Korean J. Chem. Eng., **27**(3), 1028-1034 (2010)
DOI: 10.1007/s11814-010-0156-0

Correlation between the ash composition and melting temperature of waste incineration residue

Mi-Ran Kim*, Jeong-Gook Jang, Sang-Keun Lee***, Bu-Yeon Hwang***, and Jea-Keun Lee*,†**

*Department of Environmental Engineering, Pukyong National University,
599-1, Daeyeon-3dong, Nam-gu, Busan 608-737, Korea
**Department of Environmental Engineering, Dongseo University,
San 69-1, Churye-2dong, Sasang-gu, Busan 617-716, Korea
***Byucksan Engineering & Construction Co., Ltd.,
13-25, Yoido-dong, Youngdeungpo-gu, Seoul 150-739, Korea
(*Received 9 September 2009 • accepted 4 November 2009*)

Abstract−The correlation between the ash composition of various incinerated waste residues and their melting temperatures was examined by using their chemical composition parameters. There was a low correlation between the melting temperatures and the acidic oxide content in the ashes. However, the composition parameters derived from the basic oxides showed a good correlation with the ash melting temperature. The composition parameter, P_7, which is defined as the ratio of basic oxides ($CaO+MgO+K_2O+Na_2O$) to acidic oxides ($SiO_2+Al_2O_3+Fe_2O_3$), showed a strong correlation with the ash melting temperature. By fitting the composition parameter to the experimental data, the correlation equation for the half fluid temperature (HFT) was found to be $HFT=426.77P_7^2-736.76P_7+1592.3$ with a correlation coefficient of 0.91. The correlation equation could be used to predict the melting temperatures of various waste incineration residues. The relative error between the measured and predicted melting temperature was approximately 5%. Overall, these parameters and correlation equations can be used to predict and reduce the melting temperature of incineration residues.

Key words: Ash Composition, Melting Temperature, Incineration Residues, Composition Parameter, Correlation Equation

INTRODUCTION

The operating temperature for a melting treatment of incineration residues needs to be generally kept at approximately 100-150 °C higher than the melting temperature of the residue because the ash need to be melted completely and run down smoothly. Therefore, the melting temperature is a very important factor in the operation of a melting furnace. In general, the melting process is operated at temperatures above 1,300 °C. The very high operating temperature of the process causes some problems, including high energy consumption, reduced durability of the refractory, and the vaporization of heavy metals [1,2].

Many studies have been carried out to reduce the melting temperature of incineration residues and improve the fluidity of the melts [2-5]. However, most studies have been performed on municipal solid waste (MSW) and sewage sludge incineration residues. Therefore, the results from these ashes cannot be applied directly to waste incineration ashes, such as waste water sludge and industrial waste incineration residues. Moreover, it is difficult to predict the melting temperature of the residues and estimate how much the melting temperature was reduced from previous studies. Therefore, the melting temperature of the ash should always be measured whenever the residues are treated by a melting process. In addition, the mixing ratio of the fluxing agent or other wastes should be established in order to lower the melting temperatures of ashes with various chemical compositions.

Therefore, this study examined the correlation between the chemical compositions and melting temperatures of ashes taken from incineration processes of various wastes in order to predict and reduce the melting temperature. In addition, an attempt was made to derive the correlation equation that can be used to estimate the melting temperature of ashes using only the ash composition. The results showed that the correlation equation obtained could predict the melting temperature of ashes prepared artificially.

EXPERIMENTAL

1. Ash Characteristics

The ash samples were taken from incineration processes of various wastes, such as industrial and municipal wastes, as well as the sludge produced from the waste water treatment processes. The melting temperature of the ash samples was measured using a microscope heating stage (LEITZ, Model 1350). Prior to analyzing the melting temperature, the samples were ignited in a muffle furnace to reduce the experimental error caused by the presence of combustibles in the ashes, and crushed in a ball mill (<270 mesh, 53 μm) to obtain homogeneous samples.

In this study, the melting temperature of the ashes was classified as the initial melting temperature (IMT), half fluid temperature (HFT) and fluid temperature (FT) with the change in the ash pyramid width when the ash sample had fused. IMT is the temperature at which the belt around the ash cone begins to appear as evidence of fusion, and it corresponds to the initial deformation temperature (IDT) of

†To whom correspondence should be addressed.
E-mail: leejk@pknu.ac.kr

Table 1. Composition and melting temperature of the incineration ashes used in the experiment

Items	A	B	C	D	E	F	G	H	I	J
Proximate (wt%)										
Moisture	4.55	4.15	10.41	7.43	12.13	8.63	8.41	0.51	3.22	0.47
Volatile matter	18.54	14.06	18.16	13.36	12.14	9.15	41.86	1.59	3.61	2.16
Fixed carbon	30.04	21.72	0.98	1.07	1.25	1.25	4.14	0.09	2.30	1.29
Ash	46.87	60.07	70.45	78.14	74.48	80.96	45.59	97.81	90.88	96.08
Ultimate (dry basis, wt%)										
C	24.16	17.04	3.02	2.26	4.19	3.07	17.58	0.59	0.44	0.47
H	1.25	1.03	1.86	1.42	2.48	1.85	6.24	0.21	0.51	0.39
N	0.69	0.95	1.38	1.33	1.16	1.18	2.46	0.48	1.57	1.22
S	2.07	2.18	0.46	0.32	0.49	0.34	0.37	0.40	2.44	0.003
O (difference)	22.73	16.12	14.6	10.26	6.92	4.94	23.57	0.01	1.14	1.39
Ash analysis (wt%)										
SiO_2	19.60	31.10	23.74	34.18	0.55	4.93	30.04	52.67	35.13	36.38
Al_2O_3	5.74	5.48	5.43	6.30	2.20	3.08	13.47	17.75	5.55	8.54
CaO	8.69	15.23	9.64	14.82	3.33	12.21	6.71	6.86	33.06	30.15
Fe_2O_3	52.70	33.22	47.31	29.87	85.33	65.71	29.39	12.97	2.45	3.94
K_2O	1.14	2.05	0.52	0.60	0.32	1.73	1.74	2.86	5.38	1.14
MgO	3.41	4.11	0.79	2.62	0.84	2.25	2.06	2.76	5.52	7.41
Na_2O	5.12	4.68	5.16	3.56	1.50	4.41	2.90	3.85	8.91	4.12
P_2O_5	3.47	4.01	7.19	7.91	5.73	5.53	13.57	-	3.81	8.09
TiO_2	0.12	0.12	0.21	0.14	0.18	0.16	0.12	0.26	0.19	0.22
Melting temperature (°C)										
IMT	1256	1241	1243	1240	1450	1300	1260	1290	1100	1110
HFT	1460	1325	1485	1390	1500	1470	1480	1406	1325	1290
FT	1499	1380	1500	1425	1500	1500	1500	1465	1338	1320

A, B: Industrial waste incineration ash; C, D: Metal plating sludge ash; E, F: Dyeing sludge ash; G, H: Sewage sludge ash; I, J: MSW incineration ash

the American Society for Testing and Materials (ASTM) standards. HFT is the temperature at which the ash width reduces to half that of the initial ash cone, and corresponds to the hemispherical temperature (HT) of the ASTM standards. The FT is the temperature at which the ash cone turns completely into a liquid phase, and corresponds to the fluid temperature (FT) of the ASTM standards.

As shown in Table 1, the results of the proximate, ultimate and ash analyses varied with the types of waste. Samples A-F are the ashes produced from the incineration processes of industrial waste and sludge. It was found that the ashes from the metal plating sludge (C, D) and the dyeing sludge (E, F) have a high Fe_2O_3 content. Samples G and H, which are sewage sludge ashes, have a high content of SiO_2, Al_2O_3 and Fe_2O_3. In addition, the MSW incineration ashes (I, J) have a high CaO and SiO_2 content.

The melting temperatures of the MSW incineration ashes (I, J), which have a high content of basic oxides, were lower than those of the other waste ashes, as shown in Table 1. The melting temperatures of the sludge ashes (C, E, F and G), which have a higher Fe_2O_3 content, were very high, and their fluid temperatures exceeded the detection limit. The melting temperature of the ash measured in the microscope heating stage was approximately 100 °C higher than the result measured by the ASTM [6]. This was attributed to differences in the definition of the extent of pyramid changes in the sample mold.

2. Selection of Composition Parameters (P_1-P_{16})

In general, the melting temperature of the ash and the viscosity of the melt are strongly affected by the chemical composition of the ash. It was reported that the melting temperature and viscosity of the ash increased with increasing acidic oxide content. However, the ash melting temperature decreased with decreasing Al_2O_3/SiO_2 molar ratio when the molar ratio of basic to acidic oxides was unity [2,7].

In this study, several parameters were selected to determine the effect of the ash composition on the melting temperature of the incineration ashes, as shown in Table 2. The parameters selected were classified into two groups, the first group (P_1-P_{10}) was already suggested for an estimating the fusion behavior of the ash in a coal boiler, and the second group (P_{11}-P_{16}) was recently developed.

In Table 2, P_1 is defined as the silica value [7] and P_2 is the empirical parameter developed by Schaeffer [8] for predicting the ash fusion behavior. P_3 was suggested to be the parameter most suitable for predicting the melting behavior of coal ash [2,7]. P_4 is the sum of the typical acidic oxides, such as Si and Al. P_5 is defined as the sum of Fe, Si and Al by assuming Fe_2O_3 is an acidic oxide under oxidizing conditions [3].

The composition parameter, P_6, represents the typical base/acid ratio. A typical basic oxide is considered to be Na, K, Ca, Mg and Fe oxides, and acidic oxide includes Al and Si oxides. This parameter is often used to forecast the slagging characteristics of bituminous ash [7,9,10]. On the other hand, P_7 is defined as the base/acid ratio considering Fe oxides as acid oxides. Küçükbayrak et al. [3] reported good relationships between the ash composition parameters

Table 2. Composition parameters used in the experiment

Empirical parameter	Base parameter
$P_1=100SiO_2/(SiO_2+Fe_2O_3+CaO+MgO)$ $P_2=Al_2O_3(SiO_2+Al_2O_3)/SiO_2[Fe_2O_3+0.6\ (CaO+MgO+Na_2O+K_2O)]$	$P_9=Fe_2O_3+CaO+MgO+K_2O+Na_2O$ $P_{10}=CaO+MgO+K_2O+Na_2O$ $P_{11}=K_2O+Na_2O$ $P_{12}=MgO+CaO$ $P_{13}=CaO+Na_2O$ $P_{14}=Na_2O$ $P_{15}=Fe_2O_3$ $P_{16}=CaO$
Acid parameter	
$P_3=Al_2O_3/SiO_2$ $P_4=SiO_2+Al_2O_3$ $P_5=SiO_2+Al_2O_3+Fe_2O_3$	
Base/Acid parameter	
$P_6=(Fe_2O_3+CaO+MgO+K_2O+Na_2O)/(SiO_2+Al_2O_3)$ $P_7=(CaO+MgO+K_2O+Na_2O)/(SiO_2+Al_2O_3+Fe_2O_3)$ $P_8=CaO/SiO_2$	

and the ash fusion temperatures if Fe_2O_3 is considered an acidic ash constituent. The parameter P_8, which is frequently used as an index of basicity for the melting process of the sewage sludge, represents the CaO to SiO_2 molar ratio. In general, it has been reported that the melting temperature of sewage sludge incineration ash is lowest when P_8 is 0.3 or 1.0, and the melting temperature increases if P_8 is higher or lower than 0.3 and 1.0, respectively [4,11,12].

The composition parameters, P_9-P_{13}, are derived from base oxides. P_9 represents the sum of typical basic oxides in ash. P_{10} is defined as the sum of the basic constituents of ashes by assuming Fe_2O_3 to be an acidic oxide. P_{11} represents the sum of Na and K oxides that have the lowest ionic potential and a significant fluxing action. P_{12} is defined as the sum of Mg and Ca oxides. In general, the ash melting temperatures of incineration ash decrease with increasing CaO and MgO content. The MgO content in incineration ash is generally low, and behaves like CaO in terms of its effect on the characteristics of ash fusion. However, the fluxing action of CaO is higher than that of MgO because the ionic potential of Ca^{2+} and Mg^{2+} is 2.0 and 3.0, respectively. P_{13} represents the sum of CaO and Na_2O. These compounds are generally used as fluxing agents in the melting process.

The composition parameters of P_{14}-P_{16} are defined as the single constituent of basic oxide. The composition parameter, P_{14}, is defined as Na_2O, which has significant potential fluxing activity. Na_2O is the origin of the melting phenomena observed under the initial deformation temperature (IDT) of ash. The reason is that the Na_2O component in ash functions as a fluxing agent that can form a molten material at temperatures 300-400 °C lower than the ash melting temperature [13]. P_{15} represents the Fe oxide content, which is a very important component because the Fe content in ash can be as high as 5-40%. In addition, it was reported that the fluxing action of Fe oxide is enhanced when its content is up to 20% but decreases at higher levels [14]. The composition parameter, P_{16}, is defined as CaO, which is an alkaline earth metal oxide that is often used as a base controlling or fluxing agent.

RESULTS AND DISCUSSION

1. Correlation between the Composition Parameters and the Melting Temperature

1-1. Empirical Parameters (P_1 and P_2)

Analyses were carried out to determine the correlation between the composition parameters (P_1 and P_2) and the melting temperature of incineration ash. As described above, P_1 was defined as the silica value reported by Ghosh et al. [7], and P_2 was developed by Schaeffer [8] to predict the melting behavior of ash. Fig. 1 shows the results of correlation analysis. There was a low correlation between the empirical parameters and melting temperature, and the correlation coefficients of P_1 and P_2 were 0.67 and 0.3, respectively. Küçükbayrak et al. [3] reported the correlation between the ash composition of brown coal and the melting temperature. Compared with their results, P_1 showed a similar trend, but P_2 showed a poorer correlation. This might be due to the significant differences in constituents such as SiO_2, Al_2O_3, and Fe_2O_3 in the ashes of Turkish lignite and the wastes used in this study. Therefore, P_1 and P_2 are unsuitable for predicting the ash melting temperature.

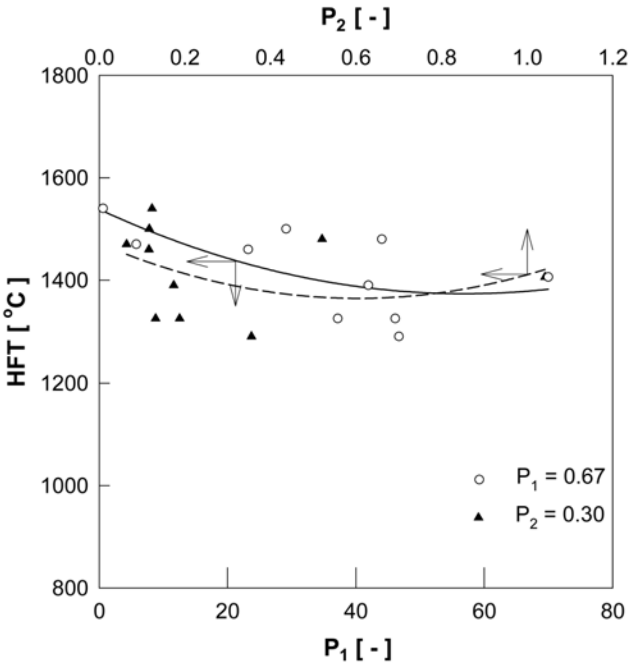

Fig. 1. Correlation between the half fluid temperature (HFT) and the empirical parameters, P_1 and P_2.

1-2. Acid Parameters (P_3, P_4 and P_5)

Fig. 2 shows the correlation between the acid parameters and melt-

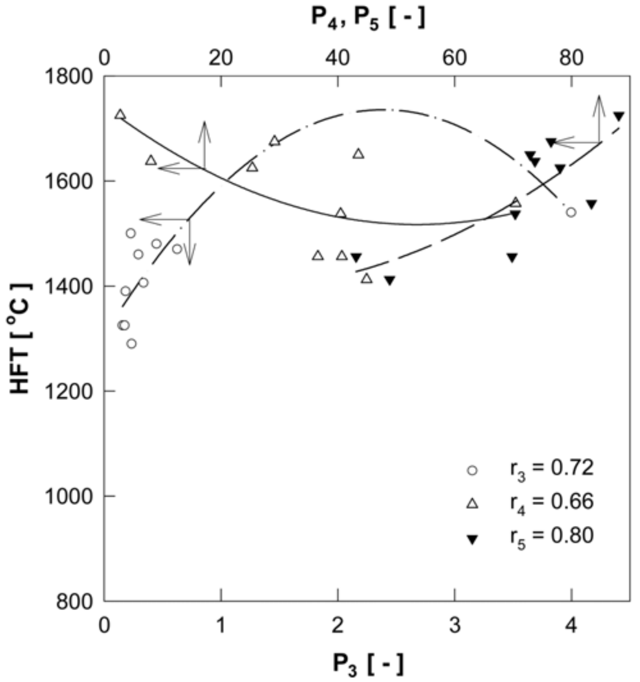

Fig. 2. Correlation between the half fluid temperature (HFT) and the empirical parameters, P_3, P_4 and P_5.

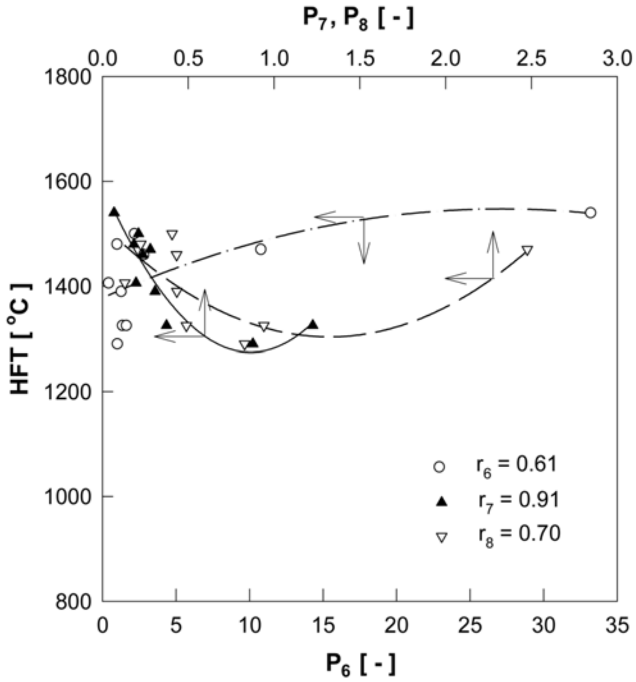

Fig. 3. Correlation between the half fluid temperature (HFT) and the empirical parameters, P_6, P_7 and P_8.

ing temperature. Silicon and aluminum oxides in the ash are typical acidic constituents. Therefore, the acid parameter P_3 is defined as the ratio of Al_2O_3 to SiO_2. Ghosh [7] and Huggins et al. [2] already used this parameter to determine the correlation between the coal ash composition and melting temperature. As shown in Fig. 2, P_3 did not show a good correlation with a correlation coefficient of 0.72. P_4 showed a correlation coefficient of 0.66. Fe_2O_3 is often considered to be an acidic constituent due to its action under oxidation atmospheres. Therefore, P_5 was defined as the sum of typical acidic constituents including Fe_2O_3. As shown in Fig. 2, the correlation coefficient of P_5 with the melting temperature was 0.8, which is a better than the correlation with P_4. Overall, the acid parameters can be used to predict the melting temperature of the incinerated waste residues used in this study.

1-3. Base/Acid Parameters (P_6, P_7 and P_8)

In general, the basic constituents in ash function as fluxing agents to reduce the melting temperature of the ash with the formation of a eutectic mixture in the low temperature region. The acidic constituents also reduce the melting temperature because the silicon (Si) in the acidic constituents reacts with basic compounds, and forms a silicate melt at a relatively low melting temperature [15]. Therefore, it is important to examine the correlation between the molar ratio of basic to acidic oxides and the melting temperature.

P_6 did not show a good correlation with a correlation coefficient of 0.61, as shown in Fig. 3. This is similar to Küçükbayrak et al. [3], who reported a correlation coefficient of 0.65. In their study, the values for P_6 were mainly concentrated in the 0.2-1.5 range but those in this study were distributed between 1-4.

The melting temperature decreased with increasing P_7, and the lowest temperature was observed at approximately P_7=0.8. In addition, P_7 showed a good correlation with a correlation coefficient of 0.91. The correlation of P_7 was better than that of P_6, which considered ferric oxides to be basic oxides. Therefore, the Fe_2O_3 in incineration residues in this experiment behave as an acidic oxide.

It was reported that the melting temperature of sewage sludge ash was the lowest at a CaO/SiO_2 ratio of 1, and can be reduced by controlling the ash composition by varying the two constituents only [12]. The simplified base/acid parameter, P_8, was defined as the CaO to SiO_2 ratio. As shown in Fig. 3, there was a low correlation between P_8 and the melting temperature with a correlation coefficient of 0.7. Therefore, among the base/acid parameters, only P_7 is suitable for predicting the melting temperature of incineration residues.

1-4. Base Parameters (P_9-P_{16})

SiO_2 is a typical acidic oxide that causes vitrification. It has a 3-dimensional network structure that is bound by the tetrahedral coordination of Si and bridged oxygen. However, in case of alkaline earth metal addition, additives such as Na and Ca constituents are alternatively bound with bridged oxygen in a 3 dimensional network structure, which decreases the bonding force in the silicate structure. Therefore, the silicate structure is partly disjoined, and the incineration residue can melt in the low temperature region.

In this study, regression analysis was carried out to examine the correlation between the basic oxide content in ash and the melting temperature. The results are plotted in Fig. 4. P_9 is defined as the sum of basic oxides such as Fe, Ca, Mg, K and Na oxides. As shown in Fig. 4, P_9 did not show a good correlation with a correlation coefficient of 0.63. However, the melting temperature decreased with increasing P_{10}, and its correlation coefficient was 0.9. The lowest melting temperature was predicted at P_{10}=45-50%. These results showed a similar trend with those reported by Küçükbayrak et al. [3]. P_{11} showed a poor correlation with a correlation coefficient of 0.57. As mentioned above, P_{12} is defined as the sum of MgO and CaO, which have similar fluxing activity. The melting temperature of incineration ash decreased with increasing P_{12}, and the minimum

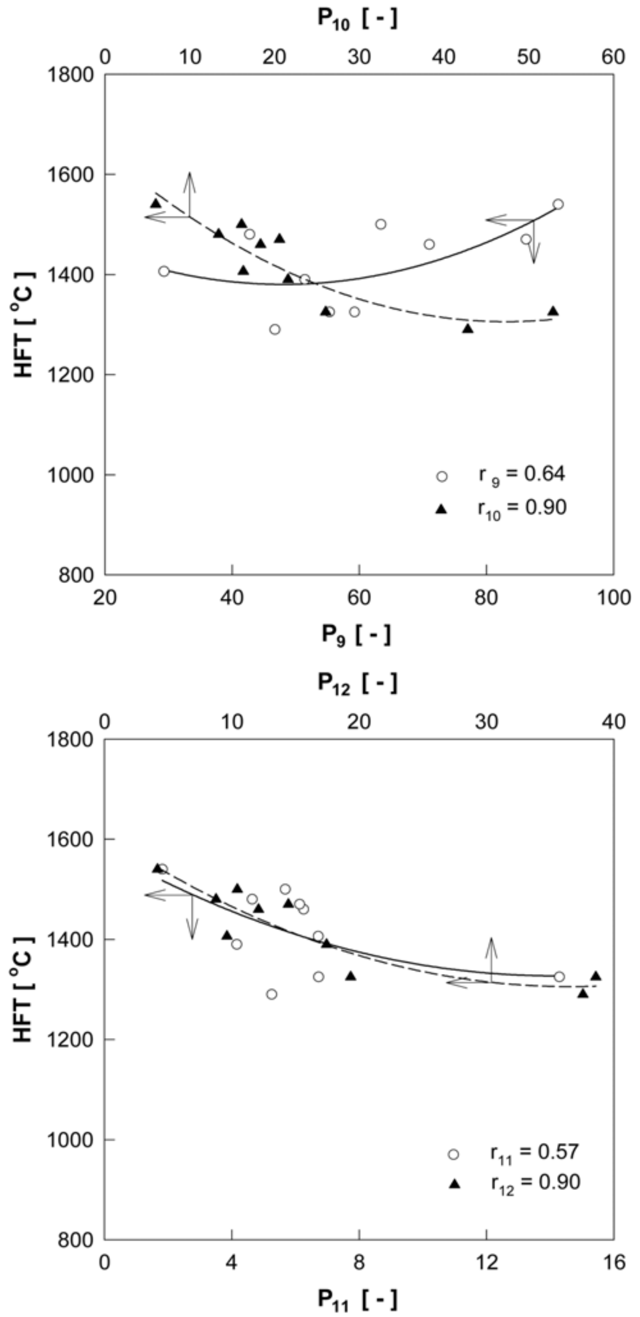

Fig. 4. Correlation between the half fluid temperature (HFT) and the empirical parameters, P_9, P_{10}, P_{11} and P_{12}.

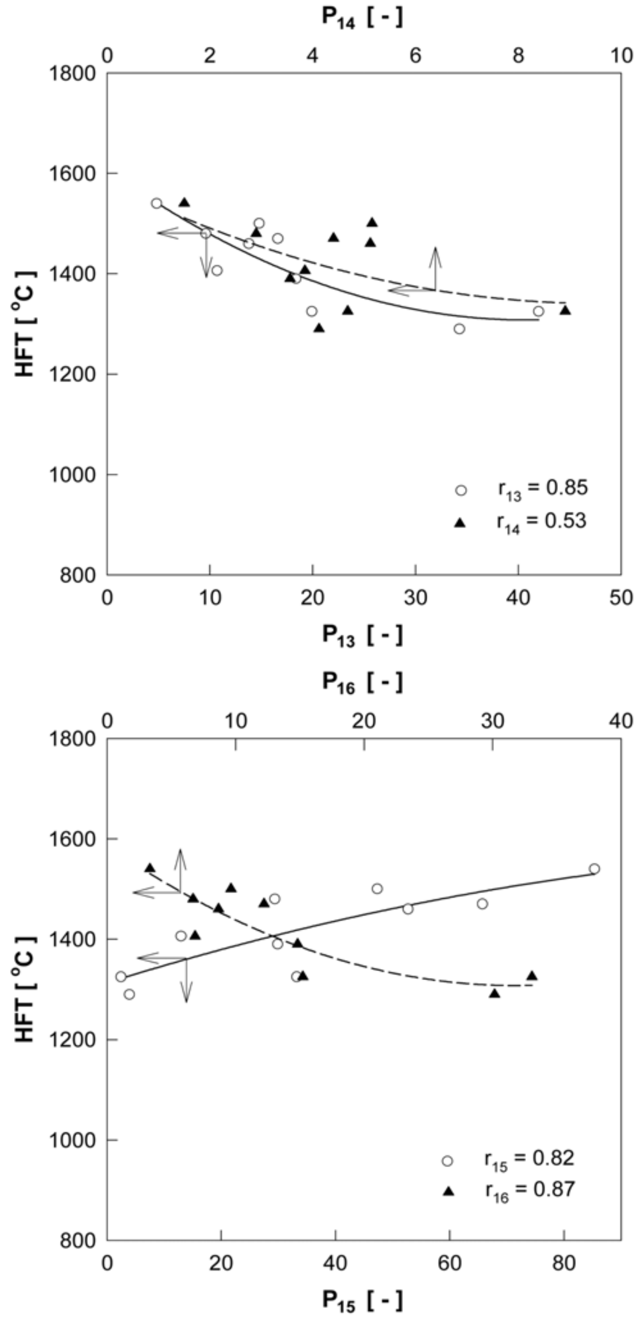

Fig. 5. Correlation between the half fluid temperature (HFT) and the empirical parameters, P_{13}, P_{14}, P_{15} and P_{16}.

melting temperature was observed at P_{12}=35-40% with a good correlation coefficient of 0.90. From these results, the fluxing action of alkaline earth metal such as MgO and CaO in the ashes was greater than that of alkali metal oxides such as K_2O and Na_2O. CaO and Na_2O are generally used as fluxing agents in the ash melting process, and P_{13} is defined as the sum of these compounds. The melting temperature decreased with increasing P_{13}, and the minimum melting temperature was observed at P_{13}=35-45%. The correlation coefficient was 0.85, which is similar to P_{12}. P_{14} is defined as the Na_2O content in ash. As shown in Fig. 5, melting temperature of incineration ash decreased considerably with increasing Na_2O content in the ash but there was a poor association with a correlation coefficient of 0.53. The melting temperature of incineration ash increased with increasing P_{15} value with a correlation coefficient of 0.82. As listed in Table 2, the Fe_2O_3 content in most incineration ashes is >20%. Regression analysis showed that the Fe_2O_3 content in ash increases the melting temperature rather than acting as a fluxing agent. The melting temperature decreased with increasing P_{16} with a correlation coefficient was 0.87. The melting temperature of ash was lowest at P_{16}=25-35% and was a similar to the result reported by Ninomiya et al. [16].

2. Application of the Composition Parameters to Artificial Ash Mixtures

In general, the aim is to reduce the melting temperature and im-

Table 3. Correlation equation and coefficient from regression analysis

Parameters	Equation	Coefficient
P_7	$HFT=426.77P_7^2-736.76P_7+1592.3$	0.9069
P_{10}	$HFT=0.1506P_{10}^2-14.246P_{10}+1642.56$	0.9029
P_{12}	$HFT=0.2278P_{12}^2-16.632P_{12}+1609.1385$	0.9039
P_{13}	$HFT=0.1815P_{13}^2-14.777P_{13}+1608.6$	0.8526
P_{16}	$HFT=0.2773P_{16}^2-17.5797P_{16}+1586.2$	0.8678

Table 4. Ash analysis data and melting temperature of the mixed ashes in the experiment

Sample	Ash analysis (wt%)								Melting temp. (°C)		
	SiO_2	Al_2O_3	CaO	Fe_2O_3	K_2O	MgO	Na_2O	TiO_2	IMT	HFT	FT
H	52.67	17.75	6.86	12.97	2.86	2.76	3.85	0.26	1290	1406	1465
K	51.06	17.21	6.65	12.58	2.78	2.68	6.80	0.25	1240	1402	1460
L	48.33	16.29	14.55	11.90	2.62	2.53	3.53	0.24	1290	1366	1393
M	36.13	12.17	36.13	8.90	1.96	1.89	2.64	0.18	1255	1329	1349

K: $0.97H+0.03Na_2O$, L: $0.92H+0.08CaO$, M: $0.69H+0.31CaO$

Table 5. Relative error between the measured and predicted melting temperatures of the test samples

Parameter	Melting temperature (°C)						Relative error (%)		
	K		L		M				
	T_{mm}	T_{mp}	T_{mm}	T_{mp}	T_{mm}	T_{mp}	K	L	M
P_7		1443		1409		1280	2.95	3.15	3.67
P_{10}		1427		1393		1309	1.79	1.98	1.51
P_{12}	1402	1474	1366	1392	1329	1306	5.12	1.90	1.72
P_{13}		1443		1401		1309	2.90	2.56	1.54
P_{16}		1482		1389		1313	5.67	1.68	1.20

T_{mm}: Measured melting temperature, T_{mp}: Predicted melting temperature

$$\text{Relative error }(\%)=\frac{|\text{Predicted temperature}-\text{Measured temperature}|}{\text{Predicted melting temperature}}\times 100$$

prove the viscosity of the melts to treat waste with a higher melting temperature by adding fluxing agents and/or mixing with other wastes. However, it is very difficult to determine the appropriate addition of fluxing agent and ash composition experimentally in the industrial field. Therefore, in order to improve on these difficulties, the measured and predicted melting temperatures were compared by using the composition parameters, P_7, P_{10}, P_{12}, P_{13}, and P_{16}. As mentioned above, these parameters were selected because of their good correlation. Table 3 shows that correlation equation and regression coefficient between these parameters and the melting temperature. The melting temperature can be predicted from the ash composition using the correlation equation. The composition parameter, P_7, which is defined as the ratio of $(CaO+MgO+K_2O+Na_2O)/(SiO_2+Al_2O_3+Fe_2O_3)$, showed the best correlation with a correlation coefficient of 0.91. The correlation equation was $HFT=426.77\ P_7^2-736.76\ P_7+1592.3$, as shown in Table 3.

Na_2O and CaO were selected as fluxing agents to reduce the melting temperature. As shown in Table 4, the basic ash selected was the sewage sludge ash(H) listed in Table 1. In addition, artificially mixed ashes (K, L and M) were prepared based on the general melting index, which has a CaO to SiO_2 ratio of 0.3 or 1.0. Table 4 lists the ash analysis data and melting temperature of the mixed ashes.

Regression analysis was performed to examine the correlation between the selected parameter and the melting temperature of the artificial ash mixtures. Table 4 shows the relative error between the measured and predicted melting temperatures of the test samples.

As shown in Table 5, the predicted melting temperature was higher than the measured value for the artificial mixtures, K and L, but the result was the opposite for mixture M. In addition, the relative error between the measured and predicted melting temperatures was quite low at approximately 5%. As a result, these parameters appear to be suitable for predicting the melting temperature artificial ash mixtures.

CONCLUSIONS

1. The ash compositions of waste incineration residue varied according to their source with corresponding variations in their melting temperature. Therefore, the ash composition has a significant effect on the ash melting temperature.

2. The correlation between the melting temperature and acid oxides in the ash was poor, but the composition parameters (P_7, P_{10}, P_{12}, P_{13}, P_{16}) derived from basic oxides generally showed a good correlation with the ash melting temperature.

3. The best correlation obtained was between the melting temperature (HFT) and P_7, which is defined as the ratio of (CaO+MgO+K_2O+Na_2O)/(SiO_2+Al_2O_3+Fe_2O_3). The correlation equation was $HFT=426.77\ P_7^2-736.76\ P_7+1592.3$ with a correlation coefficient of 0.91. In addition, the melting temperature of ashes tested was the lowest when P_7 approached 0.8.

4. The reliability of the correlation equations represented in P_7, P_{10}, P_{12}, P_{13} and P_{16} was verified, and the relative error between the measured and predicted melting temperatures was approximately 5%. Therefore, these composition parameters and correlation equations can be used to predict the melting temperature of various waste ashes. Moreover, it is expected that the ash melting temperature can be reduced by adjusting the ash composition and adding fluxing agents and/or mixing with other ash types.

ACKNOWLEDGMENTS

This subject is supported by Korea Ministry of Environment as "The Eco-Technopia 21 project".

REFERENCES

1. M. B. Chang and S.-R. Ku, *Toxicol. Environ. Chem.*, **67**, 161 (1998).
2. F. E. Huggins, D. A. Kasmack and G. P. Huffman, *Fuel*, **60**, 577 (1981).
3. S. Küçükbayrak, A. Ersoy-Meriçboyu, H. Haykiri-Açma, H. Güner and K. Urkanl, *Fuel Sci. Technol. Int.*, **11**, 1231 (1993).
4. H. Watanaba and T. Shiraishi, *Improvement of melting temperature and viscosity in sewage sludge melting process*, The 8th Int. Sym. on Environ. Tech. Development, **15**, 393 (1992).
5. M. Seggiani, *Fuel*, **78**, 1121 (1999).
6. J. G. Singer, *Combustion fossil power*, Combustion Engineering, Inc., Rand McNally (1991).
7. S. K. Ghosh, *Mining Engineering*, **37**, 158 (1985).
8. J. Schaeffer, Master's thesis, Ohio State Univ. (1993).
9. R. W. Bryers and T. E. Taylor, *J. Eng. Power*, **98**, 528 (1976).
10. E. C. Winegartner and B. T. Rhodes, *J. Eng. Power*, **97**, 395 (1975).
11. T. Murakami, T. Ishida, K. Sasaki and S. Harada, *Water Sci. Tech.*, **23**, 2019 (1991).
12. T. Murakami, T. Ishida, K. Suzuki and K. Kakuta, *Journal of Japan Sewage Works Association*, **24**, 52 (1987).
13. G. P. Huffman, F. E. Huggins and G. R. Dumyre, *Fuel*, **60**, 585 (1981).
14. T. R. Bott, in *Inorganic transformations and ash deposition during combustion*, S. A. Benson Eds., United Engineering Trustees Inc., New York (1992).
15. S. A. Benson, M. L. Jones and J. H. Harb, in *Fundamentals of coal combustion for clean and efficient use*, L. D. Smoot Eds., Elsevier Science Publishers, Amsterdam (1933).
16. Y. Ninomiya and A. Sato, *Energy Convers Mgmt.*, **38**, 1405 (1997).