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Original Research Paper

Production of Sludge Ceramsite from Sewage Sludge, Municipal Solid Waste Incineration Fly Ash and Clay

Wei Na
School of Civil Engineering and Architecture, Wuhan Polytechnic University, Wuhan, 430023, China

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ABSTRACT

The few reuses and large stockpile of sewage sludge led to a series of social and environmental problems. This study investigated the possibility of using the sewage sludge and municipal solid waste incineration (MSWI) fly ash as materials to prepare ceramsite by a high temperature sintering process. Two experiments were designed to investigate the addition of sewage sludge and MSWI and sintering treatment. The result showed that the mass ratio of sewage sludge to MSWI fly ash was 8:2 and the the pellets, sintered at 1080°C for 8 min, were beneficial to produce sludge ceramsite. Property tests of sludge ceramsite showed that sludge ceramsite was light (with an apparent density of 680kg/m^3), waterproof (with a water absorption of 6.7%), hard (with a compressive strength of 5.4Mpa) and nontoxic (contents of toxic metal leaching test were found to be within the limits of China's regulatory requirement). These results reveal the feasibility of recycling sewage sludge and MSWI fly ash by sintering as a construction material.

INTRODUCTION

Due to the rapid growth of wastewater output, sewage sludge, as an inevitable by-product of the treatment process of wastewater, is increasing very fast. Concern has been increasing about the development of new environmental friendly technologies to utilize the sewage sludge in construction applications (Joan et al. 2012, Bui et al. 2013). On the other hand, the output of municipal solid waste incineration (MSWI) fly ash has been over 3,00,000 tons per year and is increasing year by year (Gao et al. 2008, Wang et al. 2010). Due to the presence of high amount of heavy metals such as lead, zinc and potentially toxic dioxins, fly ash is identified as hazardous waste in China and its disposal may pose a significant risk to the environment (Huang et al. 2007, Qian et al. 2008). At present, various methods such as melting, solidification/stabilization, acid extraction, vitrification and sintering have been used to treat MSWI fly ash (Aloisi et al. 2004, Wey et al. 2006, Sakai et al. 2000). In view of environment protection and resource conservation, reusing would be a better strategy for the solution of MSWI fly ash.

Ceramsite, as a kind of lightweight aggregate, can be used to produce concrete mixtures. Currently, clay is widely used to produce ceramsite (Celik et al. 2010, Riley 1951), but this method requires too much natural resources. To get fine lightweight aggregate, the chemical composition of the raw material used should be similar to clay and satisfy the following requirements: SiO_2 48-70%, Al_2O_3 8-25%, $FeO+Fe_2O_3$ 3-12%, CaO+MgO 1-12%, $K_2O + Na_2O$ 0.5-7% (Riley 1950). The characteristics of sewage sludge are similar to that of clay, so it can be used as a substitutive material of clay to diminish the consumption of resources and solve some of the environmental problems caused by this waste. Because sewage sludge contains a lower content of SiO_2 and Al_2O_3 than is required to produce a lightweight aggregate, MSWI fly ash was introduced as an additive. The purpose of the study is to test the suitability of sewage sludge and municipal solid waste incineration fly ash and clay as raw materials for the production of sludge ceramsite and investigate the effects of recycled resources and heating temperature and time on sludge properties related to bloating effect.

MATERIALS AND METHODS

Characterisation of raw materials: The sewage sludge, MSWI fly ash and clay used in this study were respectively obtained from Shahu Wastewater Treatment Plant in Wuhan, and Suzhou Wastes Incineration Plant in Suzhou and Tiancheng brickfield in Huangshi. Sewage sludge, MSWI fly ash and clay were dried in stove at a temperature of 105°C for 24h and then pulverized with a ball mill until it could pass through a 45mm sieve. Some wet sewage sludge, MSWI fly ash and clay were oven dried and crushed to pass sieve No.100 (the diameter of mesh is 0.154mm) for chemical composition determination. The chemical components of dried sewage sludge, MSWI fly ash and clay were determined by X-ray fluorescence spectrometer (Shimadzu Lab Center XRF-1700, Japan). The results are given in Table 1.

Table 1: Chemical composition of dried sewage sludge, MSWI fly ash and clay (% dry weight basis).

	SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	K_2O	Na_2O
Sewage sludge	15.6	4.5	5.3	1.2	19.8	0.8	0.4
MSWI fly ash	37.8	15.5	1.3	2.7	20.6	3.4	3.7
clay	71.5	14.93	6.72	0.67	0.21	1.86	0.37

The content of trace elements in the sewage sludge (As, Cd, Cr, Cu, Ni, Pb, Zn) was determined according to ASTM method after digestion of the samples. These elements were measured by inductively coupled plasma mass spectrometry (ICP-MS, Perkin Elmer Elan 6000, USA). Meanwhile, the standard method for determining the leaching toxicity of solid wastes by horizontal vibration extraction procedure (GB5086.2-1997) (China EPA 1997) was used to evaluate the leaching of heavy metals from the raw sludge. Table 2 gives the trace elements in the dried sewage sludge sample and MSWI fly ash determined by ICP-MS and the horizontal vibration extraction procedure results of heavy metals.

Sample preparation: Sewage sludge, MSWI fly ash and clay samples were weighted and then mixed with a mechanical running mixer. In this study, the weight percentage of clay to that of total dried solids (clay+sewage sludge+MSWI fly ash) was 70%. The mixture was then pelletized to pellets with similar diameter of 5-10mm by a pelletizer. The formed samples were dried at 110°C in a blast roaster for 24 h and then rapidly shifted into an electric tube furnace (SKQ-6 with a maximum temperature of 1700°C, the sintering temperature and sintering time may vary in different experiments). After the sintering process, the pellets were naturally cooled until they reached room temperature. It should be noted that the temperature was first held at 450°C for 8 minutes during sintering process to allow pyrolysis and volatilization of the organic matter to ensure that the bulk density of the sintered products was low.

Characterization of sintered sludge ceramsite: Apparent density (AD), compressive strength (CS), and 1h water absorption rate (WAT_{1h}) were employed to characterize the quality of the sintered sludge ceramsite. AD, CS and WAT_{1h} were all determined using an established procedure described by GB/T 17431.2-1998 (China EPA 1998). In compressive strength test, the single sintered product was pressed down by a steel puncheon until the sintered product was crushed. CS was calculated as the ratio between the load and the surface area of the sintered product, in stress units. The values of WAT_{1h} and AD were obtained as follows (GB/T 17431.2-1998, China EPA 1998):

$$WAT_{1h} = (m_1 - m_0)/m_0 \times 100\%$$

Where m_1 is the 1h saturated surface-dry weight of the ceramsite bodies (g) and m_0 is the dry weight of the ceramsite bodies (g).

$$AD = (m_0 \times 1000)/V \text{ kg/m}^3$$

Where V is the volume of 1h saturated surface-dry ceramsite bodies (mL).

Experiments design: Two laboratory experiments designed to determine the optimum conditions of sludge ceramsite were investigated.

***Experiment 1*:** Raw pellets were prepared with sewage sludge and MSWI fly ash at a mass ratio of 8:2 according to earlier study. After the preheated treatment, raw pellets were rapidly sintered at the electric tube furnace at 1000, 1040, 1080, 1120 and 1150°C. Pellets were sintered for 5, 8, 10min at each sintering temperature. After the cooling treatment, the characteristics of the sintered pellets were tested and the optimum sintering temperature was determined by the results of AD, CS and WAT_{1h}.

***Experiment 2*:** Raw pellets were prepared with sewage sludge and MSWI fly ash at a range of mass ratios: 10:0, 9:1, 8:2, 7:3, 6:4. Conditions for sintering treatment were selected from experiment 1. Similarly, the characteristics of the sintered pellets were tested and the optimum mass ratio of sewage sludge:MSWI fly ash were determined by the results of AD, CS and WAT_{1h}.

Sludge ceramsite properties: In this part, sludge ceramsite was prepared according to the optimum conditions, and some properties (physical properties, crystalline phases properties, microstructure properties and toxic metal leaching properties) were tested, respectively.

Physical properties: AD, CS and WAT_{1h} were determined mainly according to GB/T 17431.2-1998.

Leaching test: The standard method for determining the leaching toxicity of solid wastes by horizontal vibration

Table 2: Heavy metal concentrations and leaching test results of the sewage sludge and MSWI fly ash.

	Zn	Cu	Cr	Pb	Ni	As	Cd
Content of trace elements in sewage sludge (mg/kg)	950	382	495	92	40	29	10
Leaching concentration of sewage sludge (mg/L)	49.1	10.7	1.9	0.3	1.6	0.2	0.1
Content of trace elements in MSWI fly ash (mg/kg)	3268	562	157	1514	76	113	51
Leaching concentration of MSWI fly ash (mg/L)	56.1	8.2	2.5	26.9	1.9	2.0	1.2

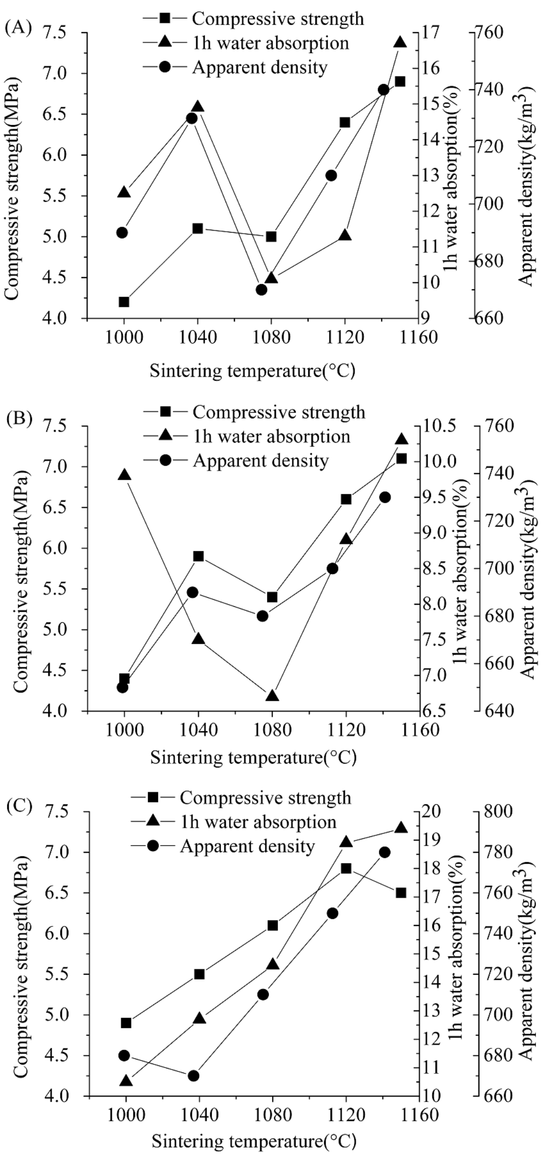

Fig.1: Effect of sintering temperature (experiment 1), (A) sintered for 5 min; (B) sintered for 8 min; (C) sintered for 10 min.

extraction procedure (GB5086.2-1997) was also used to evaluate the leaching of heavy metals from the sintered sludge ceramsite prepared in the optimum conditions. Leaching rate is often used to evaluate the leachability of waste and it is defined as a ratio of the leaching content of heavy metal in the sludge ceramsite to the total heavy metal content in the raw sludge.

RESULTS AND DISCUSSION

Sintering temperature and duration time optimization: The results of experiment 1 are shown in Fig. 1. As can be seen, WAT_{1h} of sludge ceramsite has a hard drop when sintering time varied from 5min to 8 min and then it increases when sintering is performed for 10 min. At the same time, AD of sludge ceramsite changes similarly. The reason may be that short duration does not allow the reaction to complete and the gas produced is not sufficient to create evenly-distributed voids in the ceramsite. On the other hand, sintering for 10 min causes total melting of the sludge ceramsite and most pores begin to coalesce and form irregular shaped voids. Thus, the optimum duration time was 8min. From Fig. 1(B), similarly, it can be seen that WAT_{1h} of sludge ceramsite is the lowest when sintering is performed at 1080°C. On the other hand, AD of sludge ceramsite is also relatively low when sintered at 1080°C. Depending on all the above mentioned, it can be concluded that the optimum conditions for sintering process were pellets sintered at 1080°C for 8min.

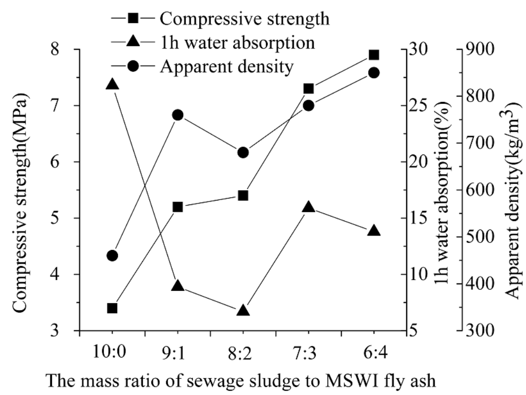

Fig. 2: The effect of mass ratio of sewage sludge to MSWI fly ash.

Table 3: Physical properties of sludge ceramsite in optimum conditions.

	Apparent density (kg/m^3)	Compressive strength (MPa)	1h water absorption rate (%)
Product	680	5.4	6.7
GB/T17431-1998	≤900	≥5	≤10

The mass ratio of sewage sludge and MSWI fly ash optimization: Raw pellets were prepared with different mass ratios before sintering treatment (sintered at 1080°C for 8min). Results of experiment 2 are shown in Fig. 2. As can be seen, WAT_{1h} was detected to be lower when the addition of MSWI fly ash was 10%-20%, which revealed the evenly-distributed voids in the ceramsite. Besides, AD was relatively lower when the addition of MSWI fly ash was 20%. Thus, the optimum mass ratio of sewage sludge to MSWI fly ash was 8:2. Though CS increased with the addition content of MSWI fly ash and the CS of sludge ceramsite was relatively lower at the mass ratio of 8:2, it is still higher than 5 Mpa and is in compliance with lightweight aggregates and its test methods (GB/T17431.1-1998).

Table 4: Horizontal vibration extraction procedure results of heavy metals in sintered products.

	Zn	Cu	Cr	Pb	Ni	As	Cd
Leaching concentration (mg/L)	0.55	0.24	0.11	0.02	0.05	0.01	0.01
Identification standard for hazardous wastes (GB5085.3-1996) (mg/L)	≤50	≤50	≤10	≤3	≤10	≤1.5	≤0.3
Environmental quality standards for surface water III (GB3838-2002) (mg/L)	≤1	≤1	≤0.05	≤0.05	≤0.02	≤0.05	≤0.05

Properties of sludge ceramsite prepared under optimum conditions: *Physical properties of sludge ceramsite*: The sludge ceramsite samples were prepared under optimum conditions (the mass ratio of sewage sludge to MSWI fly ash was 8:2, sintered at 1080°C for 8min), and the physical properties (apparent density, compressive strength and 1h water absorption rate) were tested according to GB/T17431.1-1998. Results are given in Table 3. The sludge ceramsite produced in optimum conditions was lighter (with an apparent density of 680kg/m^3) but had relatively higher compressive strength (5.4Mpa) and lower water absorption (6.7%).

***Toxic metal leaching test of sludge ceramsite*:** The horizontal vibration extraction procedure results of Zn, Cu, Cr, Pb, Ni, As and Cd analysis of the product produced in optimum condition are given in Table 4. The leaching concentrations were all in compliance with the China Identification Standard for Hazardous Wastes (GB5085.3-1996) and the China Environmental Quality Standards for Surface Water (GB3838-2002). Therefore, these results indicate that the main contaminant i.e., zinc, could be immobilized within a sintered sludge ceramsite, and that the use of ceramsite produced from sludge does not pose an environmental risk.

CONCLUSIONS

The objective of this study is to recycle sewage sludge and MSWI fly ash into sludge ceramsite. The optimum conditions for preparing sludge ceramsite were obtained as follows: the mass ratio of clay to WSS to ICM of 1:1:0.05; the raw pellets were sintered in electric tube furnace at 1180°C for 5min. The apparent density, compressive strength and 1h water absorption rate of sludge ceramsite prepared in optimum conditions were 680kg/m^3, 5.4MPa and 6.7%, and all of the characteristics conformed to the standards. The results of the toxic metal leaching test were all in compliance with the China Identification Standard for Hazardous Wastes and the China Environmental Quality Standards for Surface Water, showing that sludge ceramsite in optimum conditions was nontoxic. Fabricating artificial ceramsite through the recycling of waste resources not only provides a practical alternative to the shortage of natural resources, but also offers an ecological solution to waste management.

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