorption of the product decreases with the increase of ratio of MSWI fly ash when it is no more than 20%. While, when 25–30% fly ash is added, water adsorption increases as sintering temperature exceeds 980 °C. Besides, water absorption of Y10 decreases as temperature rises from 920 to 1020 °C, while it shows little variation after 1020 °C, resulting to a small porosity and strong density at 1020 °C.

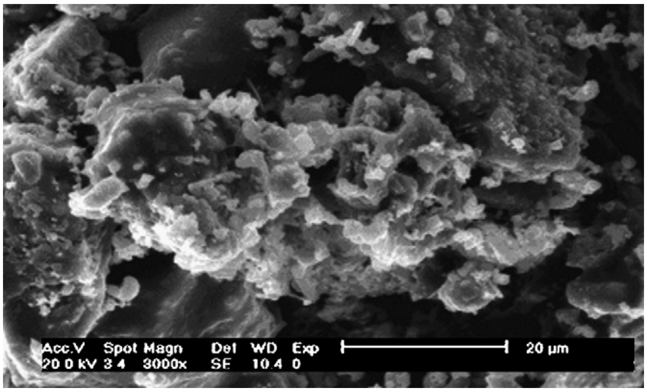

Fig. 8. SEM analysis of ceramic tile at 920 °C.

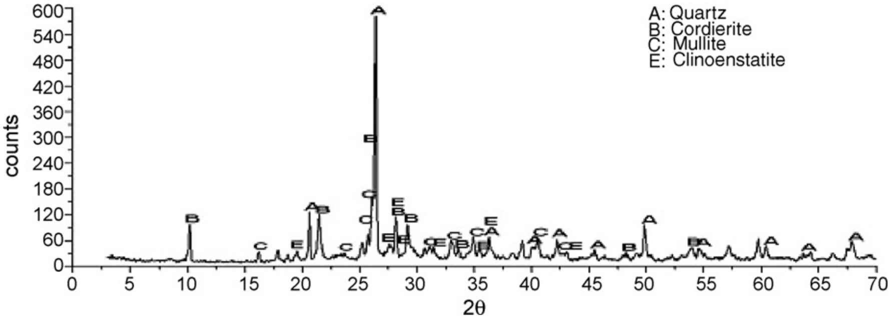

Fig. 9. XRD analysis of the product sintered at 920 °C.

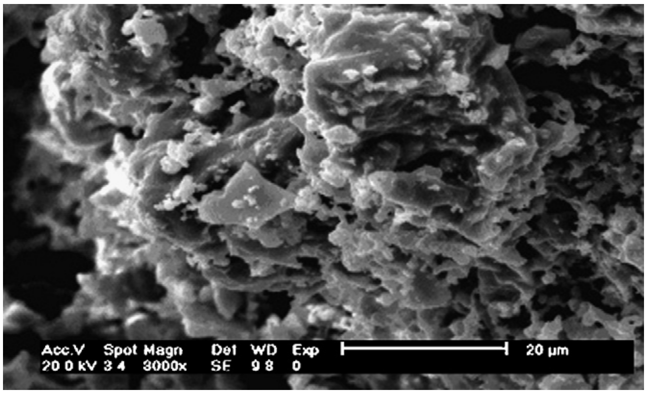

Fig. 10. SEM analysis of the product sintered at 940 °C.

Table 9
Shrinkage of the product sintered at different temperature (mm)

	Temperature (°C)						
	920	940	960	980	1000	1040	1080
Length	0.47	0.34	0.14	0.15	0.13	−0.24	−0.37
Width	0.23	0.12	0.12	0.06	0.03	0.09	−0.24
Thickness	0.10	0.11	0.09	0.08	0.08	−0.08	−0.15

3.2.3. Shrinkage

Table 9 shows specific deviation of the product at different sintering temperature. From the table, it can be seen that all the products of Y10 proportion, sintered between 960 and 1000 °C, show small shrinkage. Hence, the products sintered between 960 and 1000 °C feature sound sintering of ceramic tile.

3.3. Micro-structure analysis

3.3.1. Micro-structure sintered at 920 °C

Fig. 8 shows SEM analysis of ceramic tile sintered at 920 °C. It is clear that the product sintered at 920 °C has a relatively incompact structure with a lot of depressions in it, indicating a high rate of waste product. Interfaces among particles are clear-cut, without formation of continuous phases. In terms of macro-performance, compressive strength is relatively low and water absorption relatively high, which goes down to a decisive factor of large porosity of product.

Major crystalline phases are quartz, cordierite, clinoenstatite and mullite (Fig. 9). Diffraction peak of mullite is very obvious at d = 5.39, 3.428, 3.390, 2.886, 2.694, 2.542, 2.206 and 2.121 Å, implying that mullite has been a major crystalline phase of the product at 920 °C.

3.3.2. Micro-structure at 940 °C

When temperature rises to 940 °C, mini-cracks on surface of the product all disappear according to SEM analysis of the product sintered at 940 °C, as shown in Fig. 10.

Obvious reaction can be seen at interfaces of particles and the interfaces are much more obscure in comparison with those at 920 °C. Hence, porosity reduces considerably and density of the product increases, which may be contributed to the particle migration through liquid phases with the increase of sintering temperature.

XRD analysis shows that crystalline phases are quartz, cordierite, clinoenstatite, mullite and andradite, registering an increase over those of 920 °C (Fig. 11).

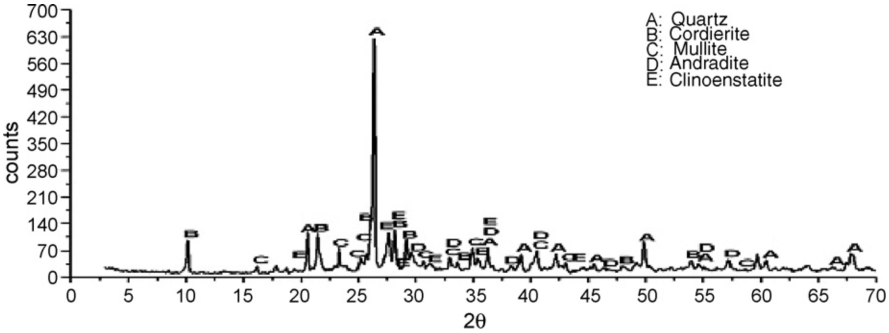

Fig. 11. XRD analysis of the product sintered at 940 °C.

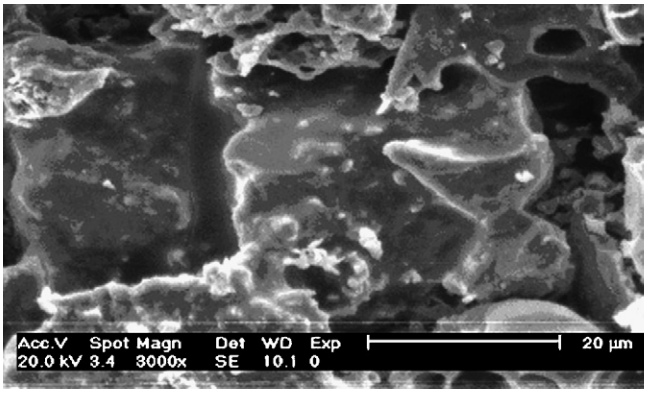

Fig. 12. SEM analysis of the product sintered at 960 °C.

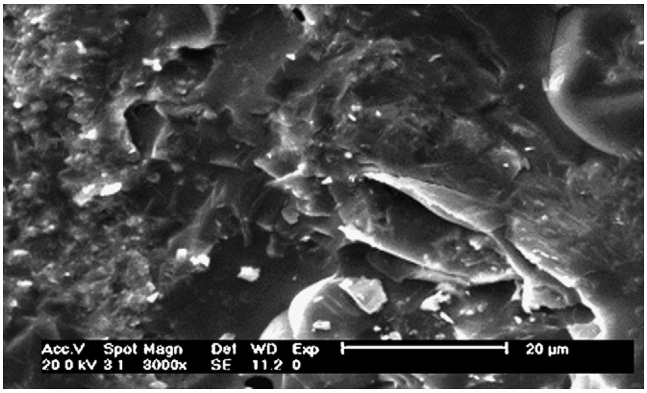

Fig. 14. SEM analysis of the product sintered at 980 °C.

3.3.3. *Micro-structure at 960 °C*

After being sintered at 960 °C, the product features smooth and sound surface, high strength and hardness, all indicating good performance of the product. From Fig. 12 (SEM analysis of the product sintered at 960 °C), it can be seen that particles are closely connected together and covered with new output to form a continuous solid consisting of a great amount of glass phases with an increase of temperature by tightly cementing particles. Meanwhile, heavy metals can be cemented by glass phases or immobilized among firm crystal lattice so that they can hardly be leached out.

From XRD analysis (Fig. 13), it is concluded that glass phases increases at 960 °C, in comparison with those at 940 °C. The major crystalline phases are still quartz, cordierite, clinoenstatite, mullite and andradite, registering a reduction in the content over those at 940 °C.

3.3.4. *Micro-structure at 980 °C*

SEM analysis and XRD analysis of the product sintered at 980 °C are, respectively, shown in Figs. 14 and 15. The product shows higher strength, smoother and darker surface, compared with the product sintered at 960 °C. It is indicated that the product shows characterization of more sound sintering, when diffusion of crystal lattice and crystal interface as well as the surface diffusion proceed together. In the SEM analysis of the product sintered at 980 °C (Fig. 14), it is clear that particles are more closely cemented together and their interfaces are invisible. A hard solid whole with high strength came into being. Apparently, heavy metals have been more tightly fixed in the solid and can hardly be leached out even at the acidic conditions.

From the XRD analysis at 980 °C (Fig. 15), it is implied that content of crystalline phases continues to reduce and more glass phases form, which is in consistent with what can be seen in the SEM analysis.

3.4. *Leaching toxicity analysis of the product*

Given macro-performance of the product and stabilization of heavy metals, the product sintered at 960 °C was chosen to test the leaching toxicity. Leaching, in accordance with standard of HVEP, of Cd from the glazed tile is reduced to 0.53% of that from the body prior to sintering, Zn reduced to 0.59% and Pb 0.08%, which is shown in Table 10. No Hg leaching was detected in accordance with HVEP standard. In accordance with ALT standard, leaching of Cd, Zn, Pb and Hg from the glazed tile was reduced, respectively, to 0.51%, 2.72%, 0.01% and 0.05% of that from the body prior to sintering (Table 11). Hence, use of fly ash making glazed tile is an effective way to stabilize such heavy metals as Cd, Hg, Pb and Zn.

From the sequential chemical extraction results in Fig. 16, it is clear that Cd, Hg, Pb and Zn mainly exist in residue phase, and only a small portion of them can be extracted. Hence, leaching toxicity of Cd, Hg, Pb and Zn is greatly reduced in the product sintered at 960 °C, compared with MSWI fly ash.

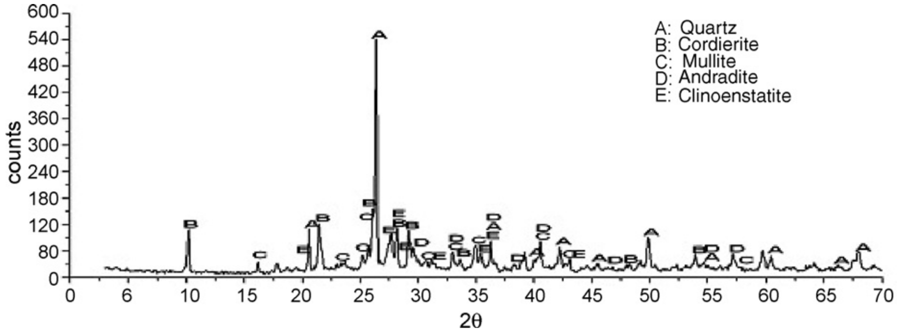

Fig. 13. XRD analysis of the product sintered at 960 °C.

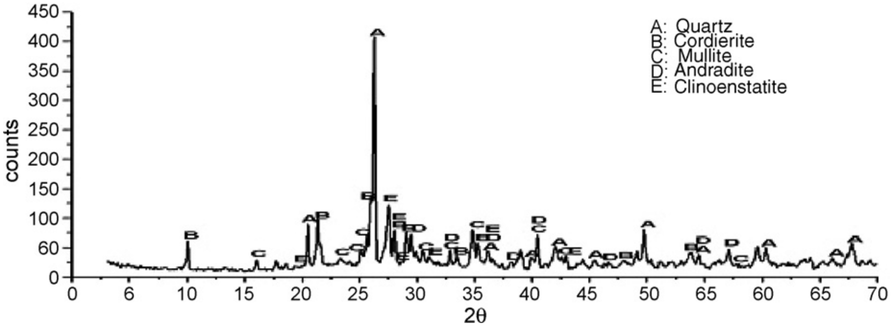

Fig. 15. XRD analysis of the product sintered at 980 °C.

Table 10
Leaching toxicity of heavy metals by HVEP standard (mg/l)

Number	Cd	Hg	Pb	Zn
Body prior to sintering				
1	0.016	0.110	7.697	6.342
2	0.023	0.092	6.935	8.431
3	0.019	0.057	9.218	8.209
Av1	0.019	0.086	7.950	7.661
Glazed tile				
1	ND	ND	0.0012	0.0356
2	ND	ND	0.0072	0.0749
3	0.0002	ND	0.0113	0.0247
Av2	0.0001	ND	0.0066	0.0451
Av2/Av1	0.0053	0	0.0008	0.0059
Limit	0.3	0.05	3	50

"Av1" and "Av2" represent the average value of three times. "ND" means that no leaching toxicity is detected.

Presence of dioxins in the product at present is unfortunately not tested. However, as traced from the relevant literatures [12,13], dioxins can decompose into innocent substances at 900 °C-plus, which is discharged quickly and will not recompose into dioxins again.

Table 11
Leaching toxicity of heavy metals by ALT standard (mg/kg)

Number	Cd	Hg	Pb	Zn
Body prior to sintering				
1	5.921	0.252	133.7	331.5
2	4.398	0.098	101.7	346.8
3	6.002	0.276	98.1	298.2
Av1	5.440	0.209	111.2	325.5
Glazed tile				
1	0.050	ND	0.0122	9.231
2	0.034	0.0001	0.0143	8.340
3	ND	0.0003	0.0013	9.025
Av2	0.028	0.0001	0.0093	8.865
Av2/Av1	0.0051	0.0005	0.0001	0.0272
Limit	3	0.5	30	500

"Av1" and "Av2" represent the average value of three times. "ND" means that no leaching toxicity is detected.

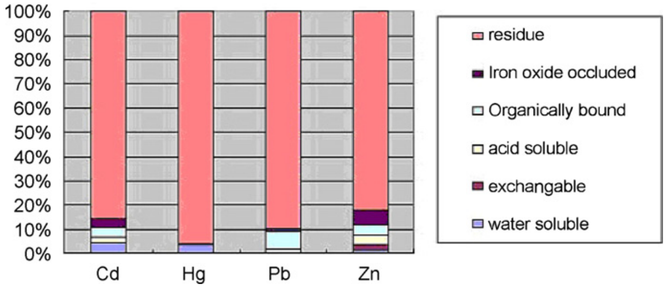

Fig. 16. Sequential chemical extraction results of the product.

4. Conclusions

Through leaching toxicity analysis by HVEP and ALT standards, it is concluded that major hazardous heavy metals of sampled MSWI fly ash are Hg, Pb, Zn and Cd. Consequently, their leaching toxicity should be reduced during its recycling or the disposal.

As major constitutions of the sampled fly ash are glass phases, silicates, aluminum silicates and quartz, it can be used as a blending of ceramic tile. Through sintering at 900 °C-plus, heavy metals can be cemented among the solid lattice in the product featuring high strength. Consequently, leaching toxicity of Hg, Pb, Zn and Cd can be substantially reduced.

Leaching analysis in accordance with HVEP standard indicates that leaching of Cd from the glazed tile is reduced to 0.53% of that from the body prior to sintering, Zn reduced to 0.59% and Pb 0.08% and no Hg is detected in the leachate. Leaching analysis in accordance with ALT standard shows that leaching of Cd, Zn, Pb and Hg from the glazed tile was reduced, respectively, to 0.51%, 2.72%, 0.01% and 0.05% of that from the body prior to sintering. Hence, use of fly ash making glazed tile is an effective way to stabilize such heavy metals as Cd, Hg, Pb and Zn.

Sequential chemical extraction shows that, through sintering at 960 °C, specifications of Hg, Pb, Zn and Cd are largely changed. Only a small portion of these heavy metals exists in soluble phase, which is the reason why Hg, Pb, Zn and Cd register a low leaching toxicity in the product.

With the increase of temperature, content of crystalline phases of the product first rises and then falls down, while the glass phases register a reverse trend. Major phases of the product are quartz, cordierite, clinoenstatite, mullite and andradite. The product sintered at 960 °C-plus boasts sound macro-performances and it can be used widely in construction.

Acknowledgements

The authors would like to acknowledge the World Expo funding for this study provided by the National Science and Technology Department of the Republic of China, and the funding provided by the Science & Technology Department of Shanghai under project number 032312044. Laboratory technicians of the State Key Laboratory of Pollution Control and Resource Reuse, Tongji University, and of Instrumental Analysis Center, Jiaotong University, are thanked for assisting with the experimental work.

References

[1] D.S. Kosson, H.A. van der Sloot, T.T. Eighmy, An approach for estimating of contaminant release during utilization and disposal of municipal waste combustion residues, J. Hazard. Mater. 47 (1996) 43–75.

[2] Y.J. Park, J. Heo, Vitrification of fly ash from municipal solid waste incineration, J. Hazard. Mater. 91 (2002) 83–93.

[3] C. Dezhen, Z. Hesheng, Preliminary study on MSWI fly ash vitrification at lower temperature, Shanghai Environ. Sci. 21 (2002) 344–349.

[4] T. Mangialardi, Sintering of MSW fly ash for reuse as a concrete aggregate, J. Hazard. Mater. 87 (2001) 225–239.

[5] GB 5086.2-1997, Solid waste-extraction procedure for toxicity of solid waste-horizontal vibration method.

[6] D.S. Kosson, H.A. van der Sloot, T. Holmes, et al., Leaching properties of untreated and treated residues tested in the USEPA program for evaluation of treatment and utilization technologies for municipal waste combustor residues [A], in: J.J.J.M. Goumans, H.A. van der Sloot, Th.G. Aalbers (Eds.), Waste Materials in Construction [C], Elsevier Science B.V., The Netherlands, 1991, pp. 119–134.

[7] H. Zhang, Study on characterization of APC fly ash from Pudong MSWI factory, Master's paper, Tongji University, Shanghai, 2003, p. 27.

[8] C.S. Kerby, J.D. Rimstidt, Mineralogy and surface properties of municipal solid waste ash, Environ. Sci. Technol. 27 (4) (1993) 652–660.

[9] S. Abanades, G. Flamant, Gagnepain, et al., Fate of heavy metals during municipal solid waste incineration, Waste Manage. Res. 20 (1) (2002) 55–68.

[10] G. Hong, Inorganic Solid Chemistry, The Science Publishing House, Beijing, 2002, pp. 227–228.

[11] GB5085.3-1996, Identification stand of hazardous waste—identification of leaching toxicity [S], China.

[12] Weber, R. Sakurai, T. Hagenmaier, et al., Formation and destruction of PCDD/PCDF during heating treatment of fly ash sample from fluidized bed incinerators, Chemosphere 38 (11) (1999) 2633–2642.

[13] R.P. Kobylecki, K. Ohira, I. Ito, et al., Dioxin and fly ash free incineration by ash pelletization and reburning, Environ. Sci. Technol. 35 (2001) 4313–4319.