Fireproof Material Derived from Recycling Incinerator Ash Using Electric-Arc Technique

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Abstract. In this study, municipal solid waste incinerator (MSWI) ashes were melted by electric-arc technique to produce man-made vitreous fiber (MMVF) using a fiber blowing method. The capacity of 50 kg/h at the pilot level was constructed to treat MSWI ashes and produce MMVF simultaneously. The fibrous derivatives were blended with cement to manufacture fireproof product. The MMVF produced in this work belong to short fiber which the characteristics are presented as follow: (1) fiber diameter range from 5.1 ± 1.2 μm; (2) shot content 6.3±0.8 wt.%; (3) fibrous length ranged from 0.3–3.5 cm. When the amount of MMVF added is at 43 wt.% in fireproof product, the density, porosity, fracture loading and flexural strength are 0.8 g/cm3, 66%, 42 kgf and 98.4 kgf/cm2, respectively. After a series of fireproof test, the fire resistant product had good performance on flammability and incombustibility characteristics. The fireproof product is stable and has satisfactory physical, mechanical and thermal properties.

1. Introduction

There are twenty-four municipal solid waste incinerators (MSWI) being operated in Taiwan. The total treatment capacity of these incinerators is 24,650 tons per day. Accordingly, more than 1.3 billion tons of ash residues including bottom ashes and fly ashes will be generated annually [1]. Fly ashes contains considerable amounts of hazardous substances and need further disposal (e.g. stabilize with cement, send to landfill site and/or stock in the incineration plant) in Taiwan. Due to the shortage of available disposal spaces and limited stability of cement solidified waste forms which may potentially release heavy metals and dioxins to contaminate the environment in the long-term future. Inappropriately treating these substances can cause secondary pollution, detrimentally affecting the environment. Therefore, an effective approach is required for treating MSWI ashes and recycling its byproduct at the same time. Vitrification to treat MSWI ashes has attracted a lot of attention, especially in countries with high population densities in metropolitan areas and very limited space available for waste disposal [2-8].

Electric-arc treatment is one of the best methods of vitrification. In electric-arc vitrification, the heat generated by the plasma is adopted to treat hazardous wastes containing heavy metals, inorganic and/or organic substances to temperatures of 1400–1600°C. During treatment, inorganic substances are melted and organic contaminants are thermally destroyed. Electric-arc melting can be used to reduce the volume of incinerator ash and neutralize harmful chemicals. Additionally, the byproduct thus generated can be reused as a promising alternative material. After completed a laboratory-scale of a man-made vitreous fiber (MMVF) production system with capacity of 3.5 kg per batch [9], the pilot plant was designed and constructed for further application. To date, little has been treated waste and recycled them directly. The aims of this study were to dispose MSWI ashes by electric-arc technique and generate MMVF from the melting MSWI ashes simultaneously. The MMVF was further to
fabricate fireproof product. The properties of MMVF s such as morphology, diameter, shot content, length and toxicity characteristic leaching procedure (TCLP) analysis are characterized in this work. The MMVF s produced in this work were further to manufacture fiber-cement board. The mechanical strengths (e.g. fracture loading and flexural strength) and fireproof test (e.g. flammability and incombustibility) were also executed in this research.

2. Experimental

2.1. Melting and Fiber Producing Devices

In this work, the electric-arc furnace with capacity of 50 kg/h was built to treat MSWI ashes and produce MMVF. Figure 1 shows the delineation of a melting furnace. It mainly consists of raw material feeding, a furnace and graphite rods. The furnace is lined with refractory materials and the melting temperature was generated by plasma discharge (Maximum temperature: 1600°C). The electrodes are automatically raised and lowered by a positioning system. The fiber blowing unit is comprised of a compressed air system (air generator and tank) and blowing nozzle (Figure 2). The diameter of the blowing nozzle is 50 mm with seven interior openings. The central one has a diameter of 4 mm and the rest are 2.5 mm with a 20 degree angle. The purpose of designing this kind of blowing nozzle was to concentrate compressed air and achieve a high velocity to break the melting material into small particles, and then attenuate those particles into MMVF s. MSWI ashes are put in feeding hoppers to be fed into the furnace by an automatic feeding unit and/or directly put in the electric-arc furnace. The starting material was melted with electrical energy which is conducted via long cylindrical graphite electrodes into a furnace. MSWI ashes are heated by the radiant energy evolved from the arc. Maximum temperature of furnace can attain 1500°C. The viscosity of the melting material in the crucible at this point is 3.8 Pa·s. The ash is molten at this temperature and oxide melt stream is flow to the crucible from the tapping spout. The melting temperature of crucible is maintained at (1300°C heating element: molybdenum silicide, MoSi2) and controlled by a programmable logic controller. The oxide melt stream is transported through the throat by gravity and blown with high pressure air (12 kg/cm²) from a fiber blowing unit to produce MMVF (Figure 3) and direct the fibers into collection equipment. The morphology and diameter of the fibers were analyzed by scanning electron microscopy (SEM) (S-4800; Hitachi, Japan). Off-gas was processed by means of the off-gas treatment system. According to the processes developed in this study, we can treat MSWI ashes and produce MMVF at the same time.

![Figure 1](image1.png)

**Figure 1.** Scheme of electric-arc furnace (A) MSWI ashes feed; (B) Exhaust gas; (C) MSWI ash melting area; (D) Crucible; (E) Blowing nozzle; (F) MMVF collector
2.2. Municipal Solid Waste Incinerator Ashes

The incinerator ashes used in this study were obtained from one of the MSWIs in Taipei. The chemical compositions of MSWI ashes were determined by inductively coupled plasma mass spectrometry (ICP-MS) (SP1000; Teledyne Leeman, USA). Table 1 presents the major chemical compositions of the incinerator ashes. The major chemical compositions of fly ash and bottom ash were CaO, SiO$_2$, Al$_2$O$_3$. The Zn, Pb, Cd, Cr, Cu, Hg and As in TCLP test of incinerator ashes were determined by Taiwan EPA standard method of NIEA R201.13C. TCLP test results of incinerator ashes are shown in Table 2. The leaching concentration of Pb was 5.5 mg/L and higher than TCLP criteria in Taiwan. According to Taiwan EPA regulations, fly ash was a hazardous waste in Taiwan and it requires to be detoxified before final disposal.

![Figure 2. Sketch of blowing nozzle](image)

**Figure 2. Sketch of blowing nozzle**

![Figure 3. Fiber blowing method to produce man-made vitreous fiber](image)

**Figure 3. Fiber blowing method to produce man-made vitreous fiber**

| Major chemical compositions (in wt\%) of fly ash and bottom ash. |
|---|---|---|---|---|---|---|---|
| CaO | SiO$_2$ | Al$_2$O$_3$ | Fe$_2$O$_3$ | Na$_2$O | K$_2$O | Cl |
| Fly ash | 41.3 | 17.3 | 9.5 | 1.3 | 6.8 | 2.9 | 18.9 |
| Bottom ash | 23.6 | 38.1 | 17.8 | 15.6 | 1.7 | 0.7 | 0.6 |

| Table 2. Toxicity characteristic leaching procedure analysis results of MSWI ashes and fiber. |
|---|---|---|---|
| Fly ash (mg/L) | Bottom ash (mg/L) | Man-made vitreous fiber | TCLP criteria (mg/L) |
| Se | <0.01 | <0.01 | <0.01 | 1.0 |
| Pb | 5.5 | <0.1 | <0.1 | 5.0 |
| Cd | <0.01 | <0.01 | <0.01 | 1.0 |
| Cr | 0.19 | <0.03 | <0.03 | 5.0 |
| Cu | <0.03 | 0.42 | <0.03 | 15 |
| Hg | <0.05 | <0.05 | <0.05 | 0.2 |
| As | <0.1 | <0.1 | <0.1 | 5.0 |
| Cr$_6^+$ | 0.12 | 0.08 | 0.06 | 2.5 |
| Ba | 4.42 | 0.85 | 0.23 | 100 |
2.3. Manufacturing Fireproof Product

The fireproof product was made using Portland cement and MMVF s. The water-to-solid ratio was 0.5. The MMVF was added in different quantities (20–50 wt.%). The preparation was as follows. The MMVF s and cement were placed in a stirred steel vessel and dispersed in the water where it was applied stainless paddle to blend mixtures to form aqueous fiber-contained concrete slurry. In order to produce the concrete with uniform material consistency and better workability, the optimal stirring time and speed were 20 minutes and 300 revolutions per minute, respectively. The mixtures were poured into a steel rectangular mold to cast a 300 × 200 × 5 mm, 220 × 220 × 10 mm and 40 × 40 × 10 mm rectangular fireproof material for fireproofing properties test and into a 200 × 150 × 8 mm steel rectangular mold for a flexural strength test. The specimens were compacted using a compression molding method, removed from the mold, and then cured in a programmable temperature and humidity chamber (at 23±2°C and 98% relative humidity) (GTH225, Giant force, Taiwan) for 28 days. Afterward, fireproofing properties and flexural strength test were conducted. For each flexural strength test, at least five samples were tested and the results were averaged. The flexural strength was conducted under third-point loading in accordance with Chinese National Standard (CNS) 3904 [10]. The flexural test was executed in a 500 kg air compression testing machine with a rate loading controller at a rate of 8 kgf/min until the load can reach the expected maximum loading in 1–3 minutes. Before testing, the surface of specimens were capped with a hard plaster on the cast face to ensure parallel loading faces of the specimens and fixed height for all test samples.

2.4. Fireproofing Properties Test

The fireproofing properties of material were confirmed by flammable and incombustible test. The flammability of fireproof material was effectively evaluated according to CNS 7614 [11]. The specimens had shape of 300 × 200 × 5 mm. The heat test was performed in the container by 45° Meker burner and the heating period was sustained 3 minutes. After the completion of test, the length of carbonization, the period of the specimen continuing to burn with flame and the state of flameless combustion were measured and observed. Basic material test and surface test were executed to reveal the grade of incombustibility of fireproof material based on CNS 6532 [12]. Five specimens with size of 40 × 40 × 10 mm were piled up and held together firmly by means of fine steel wire to perform basic material test. After adjusting and stabilizing temperature at 750±10°C, the prepared sample was inserted quickly into the heating furnace. The test was carried out for a period of 20 minutes and the furnace temperature was not higher than 810°C among two thermocouples. The surface test was conducted in the heating chamber to define the fuming density of the fireproof material by optical measuring equipment. The size of specimen was 220 × 220 × 10 mm. Main heat source and sub-heat source of furnace were electric heater and liquefied propane gas, separately. Total heating time was 10 minutes. The exhaust temperature curve and fuming factor \( C_A \) of per unit area can be obtained after completing surface test. The fuming factor can be calculated through equation (1).

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C_A = 240 \log_{10} \frac{I_0}{I}
\]

Where: \( C_A \)= fuming factor of per unit area; \( I_0 \)= optical intensity (Lux) at the time of commencement of heat test; \( I \)= minimum value of optical intensity (Lux) during heat test

3. Results and Discussion

3.1. Properties of Man-Made Vitreous Fiber

Figure 4 is presented morphology and SEM photomicrograph of MMVF. The resultant fiber pattern is a random mass of both straight and curled fibers intermingled with some variation in filament diameter and length because of the random nature of the fiber blowing process producing them. Fiber diameter is the most important factor as regards the specific performance for fiber and associated materials, since almost all major end-use behavior is determined by fiber diameter. For quality control of fiber sizes for blown fiber fabrication operation and providing accurate results, the diameter of the
filament was extracted from the product and measured by SEM. The average of fibrous diameters was 5.1 ± 1.2 μm. The fibers produced were several centimeters long. The percentage of fibrous length ranged from 0.3 – 1.9 cm and 2 – 3.5 cm were 62% and 38%, respectively. A large amount of round particles (Shot) were derived from fiber blowing process, mostly larger than 100 μm. A cyclone unit was constructed to separate and remove round particles from the MMVF product. We can obtain fibrous product of 6.3±0.8 wt.% shot content following the separating process. The round particles do not contribute to the insulating performance if MMVF is utilized to manufacture insulation board. Leachate analysis of MMVF to assess their environmental impact was performed and the metal concentration (Zn, Pb, Cd, Cr, Cu, Hg, Ba and As) in the TCLP leachate was included in Table 2. The concentrations of metals in MMVF are well below those established in the Taiwan governmental regulations for hazardous waste; therefore, MMVF is not toxic product. It can therefore be used as an additive in building materials.

3.2. Flexural Strength of Fireproof Product

Figure 5 shows the fracture loading and flexural strength of fireproof material. The fireproof product was comprised cement as a substrate and MMVF as the filling material. When the additive of fiber was increased, it can be seen the maximum fracture loading and flexural strength of specimens were declined. The products are shown flexural strengths of between 134.5 and 67.7 kgf/cm². As the fibrous additive was 43.3 wt.% (the specimen’s density and porosity were 0.8 g/cm³ and 66%), the fracture loading and flexural strength of 28 day were 42 kgf and 98.4 kgf/cm², respectively. Based on CNS 3802 [13], fiber-cement board specified that the fracture loading and flexural strength (density between 0.6 g/cm³ and 0.9 g/cm³) must meet the requirements of 33 kgf and 77.3 kgf/cm². Clearly, the mechanical strength of the specimen developed in this study is satisfying this standard and have potential application as building material.

3.3. Flammability of Fireproof Product

The thermal behaviors and measurements equivalent to the resistance to fire of fireproof material obtained in this work were defined by a series of heating test. Figure 6 shows the appearance of fiber-cement board before (left) and after (right) flammability test (amount of man-made vitreous fiber
added was 43.3 wt.%). The flammability test was accomplished by 45° Meker burner method. The length of carbonization, remaining flame and the state of flameless combustion after the completion of firing was observed through the flammability test. The results showed that there were not continuing to burn with flame and flameless combustion of the specimen surface after the completion of heating (3 minutes) by Merkel’s burner. The length of carbonization in the lengthwise direction of the supporting frame was not longer than 5 cm. There was no falling melted material that has caught the fire from the specimen in the period of test. Base on the results of length of carbonization, remaining flame and afterglow from the flammability test, the fiber-cement board produced in this work was classified as anti-flame grade 1 stipulated by CNS 7614.

![Figure 6. The appearance of fiber-cement board before (left) and after (right) flammability test](image)

3.4. Incombustibility of Fireproof Product

The incombustibility of fiber-cement board in the early stage of fire was revealed through basic material and surface test. Time dependence of temperature of fireproof product during basic material test is shown in figure 7. The specimens were placed into furnace at 750±10°C and sustained 20 minutes. Solid circle (●) and square (■) are represented temperature detected by thermocouple 1 and thermocouple 2. The heat is absorbed by specimen and the temperature of furnace was declined at the first one minute. The furnace temperature is increased to 800°C the following 1.5 minute because test sample is slightly burned and heat energy released. Afterward furnace temperature observed by thermocouple 1 and thermocouple 2 are decreased smoothly to 750°C during six minute and not more than 810°C. Fig. 8 presents measured temperature and fuming factor changes of fireproof product in surface test over 10 minutes of heating. The specimens with size of 220 × 220 × 10 mm were inserted into heating furnace and the combustion was achieved by electric heater and gas (Propane gas) burner. Standard temperature curve (Solid circle, ●) in fig. 8 was defined by heating commercial fiber reinforced cement board (Perlite board). The exhaust temperature (Solid square, ■) derived from heating fiber-cement board are not exceed the standard temperature at each recording point within whole testing period (10 minutes). The backside temperature of specimen is also continued to increase till 199°C at the end of 10 minutes. There were no detrimental deformations such as melted penetration over the whole thickness of specimen and no crack at the back side of specimen after heating test. No residual flame was occurred after completion of heating test. The fuming factor (C_A) was evaluated using optical intensity via eq. (1). As shown in fig. 8, the fuming factor is zero during the first 1-4.5 minute and then raised gradually and the maximum fuming factor of per unit area is 3. The fire resistant product manufactured in this study can be classified as grade 1 incombustibility according to standard CNS 6532. The fireproof product developed and fabricated as panel employing MMVF derived from municipal solid waste incinerator ash are stable and have promising fireproof properties regarding flammability and incombustibility and have acceptable physical and mechanical properties.
Figure 7. Time dependence of temperature of fireproof product in incombustible test (Basic material test). Specimen was introduced into furnace at 750 ± 10°C, furnace temperature was detected by two thermocouples.

Figure 8. Measured temperature and fuming factor changes of fireproof product in incombustible test (Surface test) over 10 minutes of heating. Standard temperature curve was defined by heating commercial fiber reinforced cement board (Perlite board).

4. Conclusions
In general, dispose of MSWI ashes with high temperature treatment process was to convert into slag and further to recycle them as useful product. This work demonstrated one can treat MSWI ashes and generate into MMVF product at the same time and avoid the energy-consuming. A pilot plant was built in this study that can effectively melt municipal solid waste incinerator ashes into oxide melt stream by electric-arc technique and produce man-made vitreous fiber by the application of fiber blowing method. The properties (e.g. fibrous diameters, length and shot content) of MMVF were suitable to fabricate fiber-cement board. Through the tests of mechanical strength, flammability and incombustibility, fiber-cement board can be defined as fireproof product and fulfilled the product standard established in Taiwan. The fireproof product derived from municipal solid waste incinerator ash has potential application as building material and play an important role in successfully developing the high temperature melting process.

5. References
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