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Effects of Basicity Index on Incinerator Fly Ash Melting Process and Stabilization

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Abstract: The generation of hazardous industrial waste in Taiwan has rapidly increased, reaching 1.5 million tons produced annually in 2021. Most of this waste was burned in incinerators, with about 15% (225,000 tons) of it converted into fly ash. Incinerator fly ash primarily consists of heavy metals, dioxins, chlorides, and silica. Historically, fly ash disposal has only relied on cement solidification, contributing to insufficient landfill capacity and soil-pollution concerns. To address these issues, the melting process has been a feasible solution, wherein the heavy metals can be encapsulated within a vitrified structure to prevent them from leaching out. However, the melting point of fly ash is too high, so this study aimed to explore the optimal basicity index for fly ash to conduct the melting process. Basicity indices are estimated by the ratio of CaO/SiO_2, and the melting point of the fly ash can be decreased during the melting process with the right basicity index. In this study, the characteristics of incinerator fly ashes from industrial waste and laboratory waste were initially investigated. With their basicity indices adjusted with two sources of silica, the fly ashes were tested at 1100~1400 °C to observe whether they melted. The vitrified slags were subsequently subjected to TCLP, XRF, and ICP tests to verify their stability. In summary, we discovered that fly ash could be melted through the melting process with the basicity index adjusted to under 1.28, with the silica source as either glass or silica sand powder. After melting, the heavy metals were confirmed to be stabilized in the vitrified slags. Consequently, the melting process could be an alternative solution for fly ash disposal that is sustainable and eco-friendly.

Keywords: fly ash; basicity index; vitrified structure; melting process; waste management

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1. Introduction

The growth of industrialization and economic development has led to a significant increase in the volume of hazardous industrial waste generated in Taiwan, reaching 1.5 million tons per year [1]. As part of waste management practices, these hazardous wastes are commonly incinerated, forming bottom ash (14–26%) and fly ash (15%). Fly ash is obtained from the waste gas treatment systems of incinerators and predominantly comprises heavy metals, chlorides, dioxins, and silica. Due to its composition, fly ash is classified as hazardous industrial waste because it contains heavy metals, including lead, chromium, cadmium, mercury, and zinc, as well as polychlorinated dibenzo-p-dioxins and furans (PCDD/Fs) [2]. Without proper treatment measures, the leaching of heavy metals and dioxins from fly ash can significantly risk contaminating the soil and groundwater.

Fly ash disposal treatments primarily include thermal treatment, pyrolysis, hydrothermal treatment, leaching, and solidification/stabilization [3,4]. In Taiwan, the most common treatment for fly ash disposal is cement solidification from time to time. In the method of cement solidification, fly ash is mixed with certain curing agents to solidify and is then buried. Nevertheless, improper preservation or certain circumstances surrounding cement solidification can give rise to several issues, including inadequate landfill space. Cement solidification, while serving as a waste disposal method, increases the waste volume, significantly burdening landfill capacity. Due to Taiwan's limited land area and high population density, the suitable landfills for accommodating these solidified cements have significantly decreased, exacerbating the issue at hand. Additionally, there is a concern regarding potential environmental pollution resulting from the damage or degradation of the cement used for solidification. Although the stabilized/solidified (S/S) fly ash treatment is regulated by several regulations in different countries, it is still reported that heavy metals could leach out when the solidified cement comes into contact with water [5]. The heavy metals that leach out could pollute the soil or even cause human health problems. Both situations would cause serious issues that cannot be neglected. In addition to the problems that cement solidification could cause, other processes also possess different potential problems. The pyrolysis process presents the problems of high energy consumption and high TEQ residues. Although the leaching process is capable of recycling heavy metals such as Zn, Pb, Cu, and Cd from the fly ash, the residues still need to be further treated before landfilling or use as construction materials. Moreover, through hydrothermal treatment, heavy metals such as Pb and Cd can become even more critical [3]. As environmental consciousness rises, it is urgent to find a new method for fly ash disposal. Since thermal treatment does not present any of the situations mentioned above, and the main problem resulting from it has only been the high consumption of energy, not producing even more waste, thermal treatment seems to be the most sustainable and promising process.

Thermal treatment has been successfully used in the treatment of MSWI (municipal solid waste incineration) fly ash in the U.S., Europe, and Japan [6]. The thermal treatment typically includes sintering, melting, and vitrification. Through the thermal treatment, fly ash is melted at a high temperature near the fly ash's melting point, and then cooled down into vitrified slag. Fly ashes comprise numerous heavy-metal salts with lower boiling points, a portion of which can undergo gasification (70~85%), while the remaining fraction is transferred to the slag (15~30%) [7]. It has been found that the plasma melting of fly ash can reduce the fly ash volume by 70% [8]. With the fly ash vitrified into slag, the dioxins can be decomposed, and heavy metals are stabilized, with the leachability far below regulations [9]. In addition, the vitrified slags can be used as artificial construction materials to enhance their value [10].

Gao et al. observed that when the temperature of fly ash was increased to above 1300 °C, the fly ash could be melted into molten slag. Moreover, at temperatures above the flowing point, the volatilization of several heavy metals, including Pb, Cd, Zn, and Cu, decreases due to the formation of liquid slag. Therefore, the formation of liquid slag at high temperatures improves the stability of heavy metals in the molten slag [2].

Nonetheless, the significant operational costs associated with thermal treatment of fly ash, especially the melting process, have consistently posed a major hurdle to the widespread adoption of this technology. Typically, the melting point of fly ash is about 1400~1500 °C and is mainly determined by its elemental and crystalline composition [11]. In this case, the cost of melting fly ash would be extremely high. In recent years, reducing energy consumption has been a common trend. Since the melting points of fly ashes are considerably high, the best way to reduce energy consumption would be to lower the melting temperature.

Yang et al. added three kinds of coal ash to the fly ash-melting process, using coal ash as the source of Si and Al. After blending MSWI fly ash with 40% coal ash, the flow temperature decreased from 1460 °C to about 1240 °C and 1280 °C [12]. Gao et al. added B_2O_3 to MSWI fly ash to form a system of $CaO\text{-}SiO_2\text{-}Al_2O_3\text{-}Fe_2O_3\text{-}MgO$. The results demonstrate that the flowing and melting points decreased as the amount of B_2O_3 increased. The flowing temperature decreased from 1450 °C to 900 °C, 950 °C to 681°C, and 1286 °C to 919 °C [13]. Yang et al. lowered the melting temperature from 1500 °C to 1200 °C by adding silica sand powder and a Fe_2O_3-rich and CaO-rich iron slag to MSWI fly ash and formed a glass–ceramic in the $CaO\text{-}SiO_2\text{-}Al_2O_3\text{-}Fe_2O_3\text{-}MgO$ quaternary phase system. The study also investigated the leaching behavior of the glass–ceramic and found that it was lower than the results of a cement stabilization process [14]. The crystallization temperature was lowered to 950 °C with lime mixed with the fly ash at a ratio of 10:2 (ash:lime). The vitrification of MSWI fly ash in a DC arc plasma furnace and subsequent heat treatment even led to a glass–ceramic product with outstanding properties [15]. In another study, a mixture of MSWI fly ash with coal gangue (70%) and lead–zinc tailings (30%) was applied. The study shows that the melting temperature was successfully reduced by 200–300 °C, and the fly ash turned into glass–ceramics which were prepared with great performances [16].

In addition to mixing materials with the fly ash, Kim et al. used water-washing pre-treatment to remove a large amount of Cl from the fly ash. This method lowered the melting point by 100 °C compared to the non-water-washed fly ash. However, this was insufficient to reduce the high energy consumption for high-temperature melting [17].

According to the above narrative, to decrease the melting point of fly ash, the use of basicity indices has caught great attention as a possible solution. Scholars have conducted extensive research mainly focused on basicity indices and have proven that the melting points of fly ashes could be reduced by adjusting their basicity indices. Basicity indices have been used to represent slag structure in calculating viscosities. There have been various ways to represent basicity indices; high SiO_2 is usually referred to as acidic, while high CaO is referred to as basic. Fe_2O_3 and Al_2O_3 can be classified as either acidic or basic, depending on the different situations. The simplest form for the basicity index is expressed as the ratio of CaO/SiO_2 (Equation (1)), but there are still other equations that fit better for different situations, such as Equation (2) [18].

$$\text{Basicity} = (X_{CaO} + X_{CaO})/X_{SiO_2} \tag{1}$$

$$\text{Basicity} = (X_{CaO} + X_{CaO})/(X_{SiO_2} + X_{Al_2O_3}) \tag{2}$$

A content of 35 wt.% of CaO, 20 wt.% of Al_2O_3, and 45 wt.% of SiO_2 could melt the fly ash at 1230 °C and form vitrified slag [19]. With the adjustment of the basicity index to 1.0, the melting point could be decreased to 1200 °C, and the glassy slags could be used as building materials [7]. However, different findings have been reported by other researchers. For instance, by adjusting the basicity index of the fly ash to a range of 0.33–1.5, it was observed that its melting temperature would be the lowest [20]. In a study conducted by Li et al., vitrified slags were obtained with a basicity index ranging from 0.24 to 1.24. The fly ash was melted at 1450 °C maintained for 1.5h, and the leaching amount was significantly lowered. Moreover, fly ash experienced a 50% reduction in volume as well [21].

During the process, silica is commonly introduced to the fly ash to modify its basicity index. This addition facilitates the formation of a silicon structure that effectively encapsulates the heavy metals, thereby preventing their leaching [22]. Mixing fly ash and glass sand showed that an increase in the mixing ratio resulted in a notable decrease in the leaching concentration of Pb and Zn. Furthermore, the leaching concentrations of all heavy metals remained below 1 mg/L in all cases, indicating effective containment and minimal environmental impact [23]. The result revealed that the leaching concentration of Pb, Cu, Cd, and Zn from the melted slags dramatically declined, proving that the melting process could help encapsulate the heavy metals in the silicon structure and stabilize them [20].

However, a definitive equation for calculating the optimal basicity index for fly ash thermal treatment has yet to be established. Furthermore, factors such as the glass phase incorporated into the material or variations between different types of fly ash have yet to be adequately investigated or determined.

In this study, two kinds of silica in different glass phases were mixed with two different fly ashes to adjust their basicity indices. The mixtures were then heated to several temperatures to experiment with their melting temperature. The main goal of this study is to determine the optimal basicity index calculation equation, the ultimate basicity index for the fly ash-melting process, and examine if the basicity index adjustment could be made on two different kinds of fly ash through the melting process. At last, the vitrified slags were subjected to TCLP (toxicity characteristic leaching procedure) tests to estimate if their concentrations exceeded the leaching regulations and obtain exact components.

2. Materials and Methods

2.1. Materials, Reagents and Instruments

In this study, two kinds of incinerator fly ashes were explored. The industrial waste incinerator fly ash (FA1) was from an incinerator in Changhua, Taiwan, while the laboratory-waste-incinerator fly ash (FA2) was from an incinerator at National Cheng Kung University in Tainan, Taiwan. Different sources of the fly ashes made the differences in their components. The main elements in the fly ashes were silicon, calcium, and sodium. In this process, two kinds of materials were used as the source of silica to adjust the basicity indices of the fly ashes, including glass and silica sand powder. The glass was from broken beakers in the lab and was not crystallized, while the silica sand powder was crystallized.

Components of all the materials shown in Tables 1 and 2 were examined by an XRF (X-ray fluorescence, SPECTRO XEPOS, SPECTRO, Chelmsford, MA, USA) and ICP-OES (inductively coupled plasma optical emission spectrometry, Avio 220 Max, PerkinElmer, Waltham, MA, USA). The silica sand powder was composed of 99% of SiO_2. To heat up and melt the fly ashes, a high-temperature furnace (K4, CHUANHUA PRECISION, New Taipei City, Taiwan) was used. Finally, the components and leaching concentrations of the vitrified slags were analyzed through ICP-OES.

Table 1. Elemental mass percentage concentrations of FA1, FA2, and glass.

Elements	FA1	FA2	Glass
Si	2.71%	2.60%	28.73%
Na	4.66%	9.60%	2.81%
Ca	22.57%	20.88%	0.17%
Al	0.81%	3.78%	1.32%
Mg	0.47%	0.45%	0.11%
Cu	0.75%	0.76%	0.11%
Zn	0.81%	0.56%	0.10%
Pb	0.52%	0.53%	0.14%
K	1.56%	1.21%	0.46%
Fe	0.84%	1.15%	0.36%

Table 2. Oxides mass percentage concentration of FA1, FA2, and glass.

Oxides	FA1	FA2	Glass
SiO_2	5.8%	7.55%	88.59%
Na_2O	6.28%	14.19%	5.46%
CaO	31.59%	32.23%	0.34%
Al_2O_3	1.54%	7.5%	3.59%
MgO	0.78%	0.84%	0.27%
CuO	0.94%	0.94%	0.19%
ZnO	1.01%	0.81%	0.18%
Oxides	FA1	FA2	Glass
SiO_2	5.8%	7.55%	88.59%
Na_2O	6.28%	14.19%	5.46%

2.2. Basicity Index Adjustment Experiment

2.2.1. Basicity Index Adjustment with Glass through Melting Process

Different masses of glass and fly ash were mixed to adjust the basicity index. The mass ratios included 6:1, 5:1, 4:1, 3:1, 2:1, and 1:1 (fly ash:glass). The basicity indices of the different fly ashes are shown in Table 3. After the fly ash and glass were evenly mixed, the combinations were put into a high-temperature furnace and heated up to 1100 °C, 1200 °C, 1300 °C, and 1400 °C, then maintained for 30 min. Which basicity index could successfully decrease the melting temperature of the two fly ashes was then observed after the process.

Table 3. Basicity indices of FA1 and FA2 after adjustment (with glass).

Ratio	FA1	FA2
1:0	5.45	4.27
6:1	1.54	1.54
5:1	1.35	1.28
4:1	1.13	1.09
3:1	0.90	0.87
2:1	0.63	0.62
1:1	0.34	0.34

2.2.2. Basicity Index Adjustment with Silica Sand Powder through Melting Process

In this process, FA1 and FA2 were mixed with silica sand powder in different ratios and then melted in the high-temperature furnace. With the ratios of 6:1, 5:1, and 4:1, the fly ashes were examined to see if they could successfully melt at different temperatures. The experiment temperatures included 1100 °C, 1200 °C, 1300 °C, and 1400 °C and they were also maintained for 30 min. The mixed ratio and their basicity indices are shown in Table 4. The main goal of this part was to examine if the melting basicity indices matched the results of the previous experiment. Accordingly, both melting experiments were repeated once to ensure accurate results.

Table 4. Basicity indices of FA1 and FA2 after adjustment (with silica sand powder).

Ratio	FA1	FA2
1:0	5.45	4.27
6:1	1.42	1.34
5:1	1.23	1.18
4:1	1.03	1.00

2.3. Leaching Property Test

The toxicity assessments of the vitrified slags were obtained by the TCLP (toxicity characteristic leaching procedure) method. The TCLP method is a process used to examine hazardous elements in wastes [24]. The test estimates the leaching of hazardous elements from wastes in a landfill to determine if the waste would harm the environment. In the process, the vitrified slag was extracted with an acidic fluid and then placed in a tumbler for 18 h. The solid–liquid ratio was 1:20 in this study. After extraction, the solution was filtered, and the filtered solution was subsequently examined by an ICP-OES to measure the leaching concentrations and check if the heavy metals were stabilized into the vitrified slags.

2.4. Vitrified Slag Composition Test

After the fly ashes were melted into vitrified slags, the components were estimated through an XRF. To measure the element concentrations, 1 g of each of the vitrified slags was dissolved in 35 mL of aqua regia and 5 mL of hydrofluoric acid, then diluted to 100 mL. ICP-OES was then used to measure the concentrations of the solution. All experimental processes are shown in Figure 1.

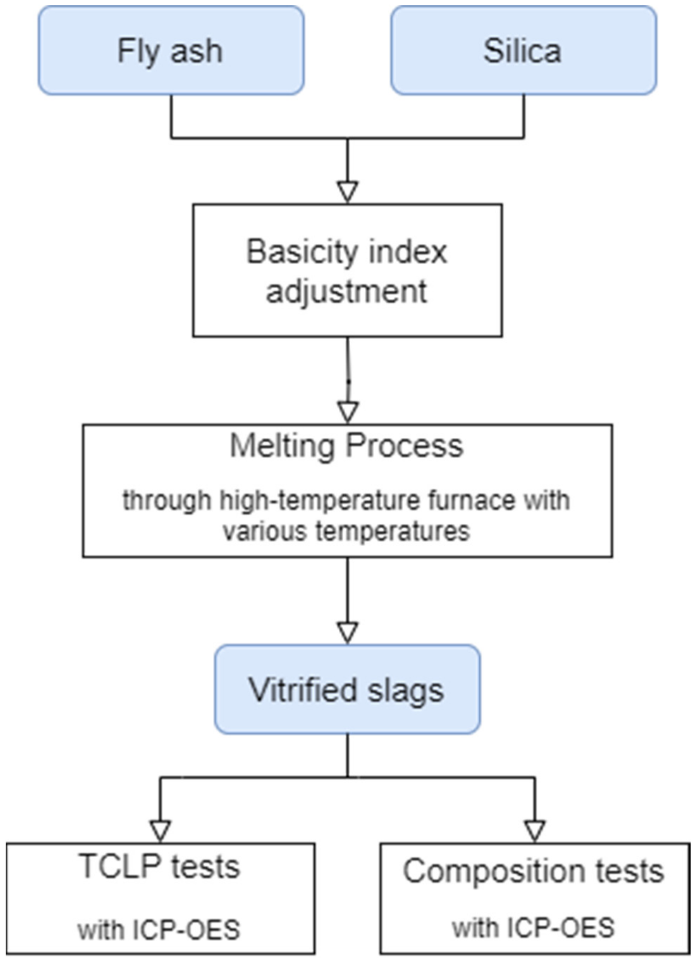

Figure 1. The experiment flowchart.

3. Results and Discussion

3.1. Basicity Index Adjustment Experiment

3.1.1. Basicity Index Adjustment with Glass through Melting Process

The basicity index adjusted fly ashes were heated to different temperatures and maintained for 30 min. The results for FA1 and FA2 are shown in Tables 5 and 6. The O stands for the fly ash that was melted, and X stands for not melted. Each fly ash was unstable at high temperatures and had a significant weight loss at around 800 °C. The weight reduction was about 50% after the melting process. For FA1, the fly ash could melt at 1200 °C starting at the ratio of 4:1 (basicity index 1.13), and for FA2, it would start to melt at 5:1 (basicity index 1.28).

Table 5. Melting process results of FA1 with glass.

	1:0	**6:1**	**5:1**	**4:1**	**3:1**	**2:1**	**1:1**
1100 °C	X	X	X	X	X	X	X
1200 °C	X	X	X	O	O	O	O
1300 °C	X	X	X	O	O	O	O
1400 °C	O	O	O	O	O	O	O

By comparing the results of FA1 and FA2, it could be determined that the basicity indices for the fly ash-thermal-melting process could be calculated by the ratio of CaO/SiO_2 (Equation (1)). In this case, with the basicity index under 1.28, fly ash could be melted at 1200 °C. The results of this experiment match the ones made by previous researchers that the melting point of fly ash could be decreased with a basicity index at around 0.33 to

1.5 [20] and similarly match the ones that vitrified slags could be obtained with a basicity index of 0.24 to 1.24 [21].

Table 6. Melting process results of FA2 with glass.

	1:0	6:1	5:1	4:1	3:1	2:1	1:1
1100 °C	X	X	X	X	X	X	X
1200 °C	X	X	O	O	O	O	O
1300 °C	X	X	O	O	O	O	O
1400 °C	O	O	O	O	O	O	O

3.1.2. High-Temperature Melting Process with Silica Sand Powder

Based on experimental evidence indicating that fly ash could be successfully melted with a basicity index of less than 1.28, determined by the CaO/SiO_2 ratio and incorporating glass, this study aimed to investigate the melting process using silica sand powder as the material for adjusting the basicity index.

Since the ultimate melting basicity index was concluded to be 1.28 in the previous experiment, the mixing ratios in this experiment were set to make the basicity indices around 1.28. The ratios were 6:1, 5:1, and 4:1, which were slightly close to the basicity index of 1.28, and the results are shown in Tables 7 and 8. For FA1, the melting temperature dropped to 1200 °C with a ratio of 5:1 (basicity index 1.23). On the other hand, the results have shown that FA2 could not be melted at 1200 °C with a ratio of 6:1 (basicity index 1.34) but was melted at 1200 °C with a ratio of 5:1 (basicity index 1.18).

Table 7. Melting process results of FA1 with silica sand powder.

	6:1	5:1	4:1
1100 °C	X	X	X
1200 °C	X	O	O
1300 °C	X	O	O
1400 °C	O	O	O

Table 8. Melting process results of FA2 with silica sand powder.

	6:1	5:1	4:1
1100 °C	X	X	X
1200 °C	X	O	O
1300 °C	X	O	O
1400 °C	O	O	O

Therefore, compared with the previous experiment, it is then proved that despite the differences in the source of the SiO_2, the fly ash could be melted at 1200 °C with its basicity index under 1.28 when calculating the ratio of CaO/SiO_2.

3.2. Analysis

3.2.1. TCLP Tests

After the fly ashes were melted into vitrified slags, they were all run through TCLP tests, and the results are shown below in Tables 9–12. For the vitrified slags of FA1 mixed with glass, only a small amount of Cr, Cu, Se, and Ba were detected, but the concentrations were extremely low. For the FA1 mixed with silica sand, extremely low amounts of Se and Ba were detected. As for FA2 with glass, a small amount of Cu, Se, and Ba were detected and were very low too. Finally, only a few Cr, Se, and Ba were found in the vitrified slags from FA2 mixed with silica sand powder.

Table 9. TCLP test results of FA1 vitrified slags with glass (mg/L).

	Regulation	FA1 4:1	FA1 3:1	FA1 2:1	FA1 1:1
Ag	5.0	ND	ND	ND	ND
As	5.0	ND	ND	ND	ND
Cd	1	ND	ND	ND	ND
Cr	5	0.16	0.15	0.21	0.14
Cu	15	0.10	0.09	ND	ND
Hg	0.2	ND	ND	ND	ND
Pb	5	ND	0.05	ND	ND
Se	1	0.04	0.05	0.03	0.02
Ba	100	0.50	0.40	0.23	0.22
Cr(VI)	2.5	ND	ND	ND	ND

Table 10. TCLP test results of FA1 vitrified slags with silica sand powder (mg/L).

	Regulation	FA1 5:1	FA1 4:1
Ag	5.0	ND	ND
As	5.0	ND	ND
Cd	1	ND	ND
Cr	5	ND	ND
Cu	15	ND	ND
Hg	0.2	ND	ND
Pb	5	ND	ND
Se	1	0.05	0.01
Ba	100	0.51	0.14
Cr(VI)	2.5	ND	ND

Table 11. TCLP test results of FA2 vitrified slags with glass (mg/L).

	Regulation	FA2 5:1	FA2 4:1	FA2 3:1	FA2 2:1
Ag	5.0	ND	ND	ND	ND
As	5.0	ND	ND	0.10	ND
Cd	1	ND	ND	ND	ND
Cr	5	0.11	0.11	0.14	0.12
Cu	15	ND	ND	ND	0.29
Hg	0.2	ND	ND	ND	ND
Pb	5	ND	ND	ND	ND
Se	1	0.18	0.13	0.12	0.19
Ba	100	0.33	0.24	0.23	0.11
Cr(VI)	2.5	ND	ND	ND	ND

Table 12. TCLP test results of FA2 vitrified slags with silica sand powder (mg/L).

	Regulation	FA1 5:1	FA1 4:1
Ag	5.0	0.01	ND
As	5.0	ND	ND
Cd	1	ND	ND
Cr	5	0.21	0.14
Cu	15	ND	ND
Hg	0.2	ND	ND
Pb	5	ND	ND
Se	1	0.01	0.01
Ba	100	0.17	0.63
Cr(VI)	2.5	ND	ND

A comprehensive analysis of the leaching concentrations of various vitrified slags in relation to the regulations governing hazardous industrial wastes showed that none of the vitrified slags exceeded the regulatory limits. Moreover, the leaching concentrations were found to be exceptionally low. This experiment matches the results of Huang et al. in that the TCLP test results of vitrified slags significantly decreased and did not exceed all regulations [25]. Consequently, it is conclusively established that the vitrified slags formed through the melting process effectively stabilized the fly ash.

3.2.2. Composition Tests

The components of the vitrified slags were thoroughly examined through XRF and ICP tests, and the results are presented in Tables 13–16. The composition analysis revealed that the vitrified slags predominantly consisted of silica, calcium oxide, and sodium oxide. Additionally, a certain amount of aluminum oxide was also present. Notably, silica constituted a significant proportion of the vitrified slags, ranging from 35% to 60%, regardless of the source material. The high concentration of silica predominantly accounted for the formation of a silicon structure within the vitrified slags, which effectively encapsulated the heavy metals and prevented their leaching.

Table 13. Components of the FA1 vitrified slags with glass (wt%).

	FA1 4:1	**FA1 3:1**	**FA1 2:1**	**FA1 1:1**
SiO_2	37.35%	37.45%	47.84%	51.75%
CaO	4.58%	16.55%	13.63%	16.44%
Na_2O	4.90%	3.06%	3.04%	4.40%
Al_2O_3	0.04%	0.27%	0.16%	0.37%

Table 14. Components of the FA1 vitrified slags with quartz (wt%).

	FA1 5:1	**FA1 4:1**
SiO_2	21.94%	27.38%
CaO	20.83%	18.52%
Na_2O	3.11%	3.18%
Al_2O_3	0.50%	0.85%

Table 15. Components of the FA2 vitrified slags with glass (wt%).

	FA2 5:1	**FA2 4:1**	**FA2 3:1**	**FA2 2:1**	**FA2 1:1**
SiO_2	33.66%	35.93%	40.17%	52.80%	60.49%
CaO	4.03%	3.61%	4.95%	6.20%	7.02%
Na_2O	9.72%	9.53%	10.40%	7.87%	6.85%
Al_2O_3	0.03%	0.03%	0.04%	0.03%	0.36%

Table 16. Components of the FA2 vitrified slags with quartz (wt%).

	FA1 5:1	**FA1 4:1**
SiO_2	31.84%	25.54%
CaO	17.69%	21.42%
Na_2O	6.41%	6.79%
Al_2O_3	0.63%	0.71%

After obtaining the optimal parameters of this research, this study is compared with other common fly ash treatments. Table 17 reveals that the thermal treatment for fly ash has the merits of stabilizing the heavy metals and not producing additional wastes. However, the energy consumption is relatively high compared to other existing methods. As a result, adjusting the basicity index to decrease the melting point of fly ash, which has been the primary goal of this study, would be a significant solution to the problem.

Table 17. Comparison of this study with other methods [3].

Method	Narrative
Thermal treatment	The thermal treatment could stabilize the heavy metals in fly ash by melting it into vitrified slags and the slags could be further used as other materials. Yet, the high energy consumption of the method still needs to be solved.
Solidification/stabilization	This method is the most commonly used method in all fly ash treatments due to its simple operation and low processing costs. However, it does lead to the problems of low heavy-metal stability and increase in waste volume.
Leaching process	This method is the only method that is able to effectively recycle the Zn, Pb, Cu, Cd and other metals from the fly ash. Yet, the residues of this method would still require further treatments before landfilling.
Pyrolysis process	This method shows good results in its dioxins degradation and PCDD/Fs decomposition. Nonetheless, it still presents the problems of high energy consumption and high TEQ residues.
Hydrothermal treatment	The hydrothermal method can significantly dichlorination and degradation the POPs in fly ash and is a relatively mature method. Nevertheless, the leaching of some heavy metals such as Pb and Cd could then become even more severe, causing further problems.

4. Conclusions

Both kinds of fly ash (FA1 and FA2) experimented with in this study were successfully melted through the melting process by adjusting their basicity index.

1. By adjusting the basicity index of the fly ash through the addition of silica, it was observed that the melting point of the fly ash could be effectively reduced from 1400 °C to 1200 °C when the basicity index was maintained below 1.28.
2. The basicity indices for fly ash's high temperature melting process were determined optimally by calculating the ratio of CaO/SiO_2.
3. Both kinds of fly ash, including industrial waste incinerator fly ash (FA1) and laboratory-waste-incinerator fly ash (FA2), could be melted and stabilized by the melting process after the adjustment of basicity indices.
4. Even if the basicity index adjustment material was changed from glass to silica sand powder, this study proved that fly ash could be melted with a basicity index under 1.28. It did not make a difference in whether the fly ash could be melted if the SiO_2 was in a crystalized phase or not.
5. The leaching concentrations for all the vitrified slags were significantly low, including the ones from FA1 mixed with glass, FA1 mixed with silica sand, FA2 mixed with glass, or FA2 mixed with silica sand powder.
6. Compared to the leaching concentration regulations in Taiwan, all of the vitrified slags were within the regulations. Thus, they were all considered stabilized.
7. Through the ICP tests, the vitrified slags were all mainly composed of SiO_2, CaO, Na_2O, and a low amount of Al_2O_3.

The utilization of basicity index adjustment proved effective in reducing the melting point of fly ash. Furthermore, the resulting vitrified slags demonstrated the successful stabilization of heavy metals, preventing their leaching. These findings highlight the feasibility of employing basicity index adjustment and high-temperature melting processes as a viable treatment method for fly ash, particularly at lower melting temperatures, to address the challenges associated with hazardous fly ash residues. Consequently, by reducing the high costs associated with plasma high-temperature melting processes, the melting process presents promising prospects as an alternative and environmentally friendly approach for fly ash disposal. Moreover, future research endeavors could focus on the structure (XRD and SEM) of vitrified slags and the use of the vitrified slags in other research fields, such as building materials, to make the whole treatment even more sustainable.

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References

1. Environmental Protection Administration Executive Yuan, R.O.C (Taiwan). Available online: https://waste.epa.gov.tw/RWD/Statistics/?page=Year1 (accessed on 10 September 2022).
2. Gao, J.; Wang, T.; Zhao, J.; Hu, X.; Dong, C. An experimental study on the melting solidification of municipal solid waste incineration fly ash. *Sustainability* **2021**, *13*, 535. [CrossRef]
3. Xue, Y.; Liu, X. Detoxification, solidification and recycling of municipal solid waste incineration fly ash: A review. *Chem. Eng. J.* **2021**, *420*, 130349. [CrossRef]
4. Fayad, M.A.; Chaichan, M.T.; Dhahad, H.A.; Al-Amiery, A.A.; Wan Isahak, W.N.R. Reducing the Effect of High Sulfur Content in Diesel Fuel on NO x Emissions and PM Characteristics Using a PPCI Mode Engine and Gasoline–Diesel Blends. *ACS Omega* **2022**, *7*, 37328–37339. [CrossRef]
5. Suzuki, K.; Ono, Y. Leaching characteristics of stabilized/solidified fly ash generated from ash-melting plant. *Chemosphere* **2008**, *71*, 922–932. [CrossRef]
6. Li, J.; Liu, K.; Yan, S.; Li, Y.; Han, D. Application of thermal plasma technology for the treatment of solid wastes in China: An overview. *Waste Manag.* **2016**, *58*, 260–269. [CrossRef] [PubMed]
7. Li, Y.; Feng, D.; Bai, C.; Sun, S.; Zhang, Y.; Zhao, Y.; Li, Y.; Zhang, F.; Chang, G.; Qin, Y. Thermal synergistic treatment of municipal solid waste incineration (MSWI) fly ash and fluxing agent in specific situation: Melting characteristics, leaching characteristics of heavy metals. *Fuel Process. Technol.* **2022**, *233*, 107311. [CrossRef]
8. Čarnogurská, M.; Lázár, M.; Puškár, M.; Lengyelová, M.; Václav, J.; Širillová, L. Measurement and evaluation of properties of MSW fly ash treated by plasma. *Measurement* **2015**, *62*, 155–161. [CrossRef]
9. Wang, Q.; Tian, S.; Wang, Q.; Huang, Q.; Yang, J. Melting characteristics during the vitrification of MSWI fly ash with a pilot-scale diesel oil furnace. *J. Hazard. Mater.* **2008**, *160*, 376–381. [CrossRef]
10. Szałatkiewicz, J. Construction Materials from Vitrified Lignite Fly Ash in Plasmatron Plasma Reactor. *Materials* **2019**, *12*, 905. [CrossRef]
11. Lin, X.; Mao, T.; Chen, Z.; Chen, J.; Zhang, S.; Li, X.; Yan, J. Thermal cotreatment of municipal solid waste incineration fly ash with sewage sludge: Phases transformation, kinetics and fusion characteristics, and heavy metals solidification. *J. Clean. Prod.* **2021**, *317*, 128429. [CrossRef]
12. Yang, G.; Ren, Q.; Xu, J.; Lyu, Q. Co-melting properties and mineral transformation behavior of mixtures by MSWI fly ash and coal ash. *J. Energy Inst.* **2021**, *96*, 148–157. [CrossRef]
13. Gao, J.; Dong, C.; Zhao, Y.; Xing, T.; Hu, X.; Wang, X. Effect of B_2O_3 on the melting characteristics of model municipal solid waste incineration (MSWI) fly ash. *Fuel* **2021**, *283*, 119278. [CrossRef]
14. Yang, J.; Xiao, B.; Boccaccini, A.R. Preparation of low melting temperature glass–ceramics from municipal waste incineration fly ash. *Fuel* **2009**, *88*, 1275–1280. [CrossRef]

15. Károly, Z.; Mohai, I.; Toth, M.; Wéber, F.; Szépvölgyi, J. Production of glass–ceramics from fly ash using arc plasma. *J. Eur. Ceram. Soc.* **2007**, *27*, 1721–1725. [CrossRef]
16. Li, C.; Zhang, P.; Zeng, L.; Yu, L.; Li, D. Study on preparation of glass-ceramics from municipal solid waste incineration (MSWI) fly ash and chromium slag. *J. Build. Eng.* **2023**, *68*, 106080. [CrossRef]
17. Kim, J.M.; Kim, H.S. Glass-ceramic produced from a municipal waste incinerator fly ash with high Cl content. *J. Eur. Ceram. Soc.* **2004**, *24*, 2373–2382. [CrossRef]
18. Mills, K.C.; Hayashi, M.; Wang, L.; Watanabe, T. The structure and properties of silicate slags. *Treatise Process Metall.* **2014**, *1*, 149–286.
19. Ma, W.; Shi, W.; Shi, Y.; Chen, D.; Liu, B.; Chu, C.; Li, D.; Li, Y.; Chen, G. Plasma vitrification and heavy metals solidification of MSW and sewage sludge incineration fly ash. *J. Hazard. Mater.* **2021**, *408*, 124809. [CrossRef]
20. Cheng, T.-W.; Chu, J.P.; Tzeng, C.-C.; Chen, Y.-X. Reutilization of Incinerated Ash Using Plasma Melting Technology. *Min. Metall.* **2000**, *44*, 87–91.
21. Li, C.T.; Huang, Y.J.; Huang, K.L.; Lee, W.J. Characterization of slags and ingots from the vitrification of municipal solid waste incineration ashes. *Ind. Eng. Chem. Res.* **2003**, *42*, 2306–2313. [CrossRef]
22. Lin, C.-Y. Effects of Basicity and Cooling Rate on the Characteristics of Flyash-Molten Slags. Master's Thesis, National Pingtung University of Science and Technology, Pingtung, Taiwan, 2008.
23. Yue, Y.; Zhang, J.; Sun, F.; Wu, S.; Pan, Y.; Zhou, J.; Qian, G. Heavy metal leaching and distribution in glass products from the co-melting treatment of electroplating sludge and MSWI fly ash. *J. Environ. Manag.* **2019**, *232*, 226–235. [CrossRef] [PubMed]
24. Lu, C.C.; Hsu, M.H.; Lin, Y.P. Evaluation of heavy metal leachability of incinerating recycled aggregate and solidification/stabilization products for construction reuse using TCLP, multi-final pH and EDTA-mediated TCLP leaching tests. *J. Hazard. Mater.* **2019**, *368*, 336–344. [CrossRef] [PubMed]
25. Huang, Y.J. Vitrification of Municipal Solid Waste Incineration Ash. Master's Thesis, National Cheng Kung University, Tainan, Taiwan, 2002.