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# Statistical analysis of physicochemical properties of monoliths solidified from a municipal incinerator fly ash

Gordon C.C. Yang*, Shiuann-Yih Chen

*Institute of Environmental Engineering, National Sun Yat-Sen University, Kaohsiung 804, Taiwan*

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**Abstract**

In this study, analysis of variance and regular analysis were employed for the determination of controlling parameters and their corresponding response values of various physicochemical properties of solidified monoliths of a municipal incinerator fly ash. Solidification was carried out in four manners, namely by ASTM Type I portland cement alone, by a partial replacement of Type I portland cement by powdered water-quenched blast furnace slag, by addition of Polymer SP (a superplasticizer) to cement, and by concurrent replacement of cement by slag and addition of Polymer SP. The $L_9$ orthogonal arrays of the Taguchi method are the experimental design employed. The weight ratio of slag-to-binders, error, weight ratio of mixing water-to-binders, and weight ratio of incinerator fly ash-to-binders are the four experimental factors used in the case of replacement of cement by slag. The error term, weight ratio of Polymer SP-to-cement, weight ratio of mixing water-to-cement, and weight ratio of incinerator fly ash-to-cement are the four experimental factors used in the case of addition of Polymer SP to cement. As for the case of concurrent replacement of cement by slag and addition of Polymer SP to cement, the weight ratios of slag-to-binders, Polymer SP-to-binders, mixing water-to-binders, and incinerator fly ash-to-binders are the four experimental factors employed. Properties of concern included unconfined compressive strength, leaching toxicity, and acid neutralization capacity. Results of analysis of variance and regular analysis have shown that the weight ratio of mixing water-to-binder(s) is the most important parameter controlling the UCS development of all solidified specimens. That is, Abrams' law is obeyed in this work. The weight ratio of slag-to-binders is the controlling parameter for acid neutralization capacities of solidified specimens whenever a partial replacement of cement by slag is involved in the solidification treatment. The weight ratio of municipal incinerator fly ash-to-binder(s) is also important to the values of unconfined compressive strength, leaching toxicity, and acid neutralization capacity of some solidified specimens.

*Keywords:* Statistical analysis; Municipal incinerator fly ash; Solidification; Controlling parameter

* Corresponding author.


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## 1. Introduction

Management of municipal solid waste (MSW) incinerator ashes has become an important issue of the environmental protection program in developed countries in the last decade or two. The rapid growth of the waste-to-energy industry worldwide has resulted in the generation of MSW incinerator ashes in unprecedented quantities. Starting from a few years back, Taiwan has devoted herself to the construction of 22 MSW incinerators because the average generation rate of MSW was reported to be 1.09 kg per capita per day in 1992 and a 10% increase would be anticipated every year [1]. After the completion of these municipal incinerators, it is estimated that about 1700 metric tons of MSW incinerator ashes will be generated per day in Taiwan [2]. Therefore, it is of importance for concerned groups in Taiwan to begin to evaluate various disposal options of MSW incinerator ashes now. It has been reported that municipal incinerator fly ash (MIFA), in general, contains many leachable heavy metals (e.g., lead, cadmium and mercury) and organic pollutants (e.g., dioxins and furans) [2–7]. In some cases, municipal incinerator bottom ash has been found to exceed the extraction procedure (EP) limits as well [5]. Thus, special attention has to be paid to the final disposal of municipal incinerator ashes, particularly MIFA. Immobilization of MIFA before landfilling is one of the acceptable options for its final disposal. Solidification/stabilization probably will be the first treatment method adopted by the ROC Environmental Protection Administration for MIFA. Due to its potential hazards, in this study a MIFA was solidified in different manners using a cement-based technique with a partial replacement of cement by water-quenched blast furnace slag or/and addition of Polymer SP to cement. The solidified monoliths were evaluated in terms of unconfined compressive strength (UCS), leaching toxicity (LETOX), and acid neutralization capacity (ANC). Experimental results obtained were further analyzed statistically.

This work is Part II of the research using statistical methods to analyze the controlling parameters, if any, for various properties of solidified monoliths of MIFA. The $L_9$ orthogonal arrays of the Taguchi method with four experimental factors were used in both Parts I and II of the research. In Part I, experimental factors of single-ingredient were used, whereas in Part II, multi-ingredient relationships. Namely, weights of slag or Polymer SP, cement, mixing water, and MIFA are the experimental factors adopted in Part I of the research. (Results of Part I research can be found elsewhere [8]). In Part II, all experimental factors were expressed as weight ratios of specific ingredients-to-(cement + slag), respectively, for the case of replacement of cement by slag. Namely, the weight ratio of slag-to-binders (S/B), error (E), weight ratio of mixing water-to-binders (W/B), and weight ratio of MIFA-to-binders (A/B). On the other hand, the error term (E), weight ratio of Polymer SP-to-cement (P/C), weight ratio of mixing water-to-cement (W/C), and weight ratio of MIFA-to-cement (A/C) were used for the case of addition of Polymer SP to cement. It is worth noting that the amounts of all ingredients used in Part II are within the ranges of Part I of the research. By doing so, findings obtained from these two parts of the research can be correlated. The objective of this study is to better understand the parameters that control the physicochemical properties of solidified MIFA.

## 2. Experimental

### 2.1. Materials

In this work, ASTM Type I portland cement (major binder) was used for solidification of fly ash that was collected by electrostatic precipitators of an MSW incinerator in northern Taiwan. The MIFA specimen used in Part II research is the same one used in Part I of the research. Water-quenched blast furnace slag (auxiliary binder, 5000 Blaine in size) was used to partially repalce the portland cement in solidification treatment of MIFA. Polymer SP added to portland cement, if applicable, is the same superplasticizer used in Part I of the research. Water/mixing water used is ASTM Type I deionized water. All chemicals used are reagent grade.

### 2.2. Experimental design

To simultaneously take into account the effects of all major experimental factors for solidification, an experimental design based on the Taguchi method and $L_9$ orthogonal arrays was adopted [9, 10]. In this context, three levels of variation are associated with each of four experimental factors. In this work, solidification treatment of MIFA was conducted by a cement-based technique in four different manners. Namely, by Type I portland cement alone, a partial replacement of cement by slag, an addition of Polymer SP to cement paste, and concurrent replacement of cement by slag and addition of Polymer SP. Detailed solidification recipes are shown in Tables 1–3.

### 2.3. Methods

All experimental methods used in this investigation are standard methods adopted by Republic of China, United States, and Canada. Details are given as follows: solidification, CNS 1230 A3043 [11]; unconfined compressive strength, CNS 1232 A3045 [12]; leaching toxicity, TCLP Test [13]; and acid neutralization capacity, ANC Test [14].

## 3. Results and discussion

In this work, analysis of variance (ANOVA) and regular analysis (RA) were employed to determine the controlling parameters for various physicochemical properties of solidified MIFA monoliths that have been cured for 28 days [9, 10]. Monoliths solidified with straight portland cement are designated the control group; whereas those with cement replacement by slag and/or addition of Polymer SP to binder(s), the sample group.

Table 1
Solidification of MSW incinerator fly ash using the $L_9$ orthogonal arrays of the Taguchi method (replacement of cement by slag)

| Solidified monolith No. | Experimental factor for solidification | | | |
|---|---|---|---|---|
| | S/B | E | W/B | A/B |
| 1 | 1 | 1 | 1 | 1 |
| 2 | 1 | 2 | 2 | 2 |
| 3 | 1 | 3 | 3 | 3 |
| 4 | 2 | 1 | 2 | 3 |
| 5 | 2 | 2 | 3 | 1 |
| 6 | 2 | 3 | 1 | 2 |
| 7 | 3 | 1 | 3 | 2 |
| 8 | 3 | 2 | 1 | 3 |
| 9 | 3 | 3 | 2 | 1 |
| Level of variation | | | | |
| 1 | 0.1 | 0 | 1.0 | 1.0 |
| 2 | 0.2 | 0 | 1.1 | 1.3 |
| 3 | 0.4 | 0 | 1.3 | 1.5 |

Notes: (1) S/B denotes the weight ratio of slag-to-binders. (2) E denotes the error term. (3) W/B denotes the weight ratio of mixing water-to-binders. (4) A/B denotes the weight ratio of incinerator fly ash-to-binders.

Table 2
Solidification of MSW incinerator fly ash using the $L_9$ orthogonal arrays of the Taguchi method (addition of Polymer SP to cement)

| Solidified monolith No. | Experimental factor for solidification | | | |
|---|---|---|---|---|
| | E | P/C | W/C | A/C |
| 1 | 1 | 1 | 1 | 1 |
| 2 | 1 | 2 | 2 | 2 |
| 3 | 1 | 3 | 3 | 3 |
| 4 | 2 | 1 | 2 | 3 |
| 5 | 2 | 2 | 3 | 1 |
| 6 | 2 | 3 | 1 | 2 |
| 7 | 3 | 1 | 3 | 2 |
| 8 | 3 | 2 | 1 | 3 |
| 9 | 3 | 3 | 2 | 1 |
| Level of variation | | | | |
| 1 | 0 | 0.008 | 1.0 | 1.0 |
| 2 | 0 | 0.013 | 1.1 | 1.3 |
| 3 | 0 | 0.018 | 1.3 | 1.5 |

Notes: (1) E denotes the error term. (2) P/C denotes the weight ratio of polymer-to-cement. (3) W/C denotes the weight ratio of mixing water-to-cement. (4) A/C denotes the weight ratio of incinerator fly ash-to-cement.

Table 3
Solidification of MSW incinerator fly ash using the $L_9$ orthogonal arrays of the Taguchi method (concurrent replacement of cement by slag and addition of Polymer SP to cement)

| Solidified monolith No. | Experimental factor for solidification | | | |
|---|---|---|---|---|
| | S/B | P/B | W/B | A/B |
| 1 | 1 | 1 | 1 | 1 |
| 2 | 1 | 2 | 2 | 2 |
| 3 | 1 | 3 | 3 | 3 |
| 4 | 2 | 1 | 2 | 3 |
| 5 | 2 | 2 | 3 | 1 |
| 6 | 2 | 3 | 1 | 2 |
| 7 | 3 | 1 | 3 | 2 |
| 8 | 3 | 2 | 1 | 3 |
| 9 | 3 | 3 | 2 | 1 |
| Level of variation | | | | |
| 1 | 0.1 | 0.008 | 1.0 | 1.0 |
| 2 | 0.2 | 0.010 | 1.1 | 1.3 |
| 3 | 0.4 | 0.018 | 1.3 | 1.5 |

Notes: (1) S/B denotes the weight ratio of slag-to-binders. (2) P/B denotes the weight ratio of polymer-to-binders. (3) W/B denotes the weight ratio of mixing water-to-binders. (4) A/B denotes the weight ratio of incinerator fly ash-to-binders.

### 3.1. *Characteristics of the municipal incinerator fly ash*

The MIFA specimen has been identified as a hazardous waste. Detailed characterization results of the MIFA specimen have been reported in Part I of the research [8].

### 3.2. *Unconfined compressive strength of solidified MIFA specimens*

#### 3.2.1. *Replacement of cement by slag*

*(1) Control group*

Table 4 shows UCS values for the control group, sample group, and the differences between the sample group and control group. It is evident that all UCS values of the sample group are greater than that of the control group. Based on the data in Table 4, experimental results can be analyzed by statistical methods such as ANOVA.

Results of ANOVA have shown that W/C is the most important controlling parameter for the control group (see Table 5). This experimental factor (W/C) has the highest degree of contribution of 67.66% and a corresponding level of significance of 1%. RA results further indicate that the largest response value is associated with the smallest W/C. This is in good agreement with Abrams' law [15]. According to Abrams' law, the greatest compressive strength of cement pastes and concretes occurs when W/C is in the vicinity of 0.3. As W/C increases, the compressive strength decreases substantially in a concave form. In addition, A/B has a degree of contribution of 25.88% with a significance level of 5%. RA results indicate that, under

Table 4
Unconfined compressive strengths of solidified MSW incinerator fly ash specimens at an age of 28 days (replacement of cement by slag)

| Solidified monolith No. | Unconfined compressive strength ($kg/cm^2$) | | |
|---|---|---|---|
| | Control group (Jn) | Sample group (In) | Difference |
| 1 | 158.35 | 164.01 | 5.66 |
| 2 | 140.78 | 151.56 | 10.78 |
| 3 | 111.00 | 118.59 | 7.59 |
| 4 | 191.95 | 192.20 | 0.25 |
| 5 | 60.85 | 72.02 | 11.17 |
| 6 | 191.70 | 195.65 | 3.95 |
| 7 | 92.16 | 130.84 | 38.68 |
| 8 | 213.09 | 242.94 | 29.85 |
| 9 | 106.42 | 160.43 | 54.01 |

Notes: (1) Control group denotes specimens solidified by ASTM Type I portland cement alone. (2) Sample group denotes specimens solidified by cement and a partial replacement of cement by water-quenched blast furnace slag. (3) Difference = In − Jn.

Table 5
Degrees of contribution and response values for unconfined compressive strengths of solidified MSW incinerator fly ash specimens at an age of 28 days (the control group)

| Experimental factor | Degree of contribution (%) | Level of variation | Response value |
|---|---|---|---|
| E | | 1 | 136.71 |
| | | 2 | 148.17 |
| | | 3 | 137.22 |
| E | | 1 | 147.49 |
| | | 2 | 138.24 |
| | | 3 | 136.37 |
| W/C | 67.66[a] | 1 | 187.71 |
| | | 2 | 146.38 |
| | | 3 | 88.00 |
| A/C | 25.88[b] | 1 | 108.54 |
| | | 2 | 141.55 |
| | | 3 | 172.01 |

Notes: (1) E denotes the error term. (2) W/C denotes the weight ratio of mixing water-to-cement. (3) A/C denotes the weight ratio of incinerator fly ash-to-cement.
[a] denotes a level of significance of 1%.
[b] denotes a level of significance of 5%.

the experimental conditions used, the greater the amount of MIFA solidified, the greater the UCS obtained. This finding is in good agreement with that of Part I. The feature that MIFA has a strong sorption capacity of water might give rise to a lower amount of mixing water available for hydration of portland cement. Effects of Abrams' law would be observed accordingly.

Table 6
Degrees of contribution and response values for unconfined compressive strengths of solidified MSW incinerator fly ash specimens at an age of 28 days (replacement of cement by slag)

| UCS values of the sample group | | | | UCS differences between the sample group and control group | | | |
|---|---|---|---|---|---|---|---|
| a | b | c | d | a | b | c | d |
| S/B | 8.83[b] | 1 | 144.72 | S/B | 73.93 | 1 | 8.01 |
| | | 2 | 153.29 | | | 2 | 5.12 |
| | | 3 | 178.07 | | | 3 | 44.70 |
| E | 1.46 | 1 | 162.35 | E | 21.09 | 1 | 14.86 |
| | | 2 | 155.51 | | | 2 | 17.27 |
| | | 3 | 158.22 | | | 3 | 25.70 |
| W/B | 68.99[a] | 1 | 200.87 | W/B | 0.96 | 1 | 13.15 |
| | | 2 | 168.06 | | | 2 | 25.53 |
| | | 3 | 107.15 | | | 3 | 19.15 |
| A/B | 20.72[b] | 1 | 132.15 | A/B | 4.02 | 1 | 27.46 |
| | | 2 | 159.35 | | | 2 | 17.80 |
| | | 3 | 184.58 | | | 3 | 12.56 |

Notes: (1) a denotes the experimental factor. (2) b denotes the degree of contribution (%). (3) c denotes the level of variation. (4) d denotes the response value. (5) S/B denotes the weight ratio of slag-to-binders. (6) E denotes the error term. (7) W/B denotes the weight ratio of mixing water-to-binders. (8) A/B denotes the weight ratio of incinerator fly ash-to-binders.
[a] denotes a level of significance of 1%.
[b] denotes a level of significance of 5%.

*(2) Sample group*
The degrees of contribution and response values for UCS values among the sample group are given in Table 6. Like that of the control group, W/B was found to be the most important controlling parameter for UCS of solidified monoliths. This parameter has a degree of contribution of 68.99% with a significance level of 1%. Table 6 also indicates that A/B and S/B have degrees of contribution of 20.72% and 8.83%, respectively. These two parameters have the same significance level of 5% for their respective degrees of contribution. On the other hand, response values indicate that the smaller the W/B and the greater the A/B and S/B are, the larger the UCS is. In other words, the replacement of cement by slag did play a role in UCS development among the sample group.

*(3) UCS differences between the sample group and control group*
Results of ANOVA have shown that no controlling parameter can be determined in this regard. According to Table 6, S/B has a degree of contribution of 73.93% with a significance level of greater than 5%. In other words, the experimental factor S/B may not be controlling in terms of UCS differences because one cannot control the probability of Type I error to be no more than 5%. However,

Table 7
Unconfined compressive strengths of solidified MSW incinerator fly ash specimens at an age of 28 days (addition of Polymer SP to cement)

| Solidified monolith No. | Unconfined compressive strength ($kg/cm^2$) | | |
|---|---|---|---|
| | Control group (Jn) | Sample group (Kn) | Difference |
| 1 | 158.35 | 164.46 | 6.11 |
| 2 | 140.78 | 158.35 | 17.57 |
| 3 | 111.00 | 116.34 | 5.34 |
| 4 | 191.95 | 203.34 | 11.39 |
| 5 | 60.85 | 79.18 | 18.33 |
| 6 | 191.70 | 200.47 | 28.77 |
| 7 | 92.16 | 96.49 | 4.33 |
| 8 | 213.09 | 237.18 | 24.09 |
| 9 | 106.42 | 120.93 | 14.51 |

Notes: (1) Control group denotes specimens solidified by ASTM Type I portland cement alone. (2) Sample group denotes specimens solidified by cement with an addition of Polymer SP to cement paste. (3) Difference = Kn − Jn.

due to its large degree of contribution, the role of S/B in UCS differences cannot be simply ignored. Perhaps S/B would become controlling for solidified MIFA monoliths with a much longer age than 28 days which was used in this research.

### *3.2.2. Addition of Polymer SP to cement*

*(1) Control group*
Like in the case of cement replacement by slag, addition of Polymer SP to cement would increase the UCS values of solidified MIFA monoliths. This is evidenced by all positive values for the UCS difference in Table 7. A similar finding was also observed in Part I of the research.

Analysis of variance for the control group has been conducted and discussed above in the case of replacement of cement by slag. It will not be repeated here.

(2) *Sample group*
Table 8 shows the degrees of contribution and response values for UCS values among the sample group and UCS differences between the sample group and control group. From this table, it is clear that W/C is the most important controlling parameter and A/C is the second. W/C has a degree of contribution of 70.79% and a corresponding significance level of 1%. A/C has a degree of contribution of 22.98% with a level of significance of 5%. Response values indicate that, under the experimental conditions used, a smaller W/C and a greater A/C would be favorable to UCS development among the sample group. It is worth noting that effects of UCS increase due to the addition of polymer have been cancelled out each other in this case, as indicated in Table 8.

Table 8
Degrees of contribution and response values for unconfined compressive strengths of solidified MSW incinerator fly ash specimens at an age of 28 days (addition of Polymer SP to cement)

| UCS values of the sample group | | | | UCS differences between the sample group and control group | | | |
|---|---|---|---|---|---|---|---|
| a | b | c | d | a | b | c | d |
| E | | 1 | 146.38 | E | | 1 | 9.67 |
| | | 2 | 167.66 | | | 2 | 19.50 |
| | | 3 | 151.53 | | | 3 | 14.31 |
| P/C | | 1 | 154.76 | P/C | 29.00 | 1 | 7.28 |
| | | 2 | 158.24 | | | 2 | 20.00 |
| | | 3 | 152.58 | | | 3 | 16.21 |
| W/C | 70.79[a] | 1 | 207.37 | W/C | 12.64 | 1 | 19.66 |
| | | 2 | 160.87 | | | 2 | 14.49 |
| | | 3 | 97.34 | | | 3 | 9.33 |
| A/C | 22.98[b] | 1 | 121.53 | A/C | | 1 | 12.98 |
| | | 2 | 158.44 | | | 2 | 16.89 |
| | | 3 | 185.62 | | | 3 | 13.61 |

Notes: (1) a denotes the experimental factor. (2) b denotes the degree of contribution (%). (3) c denotes the level of variation. (4) d denotes the response value. (5) E denotes the error term. (6) P/C denotes the weight ratio of Polymer SP-to-cement. (7) W/C denotes the weight ratio of mixing water-to-cement. (8) A/C denotes the weight ratio of incinerator fly ash-to-cement.
[a] denotes a level of significance of 1%.
[b] denotes a level of sinificance of 5%.

*(3) UCS differences between the sample group and control group*
Again, ANOVA results have shown that no controlling parameters can be determined in this regard (see Table 8). Although all values of UCS differences are positive as shown in Table 6, P/C only has a degree of contribution of 29.00% and its corresponding significance level is greater than 5%. W/C also has a low degree of contribution of 12.64% with a significance level of greater than 5%. The degree of contribution due to the combined error term in this case was found to be 58.37%.

### *3.2.3. Concurrent replacement of cement by slag and addition of Polymer SP*

The purpose of this part of work is to evaluate the joint effects, due to concurrent replacement of portland cement by water-quenched blast furnace slag and addition of Polymer SP to the cement paste, on UCS development of solidified MIFA specimens.

*(1) Control group*
Table 9 shows the UCS values for the control group and sample group and UCS differences between the above two groups. Again, results of ANOVA for the control group have been reported above in this work.

Table 9
Unconfined compressive strengths of solidified MSW incinerator fly ash specimens at an age of 28 days (concurrent replacement of cement by slag and addition of Polymer SP)

| Solidified monolith No. | Unconfined compressive strength ($kg/cm^2$) | | |
|---|---|---|---|
| | Control group (Jn) | Sample group (Ln) | Difference |
| 1 | 158.35 | 188.14 | 29.79 |
| 2 | 140.78 | 185.08 | 44.30 |
| 3 | 111.00 | 141.04 | 30.04 |
| 4 | 191.95 | 225.05 | 33.10 |
| 5 | 60.85 | 80.70 | 19.85 |
| 6 | 191.70 | 251.53 | 59.83 |
| 7 | 92.16 | 170.57 | 78.41 |
| 8 | 213.09 | 264.64 | 51.55 |
| 9 | 106.42 | 180.23 | 73.81 |

Notes: (1) Control group denotes specimens solidified by ASTM Type I portland cement alone. (2) Sample group denotes specimens solidified concurrently by cement with a partial replacement of cement by slag and an addition of Polymer SP to cement paste. (3) Difference = Ln − Jn.

Table 10
Degrees of contribution and response values for unconfined compressive strengths of solidified MSW incinerator fly ash specimens at an age of 28 days (concurrent replacement of cement by slag and addition of Polymer SP to cement)

| UCS values of the sample group | | | | UCS differences between the sample group and control group | | | |
|---|---|---|---|---|---|---|---|
| a | b | c | d | a | b | c | d |
| S/B | 4.69 | 1 | 171.42 | S/B | 56.97[a] | 1 | 34.71 |
| | | 2 | 158.76 | | | 2 | 37.59 |
| | | 3 | 205.15 | | | 3 | 67.92 |
| P/B | 8.34 | 1 | 194.59 | P/B | 8.69 | 1 | 47.10 |
| (e) | | 2 | 176.81 | | | 2 | 38.57 |
| | | 3 | 190.93 | | | 3 | 54.56 |
| W/B | 63.41[a] | 1 | 234.77 | W/B | 10.31 | 1 | 47.06 |
| | | 2 | 196.79 | (e) | | 2 | 50.40 |
| | | 3 | 130.77 | | | 3 | 42.77 |
| A/B | 23.56 | 1 | 149.69 | A/B | 24.04 | 1 | 41.15 |
| | | 2 | 202.39 | | | 2 | 60.85 |
| | | 3 | 210.24 | | | 3 | 38.23 |

Notes: (1) a denotes the experimental factor. (2) b denotes the degree of contribution (%). (3) c denotes the level of variation. (4) d denotes the response value. (5) S/B denotes the weight ratio of slag-to-binders. (6) P/B denotes the weight ratio of Polymer SP-to-binders. (7) W/B denotes the weight ratio of mixing water-to-binders. (8) A/B denotes the weight ratio of incinerator fly ash-to-binders. (9) (e) denotes the error term.

[a] denotes a level of significance of 5%.

*(2) Sample group*

As expected, dual effects resulting from slag replacement and polymer addition have greatly upgraded the UCS development of solidified MIFA specimens, as shown in Table 9. This is evident by comparing the values of UCS difference in Tables 4, 7, and 9. An additional UCS increase ranging from 8.68 to 55.88 kg/cm$^2$ was obtained for the case of Table 9.

Results of ANOVA, as shown in Table 10, have again indicated that the weight ratio of mixing water-to-binders is the most important parameter for UCS development among the sample group. The experimental factor W/B was found to have a degree of contribution of 63.41% and a corresponding level of significance of 5%. By comparing Tables 6 with 10, it was found that the role of W/B in UCS development in Table 10 has been somewhat diminished not only in terms of degree of contribution but level of significance. Moreover, the experimental factors A/B and S/B were found to be no longer controlling in this case. As for W/B, response values again indicate that a lower value will be favorable to the UCS development.

*(3) UCS differences between the sample group and control group*

Table 10 shows that the weight ratio of slag-to-binders is the only controlling parameter in this case. It has a degree of contribution of 56.97% with a corresesonding significance level of 5%. By comparing Tables 6 with 10, one would find that the experimental factor S/B is not a determined controlling parameter in Table 6. Nonetheless, as indicated above, due to its large degree of contribution (i.e., 73.93%), one should not have a disregard for the role of S/B in the case of Table 6.

### *3.3. TCLP leaching toxicity of solidified MIFA specimens*

The TCLP leached Zn and Cd concentrations of the MIFA studied were found to be greater than the then ROC EPA regulatory threshold values. Thus, zinc and cadmium were reported in Part I of the research as the two heavy metals of concern. According to the new regulations promulgated on 10 March 1994, zinc is currently not regulated by ROC EPA. In this work, however, both cadmium and zinc were studied. Additionally, the pH value of TCLP leachate was also included in the discussion.

#### *3.3.1. Replacement of cement by slag*

*(1) Control group*

No controlling parameter could be determined for LETOX of zinc and cadmium for the control group in this work. On the other hand, A/C was found to be the controlling parameter for pH values of TCLP leachates. Table 11 presents the heavy metal concentrations and pHs of TCLP leachates for the control group. Table 12 shows the degrees of contribution and response values for leached Zn and Cd concentrations and pHs among the control group. Concerning the leached concentration of Zn, results of ANOVA have indicated that the combined error term has the greatest degree of contribution (i.e., 57.36%). On the other hand, W/C has a degree

Table 11
Heavy-metal concentrations and pHs of TCLP leachates of solidified MSW incinerator fly ash specimens at an age of 28 days (replacement of cement by slag)

| Solidified monolith No. | Control group (Jn) | | | Sample group (In) | | |
|---|---|---|---|---|---|---|
| | Zn conc. (mg/l) | Cd conc. (mg/l) | pH | Zn conc. (mg/l) | Cd conc. (mg/l) | pH |
| 1 | 0.101 | 0.023 | 11.58 | 0.074 | 0.024 | 9.62 |
| 2 | 0.080 | 0.023 | 11.38 | 0.067 | 0.025 | 10.39 |
| 3 | 0.174 | 0.022 | 11.35 | 0.058 | 0.022 | 10.83 |
| 4 | 0.124 | 0.023 | 10.87 | 0.063 | 0.023 | 9.77 |
| 5 | 0.170 | 0.023 | 11.68 | 0.071 | 0.022 | 10.07 |
| 6 | 0.151 | 0.022 | 11.26 | 0.097 | 0.021 | 8.55 |
| 7 | 0.132 | 0.023 | 11.41 | 0.124 | 0.023 | 7.83 |
| 8 | 0.085 | 0.024 | 11.07 | 0.083 | 0.023 | 9.09 |
| 9 | 0.092 | 0.023 | 11.58 | 0.115 | 0.024 | 10.01 |

Notes: (1) Control group denotes specimens solidified by ASTM Type I portland cement alone. (2) Sample group denotes specimens solidified by cement with a partial replacement of cement by water-quenched blast furnace slag.

Table 12
Degrees of contribution and response values for heavy-metal concentrations and pHs of TCLP leachates of solidified MSW incinerator fly ash specimens at an age of 28 days (the control group)

| Zinc concentration | | | | Cadmium concentration | | | | pH | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| a | b | c | d × 1000 | a | b | c | d × 1000 | a | b | c | d |
| E | | 1 | 78.00 | E | | 1 | 23.00 | E | | 1 | 11.44 |
| | | 2 | 80.67 | | | 2 | 23.67 | | | 2 | 11.27 |
| | | 3 | 73.67 | | | 3 | 26.00 | | | 3 | 11.35 |
| E | | 1 | 78.33 | E | | 1 | 23.00 | E | | 1 | 11.30 |
| | | 2 | 84.00 | | | 2 | 26.00 | | | 2 | 11.28 |
| | | 3 | 70.00 | | | 3 | 23.67 | | | 3 | 11.48 |
| W/C | 42.64 | 1 | 85.67 | W/C | | 1 | 13.33 | W/C | 5.66 | 1 | 11.30 |
| | | 2 | 69.33 | | | 2 | 11.33 | | | 2 | 11.28 |
| | | 3 | 77.33 | | | 3 | 10.00 | | | 3 | 11.48 |
| A/C | | 1 | 75.33 | A/C | | 1 | 24.33 | A/C | 67.92[a] | 1 | 11.61 |
| | | 2 | 78.00 | | | 2 | 24.00 | | | 2 | 11.35 |
| | | 3 | 79.00 | | | 3 | 25.33 | | | 3 | 11.10 |

Notes: (1) a denotes the experimental factor. (2) b denotes the degree of contribution (%). (3) c denotes the level of variation. (4) d denotes the response value. (5) E denotes the error term. (6) W/C denotes the weight ratio of mixing water-to-cement. (7) A/C denotes the weight ratio of incinerator fly ash-to-cement. (8) Degrees of contribution of combined error terms for leached concentrations of Zn and Cd are 57.36% and 100%, respectively.

[a] denotes a level of significance of 5%.

of contribution of 42.64% with a significance level of greater than 5%. ANOVA results have also indicated that the combined error term has a degree of contribution of 100% for the leached cadmium concentration. The reason for this outcome of no controlling parameter may be due to an inappropriate selection of variation level values for experimental factors employed. Namely, solidification recipes used in this work were not suitable for this type of analysis. Regarding the pH value of TCLP leachate, the experimental factor A/C has the greatest degree of contribution of 67.92% and a level of significance of 5%. This is due to the fact that the pH of MIFA (i.e., 9.85) is lower than that of ordinary portland cement (i.e., 12.53). RA results also show that the greater the amount of MIFA treated, the lower the pH value of TCLP leachate.

*(2) Sample group*

ANOVA results have indicated that there is one controlling parameter for the leached concentration of zinc, but not for cadmium and pH of TCLP leachate. Table 11 gives the leached heavy metal concentrations and pHs for the sample group, whereas Table 13 shows their results of statistical analysis. For the leached Zn concentration, S/B has a degree of contribution of 56.31% with a level of significance of 5%. Under the experimental conditions used in this study, response values

Table 13
Degrees of contribution and response values for heavy-metal concentrations and pHs of TCLP leachates of solidified incinerator fly ash specimens at an age of 28 days for the sample group (replacement of cement by slag)

| Zinc concentration | | | | Cadmium concentration | | | | pH | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| a | b | c | d×1000 | a | b | c | d×1000 | a | b | c | d |
| S/B | 56.31[a] | 1 | 66.33 | S/B | 27.73 | 1 | 23.67 | S/B | 21.02 | 1 | 10.28 |
| | | 2 | 77.00 | | | 2 | 22.00 | | | 2 | 9.46 |
| | | 3 | 107.33 | | | 3 | 23.33 | | | 3 | 8.98 |
| E | | 1 | 87.00 | E | | 1 | 23.33 | E | 63.78 | 1 | 9.07 |
| | | 2 | 73.67 | | | 2 | 23.33 | | | 2 | 9.85 |
| | | 3 | 90.00 | | | 3 | 22.33 | | | 3 | 9.80 |
| W/B | | 1 | 84.67 | W/B | 27.73 | 1 | 22.67 | W/B | 4.12 | 1 | 9.09 |
| | | 2 | 81.67 | | | 2 | 24.00 | | | 2 | 10.06 |
| | | 3 | 84.33 | | | 3 | 22.33 | | | 3 | 9.58 |
| A/B | 22.36 | 1 | 86.67 | A/B | | 1 | 23.33 | A/B | 11.08 | 1 | 9.90 |
| | | 2 | 96.00 | | | 2 | 23.00 | | | 2 | 8.92 |
| | | 3 | 68.00 | | | 3 | 22.67 | | | 3 | 9.90 |

Notes: (1) a denotes the experimental factor. (2) b denotes the degree of contribution (%). (3) c denotes the level of variation. (4) d denotes the response value. (5) S/B denotes the weight ratio of slag-to-binders. (6) E denotes the error term. (7) W/B denotes the weight ratio of mixing water-to-binders. (8) A/B denotes the weight ratio of incinerator fly ash-to-binders. (9) Degrees of contribution of combined error terms for leached concentrations of Zn and Cd are 21.33% and 44.54%, respectively.

[a] denotes a level of significance of 5%.

Table 14
Heavy-metal concentrations and pHs of TCLP leachates of solidified MSW incinerator fly ash specimens at an age of 28 days (addition of Polymer SP to cement)

| Solidified monolith No. | Control group (Jn) | | | Sample group (Kn) | | |
|---|---|---|---|---|---|---|
| | Zn conc. (mg/l) | Cd conc. (mg/l) | pH | Zn conc. (mg/l) | Cd conc. (mg/l) | pH |
| 1 | 0.101 | 0.023 | 11.58 | 0.085 | 0.021 | 11.33 |
| 2 | 0.080 | 0.023 | 11.38 | 0.077 | 0.025 | 11.23 |
| 3 | 0.174 | 0.022 | 11.35 | 0.072 | 0.023 | 11.16 |
| 4 | 0.124 | 0.023 | 10.87 | 0.075 | 0.024 | 11.03 |
| 5 | 0.170 | 0.023 | 11.68 | 0.085 | 0.024 | 11.50 |
| 6 | 0.151 | 0.022 | 11.26 | 0.082 | 0.023 | 11.23 |
| 7 | 0.132 | 0.023 | 11.41 | 0.075 | 0.024 | 11.27 |
| 8 | 0.085 | 0.024 | 11.07 | 0.090 | 0.029 | 10.85 |
| 9 | 0.092 | 0.023 | 11.58 | 0.056 | 0.025 | 11.27 |

Notes: (1) Control group denotes specimens solidified by ASTM Type I portland cement alone. (2) Sample group denotes specimens solidified by cement with an addition of Polymer SP to cement paste.

indicate that the greater the S/B is, the greater the leached zinc concentration will be. This is understandable because the pH value of portland cement (i.e., 12.53) is greater than that of slag (i.e., 11.14). The greater the S/B, the lower the buffering capacity of a solidified specimen. For the leached Cd concentration, results of ANOVA show that the combined error term has the greatest degree of contribution (i.e., 44.54%). Again, a phenomenon that no controlling parameter can be determined may be due to an inappropriate selection of solidification recipes in this work.

*(3) LETOX differences between the sample group and control group*
As indicated in Table 11, the leached concentrations of zinc and cadmium and pHs for the sample group and control group are very close. Therefore, it is of no use to conduct the ANOVA for LETOX differences between these two groups.

### *3.3.2. Addition of polymer SP to cement*

*(1) Control group*
Table 14 shows the leached concentrations of Zn and Cd and pHs of TCLP leachates. A discussion on the control group has been presented above in the case of replacement of cement by slag. It will not be repeated here.

*(2) Sample group*
Like the case of cement replacement by slag, results of ANOVA have indicated that there is one controlling parameter for the leached zinc concentration, but not for the leached cadmium concentration. However, there is one controlling parameter for the pH value of TCLP leachate (see Table 15). For the leached Zn concentration, W/C has the greatest degree of contribution of 44.32% and a level of

Table 15
Degrees of contribution and response values for heavy-metal concentrations and pHs of TCLP leachates of solidified incinerator fly ash specimens at an age of 28 days for the sample group (addition of Polymer SP to cement)

| Zinc concentration | | | | Cadmium concentration | | | | pH | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| a | b | c | d×1000 | a | b | c | d×1000 | a | b | c | d |
| E | | 1 | 78.00 | E | | 1 | 23.00 | E | | 1 | 11.24 |
| | | 2 | 80.67 | | | 2 | 23.67 | | | 2 | 11.25 |
| | | 3 | 73.67 | | | 3 | 26.00 | | | 3 | 11.13 |
| P/C | 31.39 | 1 | 78.33 | P/C | | 1 | 23.00 | E | | 1 | 11.21 |
| | | 2 | 84.00 | | | 2 | 26.00 | | | 2 | 11.19 |
| | | 3 | 70.00 | | | 3 | 23.67 | | | 3 | 11.22 |
| W/C | 44.32[a] | 1 | 85.67 | W/C | | 1 | 13.33 | W/C | 12.97 | 1 | 11.14 |
| | | 2 | 69.33 | | | 2 | 11.33 | | | 2 | 11.18 |
| | | 3 | 77.33 | | | 3 | 10.00 | | | 3 | 11.31 |
| A/C | | 1 | 75.33 | A/C | | 1 | 24.33 | A/C | 65.94[a] | 1 | 11.37 |
| | | 2 | 78.00 | | | 2 | 24.00 | | | 2 | 11.24 |
| | | 3 | 79.00 | | | 3 | 25.33 | | | 3 | 11.01 |

Notes: (1) a denotes the experimental factor. (2) b denotes the degree of contribution (%). (3) c denotes the level of variation. (4) d denotes the response value. (5) E denotes the error term. (6) P/C denotes the weight ratio of Polymer SP-to-cement. (7) W/C denotes the weight ratio of mixing water-to-cement. (8) A/C denotes the weight ratio of incinerator fly ash-to-cement. (9) Degrees of contribution of combined error terms for leached concentrations of Zn and Cd are 24.20% and 100%, respectively.
[a] denotes a level of significance of 5%.

significance of 5%. Although P/C has a degree of contribution of 31.39%, its corresponding significance level is greater than 5%. For the leached Cd concentration, no controlling parameter can be determined because the combined error term has a degree of contribution of 100%. Regarding the pH of TCLP leachate, A/C was found to be the only controlling parameter with a degree of contribution of 65.94% and a significance level of 5%. This finding is in good agreement with that of the control group. In the sample group, only a very small amount of Polymer SP ranging from 0.8 to 1.8 wt% of cement was added to the cement paste. This practice was found to alter the condition of the control group a bit.

*(3) LETOX differences between the sample group and control group*

Due to the same reason for the case of cement replacement by slag, no statistical analysis was conducted for LETOX differences between the sample group and control group.

### *3.3.3. Concurrent replacement of cement by slag and addition of Polymer SP*

*(1) Control group*

Table 16 presents the leached concentrations of Zn and Cd and pHs of TCLP leachates. A discussion on ANOVA results for this group has already been given above.

Table 16
Heavy-metal concentrations and pHs of TCLP leachates of solidified MSW incinerator fly ash specimens at an age of 28 days (concurrent replacement of cement by slag and addition of Polymer SP to cement)

| Solidified monolith No. | Control group (Jn) | | | Sample group (Ln) | | |
|---|---|---|---|---|---|---|
| | Zn conc. (mg/l) | Cd conc. (mg/l) | pH | Zn conc. (mg/l) | Cd conc. (mg/l) | pH |
| 1 | 0.101 | 0.023 | 11.58 | 0.070 | 0.022 | 11.04 |
| 2 | 0.080 | 0.023 | 11.38 | 0.057 | 0.024 | 10.32 |
| 3 | 0.174 | 0.022 | 11.35 | 0.059 | 0.024 | 10.39 |
| 4 | 0.124 | 0.023 | 10.87 | 0.085 | 0.025 | 9.38 |
| 5 | 0.170 | 0.023 | 11.68 | 0.057 | 0.025 | 11.10 |
| 6 | 0.151 | 0.022 | 11.26 | 0.060 | 0.029 | 9.77 |
| 7 | 0.132 | 0.023 | 11.41 | 0.052 | 0.022 | 9.57 |
| 8 | 0.085 | 0.024 | 11.07 | 0.112 | 0.029 | 8.36 |
| 9 | 0.092 | 0.023 | 11.58 | 0.098 | 0.025 | 10.19 |

Notes: (1) Control group denotes specimens solidified by ASTM Type I portland cement alone. (2) Sample group denotes specimens solidified concurrently by cement with a partial replacement of cement by slag and an addition of Polymer SP to cement paste.

Table 17
Degrees of contribution and response values for heavy-metal concentrations and pHs of TCLP leachates of solidified incinerator fly ash specimens at an age of 28 days for the sample group (concurrent replacement of cement by slag and addition of Polymer SP to cement)

| Zinc concentration | | | | Cadmium concentration | | | | pH | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| a | b | c | d × 1000 | a | b | c | d × 1000 | a | b | c | d |
| S/B | 27.97 | 1 | 62.00 | S/B | 15.38 | 1 | 23.33 | S/B | 36.70[a] | 1 | 10.58 |
| | | 2 | 67.33 | | | 2 | 26.33 | | | 2 | 10.08 |
| | | 3 | 87.33 | | | 3 | 25.33 | | | 3 | 9.37 |
| P/B (e) | 6.67 | 1 | 69.00 | P/B | 23.08 | 1 | 23.33 | P/B (e) | 3.76 | 1 | 10.00 |
| | | 2 | 75.33 | | | 2 | 26.00 | | | 2 | 9.93 |
| | | 3 | 72.33 | | | 3 | 26.00 | | | 3 | 10.12 |
| W/B | 31.14[a] | 1 | 80.67 | W/B | 15.38 | 1 | 26.67 | W/B | 9.35 | 1 | 9.72 |
| | | 2 | 80.00 | | | 2 | 24.67 | | | 2 | 9.96 |
| | | 3 | 56.00 | | | 3 | 23.67 | | | 3 | 10.35 |
| A/B | 34.22[a] | 1 | 75.00 | A/B (e) | 46.15 | 1 | 24.00 | A/B | 50.18[a] | 1 | 10.78 |
| | | 2 | 56.33 | | | 2 | 25.00 | | | 2 | 9.89 |
| | | 3 | 85.33 | | | 3 | 26.00 | | | 3 | 9.38 |

Notes: (1) a denotes the experimental factor. (2) b denotes the degree of contribution (%). (3) c denotes the level of variation. (4) d denotes the response value. (5) S/B denotes the weight ratio of slag-to-binders. (6) P/B denotes the weight ratio of Polymer SP-to-binders. (7) W/B denotes the weight ratio of mixing water-to-binders. (8) A/B denotes the weight ratio of incinerator fly ash-to-binders. (9) (e) denotes the error term.

[a] denotes a level of significance of 5%.

Table 18
Acid neutralization capacities of solidified MSW incinerator fly ash specimens at an age of 28 days (replacement of cement by slag)

| Solidified monolith No. | Acid neutralization capacity (2N $HNO_3$ added, meq/g dry waste) | | |
|---|---|---|---|
| | Control group (Jn) | Sample group (In) | Difference |
| 1 | 11.01 | 9.42 | −1.59 |
| 2 | 10.64 | 9.49 | −1.15 |
| 3 | 10.47 | 9.18 | −1.29 |
| 4 | 9.74 | 8.65 | −1.09 |
| 5 | 11.58 | 9.37 | −2.21 |
| 6 | 10.63 | 8.99 | −1.64 |
| 7 | 10.28 | 8.00 | −2.28 |
| 8 | 10.34 | 8.52 | −1.82 |
| 9 | 10.61 | 8.86 | −1.75 |

Notes: (1) Control group denotes specimens solidified by ASTM Type I portland cement alone. (2) Sample group denotes specimens solidified by cement with a partial replacement of cement by water-quenched blast furnace slag. (3) Difference = In − Jn. (4) pH = 7 is the basis for ANC comparison.

*(2) Sample group*

Results of ANOVA have shown that the controlling parameters obtained in this case (see Table 17) are very different from the ones in the cases of replacement of cement by slag or addition of Polymer SP alone. For leached zinc concentrations, A/B and W/B were found to be controlling. The degrees of contribution for these two experimental factors are 34.22% and 31.14%, respectively. Both have a significance level of 5%. For leached cadmium concentrations, however, no controlling parameter could be determined. As for pHs of TCLP leachates, experimental factors A/B and S/B are both controlling. The degrees of contribution for these two experimental factors are 50.18% and 36.70%, respectively, and both have a significance level of 5%.

*(3) LETOX differences between the sample group and control group*

Since LETOX differences between the sample group and control group are insignificant, no further analysis was conducted.

### 3.4. Acid neutralization capacity of solidified MIFA specimens

#### 3.4.1. Replacement of cement by slag

*(1) Control group*

Table 18 shows the determined ANC values for the control group and sample group and ANC differences between these two groups. From Table 18, it is clear that values of ANC for the sample group are all smaller than that of the control group. This is not surprising because the pH value of slag (i.e., 11.14) is lower than that of portland cement (i.e., 12.53).

Table 19
Degrees of contribution and response values for acid neutralization capacities of solidified MSW incinerator fly ash specimens at an age of 28 days (the control group)

| Experimental factor | Degree of contribution (%) | Level of variation | Response value |
|---|---|---|---|
| E | | 1 | 10.71 |
| | | 2 | 10.65 |
| | | 3 | 10.41 |
| E | | 1 | 10.34 |
| | | 2 | 10.85 |
| | | 3 | 10.57 |
| W/C | | 1 | 10.66 |
| | | 2 | 10.33 |
| | | 3 | 10.78 |
| A/C | 44.07 | 1 | 11.07 |
| | | 2 | 10.52 |
| | | 3 | 10.18 |

Notes: (1) E denotes the error term. (2) W/C denotes the weight ratio of mixing water-to-cement. (3) A/C denotes the weight ratio of incinerator fly ash-to-cement.

Table 20
Degrees of contribution and response values for acid neutralization capacities (ANC) of solidified incinerator fly ash specimens at an age of 28 days (replacement of cement by slag)

| ANC values of the sample group | | | | ANC differences between the sample group and control group | | | |
|---|---|---|---|---|---|---|---|
| a | b | c | d | a | b | c | d |
| S/B | 55.38[a] | 1 | 9.36 | S/B | 35.28 | 1 | −1.34 |
| | | 2 | 9.00 | | | 2 | −1.65 |
| | | 3 | 8.46 | | | 3 | −1.95 |
| E | | 1 | 8.69 | E | 11.58 | 1 | −1.65 |
| | | 2 | 9.13 | | | 2 | −1.73 |
| | | 3 | 9.01 | | | 3 | −1.56 |
| W/B | | 1 | 8.98 | W/B | 34.45 | 1 | −1.68 |
| | | 2 | 9.00 | | | 2 | −1.33 |
| | | 3 | 8.85 | | | 3 | −1.93 |
| A/B | 8.76 | 1 | 9.22 | A/B | 18.69 | 1 | −1.85 |
| | | 2 | 8.83 | | | 2 | −1.69 |
| | | 3 | 8.78 | | | 3 | −1.40 |

Notes: (1) a denotes the experimental factor. (2) b denotes the degree of contribution (%). (3) c denotes the level of variation. (4) d denotes the response value. (5) S/B denotes the weight ratio of slag-to-binders. (6) E denotes the error term. (7) W/B denotes the weight ratio of mixing water-to-binders. (8) A/B denotes the weight ratio of incinerator fly ash-to-binders.

[a] denotes a level of significance of 5%.

ANOVA results have shown that no controlling parameter could be determined for the control group. Table 19 shows the degrees of contribution and response values of experimental factors in the control group. Even A/B has a degree of contribution of 44.07%, its corresponding significance level is greater than 5%. Hence, this experimental factor is not controlling. This is ascribed to the fact that the combined error term has a degree of contribution of 55.93%, which would overshadow that of the experimental factor A/B.

*(2) Sample group*

S/B was found to be the controlling parameter in this regard (see Table 20). According to ANOVA results, the experimental factor S/B has the greatest degree of contribution of 55.38% with a significance level of 5%. This is attributed to the fact that cement replacement by slag would result in solidified monoliths of lower pHs. The greater the amount of cement replaced by slag is, the lower the ANC will be. This statement is verified by the response values obtained from the RA.

*(3) ANC differences between the sample group and control group*

As far as ANC differences between the sample group and control group are concerned, no controlling parameter can be determined (see Table 20). Although S/B and W/B both have a degree of contribution in the neighborhood of 35%, their levels of significance are greater than 5%.

### *3.4.2. Addition of Polymer SP to cement*

*(1) Control group*

Table 21 shows the ANC values for the control group and sample group and ANC differences between these two groups. It is worth noting that the control group

Table 21
Acid neutralization capacities of solidified MSW incinerator fly ash specimens at an age of 28 days (addition of Polymer SP to cement)

| Solidified monolith No. | Acid neutralization capacity (2N $HNO_3$ added, meq/g dry waste) | | |
|---|---|---|---|
| | Control group (Jn) | Sample group (Kn) | Difference |
| 1 | 11.01 | 12.42 | 1.41 |
| 2 | 10.64 | 11.81 | 1.17 |
| 3 | 10.47 | 11.75 | 1.28 |
| 4 | 9.74 | 12.02 | 2.28 |
| 5 | 11.58 | 13.16 | 1.58 |
| 6 | 10.63 | 12.16 | 1.53 |
| 7 | 10.28 | 11.95 | 1.67 |
| 8 | 10.34 | 11.93 | 1.59 |
| 9 | 10.61 | 10.96 | 0.35 |

Notes: (1) Control group denotes specimens solidified by ASTM Type I portland cement alone. (2) Sample group denotes specimens solidified by cement with an addition of Polymer SP to cement paste. (3) Difference = Kn − Jn. (4) pH = 7 is the basis for ANC comparison.

Table 22
Degrees of contribution and response values for acid neutralization capacities (ANC) of solidified MSW incinerator fly ash specimens at an age of 28 days (addition of Polymer SP to cement)

| ANC values of the sample group | | | | ANC differences between the sample group and control group | | | |
|---|---|---|---|---|---|---|---|
| a | b | c | d | a | b | c | d |
| E | 100.00 | 1 | 11.99 | E | | 1 | 1.29 |
| | | 2 | 12.45 | | | 2 | 1.80 |
| | | 3 | 11.65 | | | 3 | 1.20 |
| P/C | | 1 | 12.13 | P/C | 18.09 | 1 | 1.79 |
| | | 2 | 12.30 | | | 2 | 1.45 |
| | | 3 | 11.62 | | | 3 | 1.05 |
| W/C | | 1 | 12.17 | W/C | | 1 | 1.51 |
| | | 2 | 11.60 | | | 2 | 1.27 |
| | | 3 | 12.29 | | | 3 | 1.51 |
| A/C | | 1 | 12.18 | A/C | | 1 | 1.11 |
| | | 2 | 11.97 | | | 2 | 1.46 |
| | | 3 | 11.90 | | | 3 | 1.72 |

Notes: (1) a denotes the experimental factor. (2) b denotes the degree of contribution (%). (3) c denotes the level of variation. (4) d denotes the response value. (5) E denotes the error term. (6) P/C denotes the weight ratio of Polymer SP-to-cement. (7) W/C denotes the weight ratio of mixing water-to-cement. (8) A/C denotes the weight ratio of incinerator fly ash-to-cement. (9) The degree of contribution of the combined error term for ANC differences is 81.91%.

in this case is the same as that of the case of replacement of cement by slag. Thus, no further discussion will be given.

*(2) Sample group*

ANOVA results have shown that no controlling parameter could be determined in this regard (see Table 22). In this case, the combined error term was found to have a degree of contribution of 100%. In other words, all concerned experimental factors are trivial at this time.

*(3) ANC differences between the sample group and control group*

Again, results of ANOVA have indicated that no controlling parameter could be determined for ANC differences between the sample group and control group. The degree of contribution of the combined error term is 81.91%, which would overshadow the contribution due to P/C (see Table 22).

### *3.4.3. Concurrent replacement of cement by slag and addition of Polymer SP*

*(1) Control group*

Table 23 presents the ANC values for the control group and sample group and ANC differences between these groups. Again, the analysis for the control group has been given above.

Table 23
Acid neutralization capacities of solidified MSW incinerator fly ash specimens at an age of 28 days (concurrent replacement of cement by slag and addition of Polymer SP to cement)

| Solidified monolith No. | Acid neutralization capacity (2N $HNO_3$ added, meq/g dry waste) | | |
|---|---|---|---|
| | Control group (Jn) | Sample group (Ln) | Difference |
| 1 | 11.01 | 11.00 | −0.01 |
| 2 | 10.64 | 10.53 | −0.11 |
| 3 | 10.47 | 9.50 | −0.97 |
| 4 | 9.74 | 9.25 | −0.49 |
| 5 | 11.58 | 10.43 | −1.15 |
| 6 | 10.63 | 9.30 | −1.33 |
| 7 | 10.28 | 8.94 | −1.34 |
| 8 | 10.34 | 8.19 | −2.15 |
| 9 | 10.61 | 9.45 | −1.16 |

Notes: (1) Control group denotes specimens solidified by ASTM Type I portland cement alone. (2) Sample group denotes specimens solidified concurrently by cement with a partial replacement of cement by slag and an addition of Polymer SP to cement paste. (3) Difference = Ln − Jn. (4) pH = 7 is the basis for ANC comparison.

Table 24
Degrees of contribution and response values for acid neutralization capacities (ANC) of solidified MSW incinerator fly ash specimens at an age of 28 days (concurrent replacement of cement by slag and addition of Polymer SP to cement)

| ANC values of the sample group | | | | ANC differences between the sample group and control group | | | |
|---|---|---|---|---|---|---|---|
| a | b | c | d | a | b | c | d |
| S/B | 52.05* | 1 | 10.34 | S/B | 50.55 | 1 | −0.36 |
| | | 2 | 9.66 | | | 2 | −0.99 |
| | | 3 | 8.86 | | | 3 | −1.55 |
| P/B | 1.57 | 1 | 9.73 | P/B | 7.76 | 1 | −0.61 |
| | | 2 | 9.72 | | | 2 | −1.14 |
| | | 3 | 9.42 | | | 3 | −1.15 |
| W/B (e) | 5.91 | 1 | 9.50 | W/B | 10.19 | 1 | −1.16 |
| | | 2 | 9.74 | | | 2 | −0.59 |
| | | 3 | 9.62 | | | 3 | −1.15 |
| A/B | 40.47* | 1 | 10.29 | A/B (e) | 31.50 | 1 | −0.77 |
| | | 2 | 9.59 | | | 2 | −0.93 |
| | | 3 | 8.98 | | | 3 | −1.20 |

Notes: (1) a denotes the experimental factor. (2) b denotes the degree of contribution (%). (3) c denotes the level of variation. (4) d denotes the response value. (5) S/B denotes the weight ratio of slag-to-binders. (6) P/B denotes the weight ratio of Polymer SP-to-binders. (7) W/B denotes the weight ratio of mixing water-to-binders. (8) A/B denotes the weight ratio of incinerator fly ash-to-binders. (9) (e) denotes the error term.

[a] denotes a level of significance of 5%.

*(2) Sample group*

Results of ANOVA have indicated that S/B and A/B are the controlling parameters in this case (see Table 24). The degrees of contribution for these two experimental factors are 52.05% and 40.47%, respectively. They both have a significance level of 5%. RA results have also shown that the greater the S/B and A/B are, the lower the ANC value will be. This finding is reasonable and self-explanatory.

*(3) ANC differences between the sample group and control group*

Like in the case of replacement of cement by slag, no controlling parameter can be determined in this case (see Table 24). Although the degree of contribution for the experimental factor S/B is 50.55%, its probability of having Type I error is greater than 5% anyhow.

## 4. Conclusions

In this work, analysis of variance and regular analysis were employed for determining the controlling parameters for various properties of solidified monoliths of a municipal incinerator fly ash. The solidification treatment was carried out in four different manners: (1) by Type I portland cement alone, (2) by partially replacing cement with slag, (3) by adding a polymer to cement paste, and (4) by partially replacing cement with slag and adding a polymer simultaneously. The properties of solidified monoliths of interest are unconfined compressive strength (UCS), TCLP

Table 25
Controlling paramaters for various physicochemical properties of monoliths of MSW incinerator fly ash solidified by a partial replacement of cement by slag

| | Controlling parameter(s) | | |
|---|---|---|---|
| | UCS | TCLP leaching toxicity | ANC |
| Control group | W/B (primary)<br>A/B (secondary) | None | None |
| Sample group | W/B (primary)<br>A/B (secondary)<br>S/B (secondary) | S/B for leached Zn | S/B |
| Difference between two groups | None | None | None |

Notes: (1) UCS denotes the unconfined compressive strength. (2) ANC denotes the acid neutralization capacity. (3) Control group denotes specimens solidified by ASTM Type I portland cement alone. (4) Sample group denotes specimens solidified by cement and a partial replacement of cement by water-quenched blast furnace slag. (5) A/B denotes the weight ratio of incinerator fly ash-to-binder(s). (6) S/B denotes the weight ratio of slag-to-binder(s). (7) W/B denotes the weight ratio of mixing water-to-binder(s).

Table 26
Controlling paramaters for various physicochemical properties of monoliths of MSW incinerator fly ash solidified by an addtion of Polymer SP to cement paste

| | Controlling parameter(s) | | |
|---|---|---|---|
| | UCS | TCLP leaching toxicity | ANC |
| Control group | W/B (primary)<br>A/B (secondary) | None | None |
| Sample group | W/B (primary)<br>A/B (secondary) | W/B for leached Zn | None |
| Difference between two groups | None | None | None |

Notes: (1) UCS denotes the unconfined compressive strength. (2) ANC denotes the acid neutralization capacity. (3) Control group denotes specimens solidified by ASTM Type I portland cement alone. (4) Sample group denotes specimens solidified by cement and an addition of Polymer SP to cement paste. (5) A/B denotes the weight ratio of incinerator fly ash-to-binder(s). (6) W/B denotes the weight ratio of mixing water-to-binder(s).

Table 27
Controlling paramaters for various physicochemical properties of monoliths of MSW incinerator fly ash solidified concurrently by a partial replacement of cement by slag and an addtion of Polymer SP to cement

| | Controlling parameter(s) | | |
|---|---|---|---|
| | UCS | TCLP leaching toxicity | ANC |
| Control group | W/B (primary)<br>A/B (secondary) | None | None |
| Sample group | W/B | A/B and W/B for leached Zn<br>A/B and S/B for leached pHs | S/B and A/B |
| Difference between two groups | S/B | None | None |

Notes: (1) UCS denotes the unconfined compressive strength. (2) ANC denotes the acid neutralization capacity. (3) Control group denotes specimens solidified by ASTM Type I portland cement alone. (4) Sample group denotes specimens solidified concurrently by cement and a partial replacement of cement by water-quenched blast furnace slag and an addition of Polymer SP. (5) A/B denotes the weight ratio of incinerator fly ash-to-binder(s). (6) S/B denotes the weight ratio of slag-to-binder(s). (7) W/B denotes the weight ratio of mixing water-to-binder(s).

leaching toxicity (LETOX), and acid neutralization capacity (ANC). The primary, and secondary if any, parameter(s) controlling these properties are summarized in Tables 25–27 for each of different solidification manners.

In general, findings of Part II research are in agreement with that of Part I of the research. Furthermore, from the results shown in Tables 25–27, the following conclusions can be drawn:

(1) The controlling parameters for various properties of monoliths solidified in different manners differ. Coexistence of a slag and a polymer in solidified specimens would result in controlling parameters, which are different from that of with a slag or a polymer alone.

(2) The weight ratio of mixing water-to-binder(s) is the most important parameter governing the development of unconfined compressive strength of monoliths of municipal incinerator fly ash regardless of their solidification manner. This is in good agreement with Abrams' law. In addition to UCS, this parameter is also significant in affecting the LETOX of solidified specimens.

(3) The weight ratio of slag-to-binders is a controlling parameter for ANC of solidified specimens when involving a partial replacement of cement by slag. This is due to a lower pH value of slag than that of Type I portland cement. In fact, this nature has been found to be of importance in terms of LETOX.

(4) The weight ratio of municipal incinerator fly ash-to-binder(s) has been found to be an important parameter in UCS, LETOX, and ANC of various solidified specimens. It is postulated that the porous nature, water sorption capacity, and pH of the incinerator fly ash are responsible for this finding. Further studies in this regard deem to be worth the effort.

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## References

[1] G.C.C. Yang, Res. Conserv. Recyc., 13 (1995) 15.
[2] C.T. Liaw, in: Proc. Conf. on Incinerator Ash Treatment Technology, Hsinchu, Taiwan, 1993, p. 3.1 (in Chinese).
[3] P. Cote, in: T.T. Eighmy and W.H. Chesner (Eds.), Proc. 1st Internat. Conf. on Municipal Solid Waste Combustor Ash Utilization, Philadelphia, PA, 1988, p. 171.
[4] W.F. Yang and M.S. Lee, Bull. Chinese Inst. Environ. Eng., 1 (1990) 52 (in Chinese).
[5] R.A. Dension and J. Ruston (Eds.), Recycling and Incineration – Evaluating the Choices, Island Press, Washington, DC, 1990, p. 177.
[6] W.M. Shaub, in: R. Clement and R. Kagel (Eds.), Emissions from Combustion Processes – Origin, Measurement, Control, Lewis Publisher, Chelsea, MI, 1990, p. 183.
[7] Y. Gong and D.W. Kirk, J. Hazard. Mater., 36 (1994) 249.
[8] G.C.C. Yang and S.Y. Chen, J. Hazard. Mater., 39 (1994) 317.
[9] Y.Y. Wu, Experimental Design Methods, 3rd edn., Chunghsing Management Consulting Co., Taipei, Taiwan, 1988 (in Chinese).
[10] C.N. Chang et al. (translators), Introduction to Quality Engineering by the Taguchi Method, ROC Quality Control Institute, Taipei, Taiwan, 1991 (in Chinese).
[11] ROC National Bureau of Standards, Laboratory Method for Making and Curing Concrete Test Specimens, CNS 1230 A3043, 1985 (in Chinese).

[12] ROC National Bureau of Standards, Method of Test for Compressive Strength of Cylindrical Concrete Specimens, CNS 1232 A3045, 1982 (in Chinese).
[13] US EPA, Toxicity Characteristic Leaching Procedure (TCLP), Method 1311, Test Methods for Evaluating Solid Waste, SW-846, 4th edn., 1990.
[14] Environment Canada and Alberta Environmental Centre, Acid Neutralization Capacity, Method No. 7, Test Methods for Solidified Waste Characterization, 1986.
[15] I. Soroka, Portland Cement Paste and Concrete, Chemical Publishing Co., New York, 1980, pp. 205–208.