ELSEVIER

Journal of Hazardous Materials 59 (1998) 201–210

JOURNAL OF HAZARDOUS MATERIALS

The characteristics study on sintering of municipal solid waste incinerator ashes

Kuen-Sheng Wang [a,*], Kung-Yuh Chiang [b], Jing-Kae Perng [a], Chang-Jung Sun [a]

[a] *Graduate Institute of Environmental Engineering, National Central University, Chung-Li, Taiwan, ROC*

[b] *Department of Environmental Engineering and Health, Yuan-Pei Institute of Medical Technology, Hsin-Chu, Taiwan, ROC*

Received 4 April 1997; received in revised form 10 October 1997; accepted 13 October 1997

Abstract

The study examines the sintering of incinerator ashes from municipal solid waste while considering the compact pressure, sintering temperature, and sintering time. Experimental results indicate that the compressive strength primarily influences the compact pressure used in forming the specimens. The specimens' strengths increase at a sintering temperature ranging from 1120°C to 1140°C. However, the strength decreases with an increasing ignition loss of incinerator residues. As heavy metals are fixed and/or sealed in the sintered incinerator ashes, the process generates a ceramic-like solid having a sufficiently low metal leachability. The Pb, Cd, and Cr concentrations of the leachate from the Toxicity Characteristic Leaching Procedure (TCLP) test are 0.10–0.70 mg/l, 0.05–0.30 mg/l, and 0.35–1.25 mg/l, respectively, all complying with the regulatory limits of Taiwan EPA. The above results point toward the feasibility of recycling the incinerator ashes as a construction material by sintering. © 1998 Elsevier Science B.V.

Keywords: Sintering process; Municipal solid waste; Incinerator ash

1. Introduction

Limited disposal sites, and along with constantly growing generation rate and disposal costs of the municipal solid waste (MSW), have hastened efforts to adopt incineration technologies and energy recovery strategies for managing MSW in Taiwan.

* Corresponding author.

0304-3894/98/$19.00 © 1998 Elsevier Science B.V. All rights reserved.
PII S0304-3894(97)00147-7

More than twenty-two incinerators are being planned and constructed to be operating on this island by the year 2000. These incinerators will generate more than 1500 tons of incinerator ash daily by processing two-thirds of the MSW islandwide [1]. The large quantity coupled with the potential leachability of high metal concentrations in the residues has necessitated the study of treatment and disposal related problems. Sintering is a thermal treatment for coherently bonding particles to enhance the strength and other engineering properties of compacted particles. This process has long been employed in a diverse manner for products such as ceramic, metals and various composite materials. The process has also been recently applied to treat incinerator residues for safely disposing, recycling and reusing of the ashes as aggregates for construction material, granules for road, bricks for walkway and possibly other uses [2]. Prerequisites for such purposes stipulate that the sintered ashes be extremely low in heavy metals' leachability and have sufficient compressive strength. However, sintering conditions, including compact pressure, sintering time and temperature, affect the characteristics of sintered specimens [3–5]. A more thoroughly understanding the effects of the sintering conditions on the characteristics of the sintering process is critical, particularly in applying this technology to incinerator ashes. Therefore, this study investigates the effects of sintering conditions on the leachability and the physical properties of the ash sinter, while considering various compact pressures, sintering times and temperatures, as well as the initial ignition of the incinerator ashes. The leachability, compressive strength, moisture absorption, and apparent density after sintering were discussed.

2. Materials and methods

2.1. Sample preparation

All fly ash samples used in this study were collected from a mass burning incineration plant located in the northern part of Taiwan. The plant can process 1350 tons of the local MSW daily. Air pollution control devices equipped in this plant consist of a cyclone, an adsorption reactor, and a fabric filter. Herein, the fly ash obtained from what is separated by the cyclone was initially sieved to remove coarse impurities. Next, the ash passing through mesh 50 (#50) was compacted with pressures ranging from 140 kgf/cm^2 (2000 psi) to (5000 psi), subsequently forming cylindrical specimens 3 cm in height and 2 cm in diameter. Table 1 summarizes the principal properties and the metal contents of the fly ash.

2.2. Experimental procedures

The effects of operating conditions of the characteristics of the subsequent sinter were investigated, by performing experiments in which compact pressures ranged from 140 kgf/cm^2 (2000 psi)–350 kgf/cm^2 (5000 psi), sintering temperatures ranged from

Table 1
Principal properties and concentrations of heavy metals in MSW incinerator fly ash

Principal properties	Size distribution					
	#50–80	#80–120	#120–200	#200–325	> #325	Particle size
pH (in H_2O)	–	–	–	–	–	11.75
Moisture content (%)	–	–	–	–	–	4.49
Ignition loss (%)	4.43	4.88	4.72	5.21	8.08	5.05
Mass percentage (%)	14.56	19.09	40.41	18.62	7.32	–
Accumulation mass percentage (%)	100	85.44	66.35	25.94	7.32	–
Total concentration of heavy metal (mg / kg)						
Pb	3440	3310	4623	6538	8375	5239
Cd	137	148	212	306	406	244
Cr	1460	2020	2010	2246	2064	1785
TCLP leachate concentration (mg / l)						
Pb	3.81	4.2	7.7	10.2	11.1	7.34
Cd	0.49	0.49	0.51	0.54	0.55	0.51
Cr	1	0.86	1.91	2.19	2.59	1.68

1100°C–1140°C, and sintering times ranged from 10–60 min. Compact specimens after sintering were then tested to determine their TCLP leaching toxicities for Pb, Cd, and Cr, and their physical properties. These properties included the unconfined compressive strength, the apparent density, the dimensional change, and the moisture absorption capacity.

2.3. The analysis methods

Compact specimens and sintered samples were characterized according to the following chemical and physical tests:

Chemical tests	
pH	ROCEPA[*1] Method 424.1
TCLP target methods (Pb,Cd,Cr)	ROCEPA Method 4210.0
Heavy Metal Contents (Pb, Cd, Cr)	ROCEPA Method 4614,4616,4621
Loss on ignition of the residues	ROCEPA Method 4216
Physical tests	
Particle Size Distribution	CNS[*2] 486(A3005)
Moisture	Content CNS 488(A3007)
Apparent Density	ASTM[*3] D 698
Unconfined Compressive Strength	CNS 1230(A3043)

[*1] ROCEPA: Environmental Protection Administration, R.O.C.; [*2] CNS: Chinese National Standard; [*3] ASTM: American Society for Testing and Materials.

3. Results and discussion

3.1. Effects of the ignition loss

Increasing the ignition loss of the compact specimen can increase the porosity and decrease the densification effect after sintering. Organic compounds in the compact specimen can gasify and/or oxidize to CO_2 and H_2O. In addition, inorganic compounds such as $CaCO_3$ may decompose into CO_2 at higher temperature [6,7]. All these reactions involving organic and inorganic components during sintering can contribute toward weight loss of the specimens. As Fig. 1 indicates, the weight loss increases with either a decreasing compact pressure or increasing sintering time. Also, a low compact pressure coupled with a long sintering time may yield a higher weight loss during the sintering process. The higher the compact compressive stress, the smaller the porosity and the longer the path among the particles for the gas to diffuse. This may (a) hinder the gasification or (b) block the gases inside the sinter matrix. Consequently, the weight loss decreases with an increasing compact pressure. However, a longer sintering time may provide sufficient time for a larger weight loss. Herein, the maximum weight loss is around 12% at a compact pressure of 104 kgf/cm^2 (2000 psi) and a sintering time 60 min.

3.2. Dimensional change after sintering

The dimensional change in incinerator ash compact is a prominent sintering monitor. With respect to recycling and reusing sintered ash, controlling shrinkage or swelling is a critical concern. The linear dimensional change is formally defined as (Lo–Ls)/Lo, reflecting the change in an initial green length Lo to a final sintered length Ls. A positive change is termed as either swelling or negative shrinking. Herein, a maximum

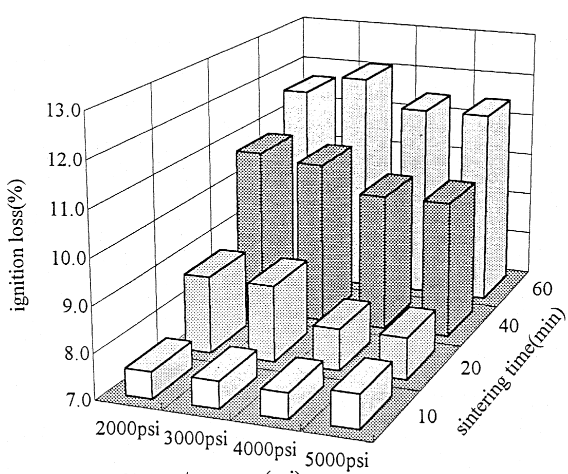

Fig. 1. Changes in ignition loss for sintered specimens.

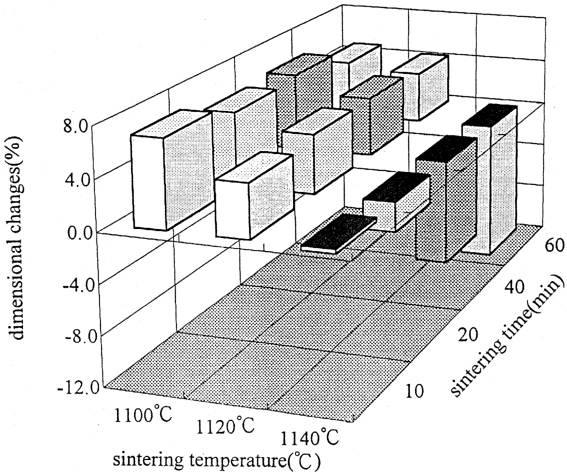

Fig. 2. Dimensional changes for sintered specimens.

of 7% swelling occurs at 1100°C, possibly owing to the interaction among thermal expansion, bubble formation and crystalline phase change during the sintering process. As Fig. 2 reveals, increasing the sintering temperature to 1120°C, caused the swelling rate to decrease due to only a slight change in crystalline phase, a state close to stable phase. Meanwhile, the swelling effect might be offset by the decreasing porosity among ash particles. However, elevating the sintering temperature to 1140°C, produces a significant densification, resulting in a total shrinkage in volume [8,9]. Similarly, increasing the sintering time increases the effect of densification, but decreases the swelling rate, subsequently leading to a total shrinkage after sintering [8]. However, effects of compact pressure on the shrinkage of specimens are insignificant.

3.3. Moisture absorption

The moisture absorption rate is defined as the weight of moisture in the pores to the sintered specimen's weight. The moisture absorption rate is an effective index in evaluating the sintered product's quality; it is also a function of compressive strength and the density of the sintered specimen [7]. According to our results, the rate decreases with increasing sintering temperature (Fig. 3). Sintering at high temperature may enhance densification, close some of the open pores, and decrease the moisture adsorption rate. In this work, moisture absorption decreases by 23% when temperature is raised from 1110°C to 1140°C. Fig. 4 also reveals that moisture absorption rate decreases with an increasing compact pressure. In addiction, decreasing absorption implies a decrease in the amounts of open pores and an increasing densification and, again, an increase in compressive strength [6,9]. Morphologically analyzing the sintered specimen with scanning electron microscopy (SEM) confirms the same results. The morphology analysis in a previous study demonstrates that the average pore diameter decreases as specimens are filled by smaller particles when sintering temperature elevated [10].

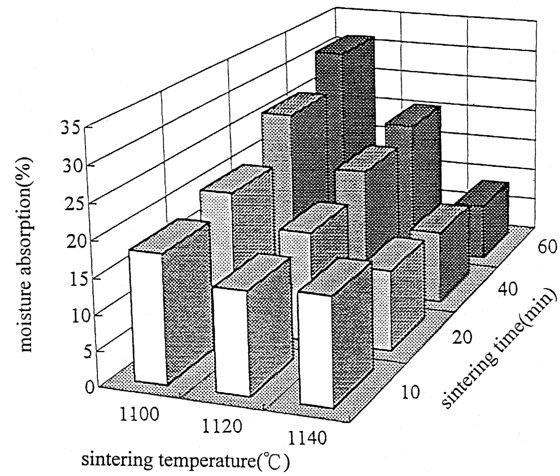

Fig. 3. Changes in moisture absorption for sintered specimens (sinterng temperature).

3.4. Apparent density of sintered specimens

The apparent density is defined as the ratio of the weight to the total volume of the mass and the open pores. Accordingly, the mass density and the open pore volume affect the apparent density of the sintered specimens. The sintering results between 1100°C and 1120°C indicate that the expansion at elevated temperatures increases the open pore volume, as well as decreases the closed pore volume, thereby causing an increase in apparent density. The effect is most profound at 1120°C. However, at 1140°C, the surface sintering effect provides a much more closed pore volume, which decreases the apparent density by counter balancing part of the effect of expansion (Fig. 5). On the

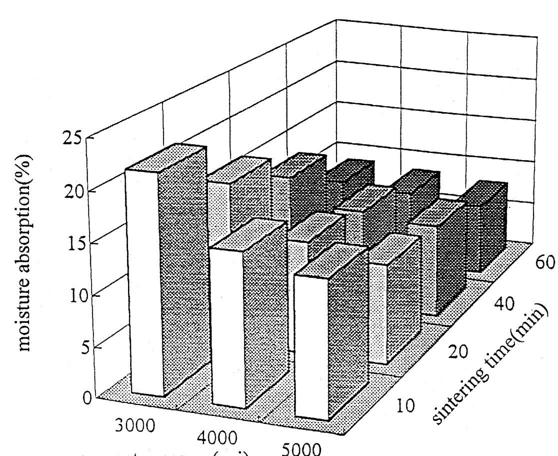

Fig. 4. Changes in moisture absorption for sintered specimens (compact pressure).

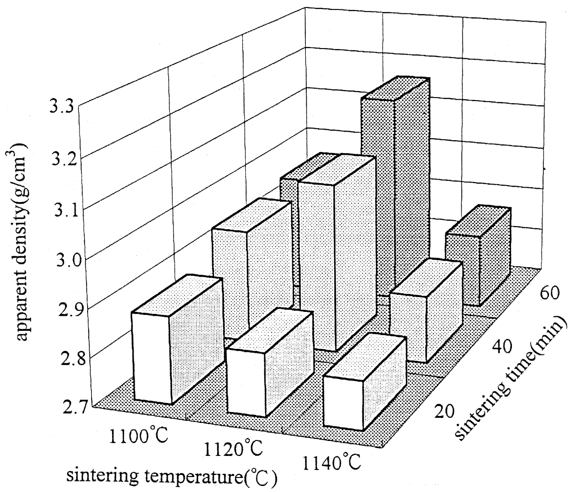

Fig. 5. Changes in apparent density for sintered specimens.

other hand, a longer sintering time reduces the closed pore volume and, eventually, increases the sintered specimens' apparent density.

3.5. Leaching characteristics of heavy metals

Table 2 summarizes the leaching results of Pb, Cd, and Cr for specimens sintered at 1100°C–1140°C for 10–60 min. The concentrations of TCLP leachate for Pb, Cd, and Cr reveal a decreasing tendency when the sintering time ranges from 10–60 min. However, leaching concentrations at different sintering temperatures reflect that the leaching behaviors depend primarily on the types of heavy metals and/or their compounds formed at that temperature [11–13]. According to Figs. 6–8, the leaching concentrations of Pb increases with increasing temperature, while Cd exhibits a declining tendency. The heavy metal Cr responds differently, initially increasing with an elevated temperature to 1100°C, peaking at 1120°C, and then decreasing to 1140°C.

Table 2
TCLP leachate concentration for sintered specimens

Sintering time (min)	Metals								
	Pb (mg/l)[a]			Cd (mg/l)[a]			Cr (mg/l)[a]		
	1100°C	1120°C	1140°C	1100°C	1120°C	1140°C	1100°C	1120°C	1140°C
10	0.239	0.301	0.359	0.31	0.27	0.25	0.76	0.98	0.93
20	0.169	0.208	0.317	0.19	0.12	0.10	0.84	0.99	0.88
40	0.085	0.109	0.289	0.09	0.07	0.06	1.03	1.07	0.43
60	0.089	0.098	0.261	0.06	0.06	0.04	0.99	1.27	0.15

[a]Regulatory limits: 5 mg/l for Pb, 1 mg/l for Cd, 5 mg/l for Cr.

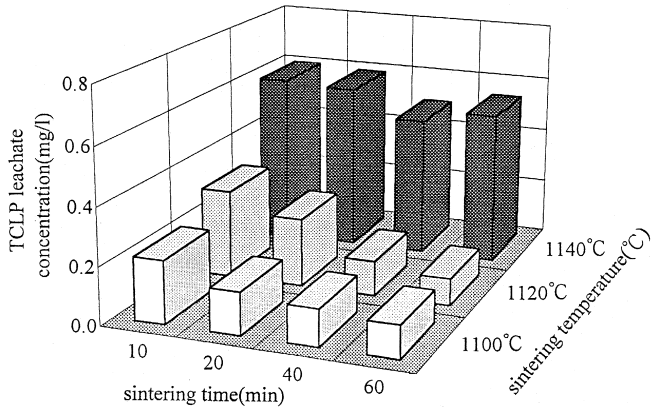

Fig. 6. Pb TCLP leachate concentrations for sintered specimens.

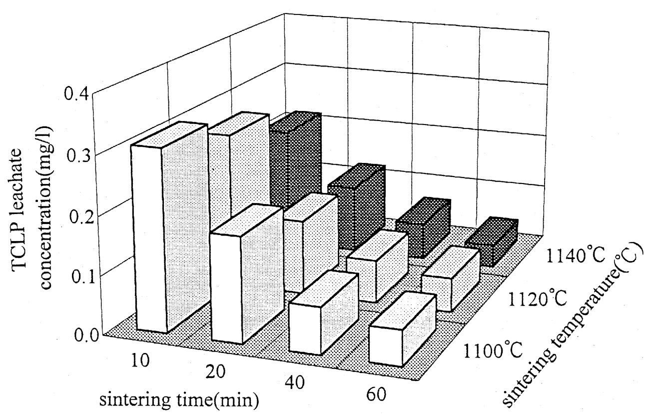

Fig. 7. Cd TCLP leachate concentrations for sintered specimens.

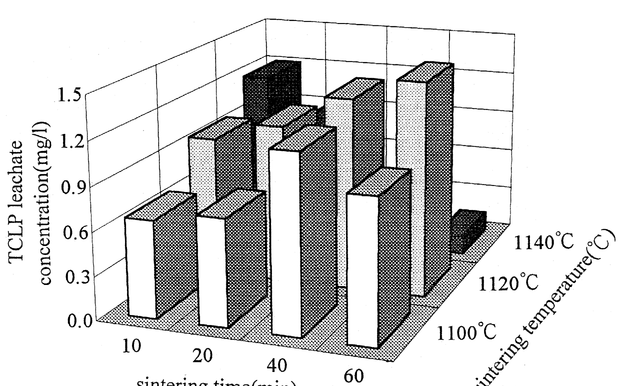

Fig. 8. Cr TCLP leachate concentrations for sintered specimens.

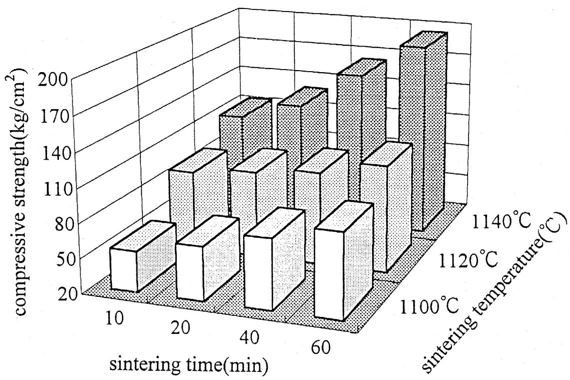

Fig. 9. Changes in compressive strength for sintered specimens.

Although leaching concentrations vary with sintering conditions, all concentrations for heavy metals evaluated were in compliance with the Taiwan EPA's regulatory limits.

3.6. Compressive strength of the sintered specimens

Compressive strength is a prerequisite for the sintered ash to be recycled as a construction material. As this study shows, the compressive strengths were mainly affected by compact pressure, sintering temperature and sintering time. Specimens sintered at 1100°C display a compressive strength ranging from 60–80 kg/cm^2, while those sintered at 1140°C have enhanced the strengths up to 120 kg/cm^2. Fig. 9 reveals that the maximum strength developed at 1140°C, 280 kgf/cm^2 (4000 psi) for 60 min is 230 kg/cm^2, thereby fulfilling the code requirement with respect to aggregates for the cementing agent.

4. Conclusions

This study examines the characteristics of incinerator ashes sintered at various sintering conditions while considering compact pressure, sintering temperature, and sintering time. Based on the results presented herein, we can conclude the following.

(1) Increasing ignition loss of a compact specimen may increase the porosity and decrease the densification effect after sintering. The ignition loss increases with either a decreasing compact pressure and/or increasing sintering time. Also, a lower compact pressure coupled with a longer sintering time yields a higher weight loss during the sintering process.

(2) Increasing the sintering temperature to 1120°C, causes both a decreasing swelling rate due to only a slight change in crystalline phase and a decreasing porosity. However, elevating the sintering temperature again to 1140°C, causes the densification to become more increasingly significant, leading to a total shrinkage in volume. Similarly, a longer sintering time also produces total shrinkage after sintering.

(3) Sintering at a high temperature enhances the densification, closes some of the open pores, and causes moisture absorption rate to decrease. The absorption also decreases with increasing sintering time and compact pressure. In addition, decreasing the absorption implies a decrease in open pores and an increase in compressive strength. The morphology analysis reveals a decreased average diameter in the pores, due to filling by smaller particles when the sintering temperature is elevated.

(4) Expansion at temperatures ranging from 1100°C to 1120°C not only increases the open pore volume, but also decreases the closed pore volume, thereby increasing the apparent density. However, at 1140°C, surface sintering effects provide a much closed pore volume which counter balances part of the effect of expansion, subsequently decreasing the apparent density. A longer sintering time also reduces the closed pore volume, eventually increasing the sintered specimens' apparent density.

(5) The concentration of TCLP leachate for Pb, Cd, and Cr denotes a decreasing leaching tendency with increasing sintering time. However, specimens at different sintering temperatures reflect that the leaching behaviors depend primarily on the types of heavy metals and/or their compounds formed at that temperature. All concentrations for evaluated heavy metals comply with the Taiwan EPA's regulatory limits.

(6) The specimens sintered at 1100°C exhibit a compressive strength ranging from 60–80 kg/cm^2, while those sintered at 1140°C enhance the strength to 120 kg/cm^2. The maximum strength developed at 1140°C, and 280 kgf/cm^2 (4000 psi) for 60 min is 230 kg/cm^2, i.e. satisfying the code requirements as aggregates for the cementing agent.

Acknowledgements

The authors would like to thank the National Scientific Council, ROC. for financially supporting this work under project No. NSC-84-2211-E-008-008.

References

[1] W.Q. Hsu, S.H. Chen, H.L. Chang, S.Z. Hsu, J.C. Liao, Proceedings of Ninth Waste Management Technology Conference, Taiwan, ROC, 1992, pp. 505–518 (in Chinese).
[2] H.I. Hollander, A.L. Plumley, R.S. DeCesare, J. Hazard. Mater. 47 (1996) 369–381.
[3] W. Nowok, S.A. Benson, E.G. Glen, Fuel 69 (1990) 67–141.
[4] J.R. Radeka, N.R. Marinkovic, B. Zivanovic, Ceramics Int. 21 (1995) 249–255.
[5] J. Skrifvar, M. Hupa, R. Backman, M. Hiltunen, Fuel 73 (1994) 171–176.
[6] M.R. Shieh, Ceramic Industry 6 (1987) 27, in Chinese.
[7] D.Y. Chen, W.H. Tseng, Industrial Ceramics, Hsu Foundation Publication, Taipei, Taiwan, 1980 (in Chinese).
[8] L.M. Wang, G.W. Pong, S.B. Wen, Proceedings of Ninth Waste Management Technology Conference, Taiwan, ROC, 1994, pp. 403–412 (in Chinese).
[9] D.H. Pan, S.H. Guo, Making Heat Insulator Bricks from Fly Ash, Research Report of Taiwan Power Cooperation, 1987, pp. 37–50 (in Chinese).
[10] J. Zheng, J.S. Reed, Am. Soc. Bull. 71 (1992) 1410–1416.
[11] B.A. Buchholdz, S. Landsberger, J. Environ. Sci. Health A 28 (2) (1993) 423–441.
[12] M.A. Fernandez, L. Martlnez, M. Segarra, J.C. Garcia, F. Esplell, Environ. Sci. Technol. 26 (1992) 1040–1047.
[13] T.H. Christensen, X.Z. Lun, Water Res. 23 (1989) 73–80.