ELSEVIER
Journal of Hazardous Materials 39 (1994) 317–333
JOURNAL OF HAZARDOUS MATERIALS

Statistical analyses of control parameters for physicochemical properties of solidified incinerator fly ash of municipal solid wastes

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

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

Received 5 February 1994; accepted in revised form 11 June 1994

Abstract

In this work, statistical analyses of control parameters for various physical and chemical properties of solidified incinerator fly ash of municipal solid wastes were conducted. Fly ash obtained from a domestic garbage incinerator was solidified by a cement-based technique. The solidification recipes employed were following the L_9 orthogonal arrays of the Taguchi method. ASTM Type I portland cement, mixing water, incinerator fly ash, and partial replacement of cement by water-quenched blast furnace slag or addition of a modified lignosulphonate to cement paste were used as experimental factors accompanied by three levels of variation for each experimental factor. Experimental results showed that solidification indeed yielded solidified monoliths with satisfactory physicochemical properties such as unconfined compressive strength, TCLP leaching toxicity, and acid neutralization capacity. These measured values of various properties then were subjected to the variance analysis for determining the respective degree of contribution for each experimental factor and the regular analysis for determining the response value for each corresponding variation level. The findings are discussed in this paper.

1. Introduction

The quantity of municipal solid wastes (MSW) generated in Taiwan has greatly increased during the past decade. In 1990, the amount of MSW generated was 18 750 metric tons per day representing an increase of 115% in ten years since 1980 [1]. A 10% increase of MSW quantity for the year of 1992 compared with that of 1991 was also reported [2]. On the per capita basis, the MSW generation rates were 0.78, 0.82, and 1.0 kg/day in 1987, 1988, and 1991, respectively [1, 3]. It was estimated that 1.09 kg/day per capita of MSW was generated in 1992 in Taiwan area; 1.28 kg/day per capita in Taipei City; and 1.13 kg/day per capita in Kaohsiung City [2]. Up to now,

*Corresponding author.

0304-3894/94/$07.00
SSDI 0304-3894(94)00072-O

landfilling is still the most common disposal method used in Taiwan. A majority of existing sanitary landfills in Taiwan, however, will reach their maximum capacities in a couple of years. Furthermore, new landfill sites are difficult to obtain due to the objection of the public (i.e., NIMBY syndrome). At the time of preparation of this manuscript, there are only two large-capacity MSW incinerators in operation in Taiwan. To alleviate the disposal problem of MSW, there will be additional 21 MSW incinerators built and operated in Taiwan in the next few years. At that time, about 645 000–1290 000 metric tons of incinerator ash (fly ash and bottom ash collectively) will be generated every year in Taiwan [4].

Incineration per se is only an intermediate waste treatment technology. Ash resulting from MSW incineration still needs an appropriate ultimate disposal. Previous investigations have indicated that MSW incinerator fly ash is hazardous [4, 5]. If the incinerator fly ash is improperly disposed of, it would result in soil and groundwater contamination due to the leaching of heavy metals (e.g., lead, zinc, cadmium, etc.) and organic hazardous constituents like dioxins and furans. One common way to mitigate this problem is to solidify and/or to stabilize the incinerator fly ash before it is landfilled.

In this investigation, control parameters for various physicochemical properties of solidified MSW incinerator fly ash will be analyzed from a statistical viewpoint. The variance analysis will be employed for determining the degree of contribution for each experimental factor [6]. By doing so, control parameters for values of unconfined compressive strength, TCLP leaching toxicity, and acid neutralization capacity of solidified specimens can be identified. On the other hand, the regular analysis will be used for determining the response value of each variation level for each control parameter [7].

2. Experimental

2.1. Materials

The fly ash sample studied in this work was obtained from an MSW incinerator located in northern Taiwan. The major binder used for solidification treatment of the incinerator fly ash was ASTM Type I portland cement. Water-quenched blast furnace slag of 5000 Blaine was used to partially replace portland cement. The powdered slag was generously provided by China Hi-Ment Corporation in Kaohsiung City, Taiwan. A modified lignosulphonate (designated Polymer SP) was used as an additive to portland cement. Polymer SP, a high range water-reducing agent, was categorized as a Type F chemical admixture of ASTM C 494-86. The sample of Polymer SP was provided by an anonymous, generous firm in Kaohsiung City.

All chemicals used in this investigation were all reagent grades. Water used was ASTM Type I deionized water.

2.2. Experimental design

In this work, the solidification recipes employed were following the L_9 orthogonal arrays based on the Taguchi method [6, 7]. The experimental factors adopted

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.	Solidification recipe			
	Slag	Cement	Mixing water	Incinerator fly ash
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	Slag (g)	Cement (g)	Mixing water (g)	Incinerator fly ash (g)
1	240	360	510	400
2	100	400	530	600
3	50	450	560	800

included weights of portland cement, mixing water, incinerator fly ash, and cement replaced by slag or Polymer SP addition to cement paste. Each experimental factor had three levels of variation. Detailed solidification recipes are shown in Tables 1 and 2.

2.3. *Methods*

The incinerator fly ash specimen was first characterized using various standard methods adopted by ROC EPA and US EPA [8, 9]. The determined properties included total contents of heavy metals, pH, and acid neutralization capacity [10]. Particle size distribution was carried out by a sieve analysis. The loss on ignition was determined by a method described in ASTM C 114. The leaching toxicity was determined by TCLP test and atomic absorption spectroscopy (AAS).

Making and curing of solidified specimens were conducted according to CNS 1230 A3043. In this work, PVC molds of cylindrical shape (5 mm × 100 mm; d × h) were used for all test specimens. The mixing of binder(s), water, and waste was conducted in an electrically driven mechanical mixer of the epicylic type, which imparts both a planetary and a revolving motion to the mixer paddle. Measurements of unconfined compressive strength of solidified monoliths were following CNS 1232 A3045. The leaching toxicity of each solidified specimen was determined by TCLP test and AAS. A chemical property also determined for solidified specimens was acid neutralization capacity [10].

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

Solidified monolith No.	Solidification recipe			
	Polymer SP	Cement	Mixing water	Incinerator fly ash
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	Polymer SP (g)	Cement (g)	Mixing water (g)	Incinerator fly ash (g)
1	8	450	550	400
2	5	550	600	600
3	2	650	650	800

3. Results and discussion

3.1. Characterization of MSW incinerator fly ash

Physical and chemical properties of the MSW incinerator fly ash studied in this work were found to be as follows: (1) total contents of heavy metals (mg/kg): zinc, 9150; cadmium, 640; lead, 1510; and copper, 1780, (2) pH: 9.85, (3) acid neutralization capacity: see Fig. 1, (4) loss on ignition: 24.01%, (5) particle size distribution: < 45 μm, 23.95 wt%; 45–53 μm, 7.25 wt%; 53–75 μm, 12.15 wt%; 75–106 μm, 12.37 wt%; 106–125 μm, 5.05 wt%; 125–150 μm, 6.26 wt%; 150–212 μm, 9.64 wt%; 212–425 μm, 17.93 wt%; > 425 μm, 5.40 wt%, (6) heavy metal concentrations of the TCLP leachate (mg/l): zinc, 38.5; cadmium, 5.1; lead, < 0.2 and copper, 11.2. The current ROC EPA regulatory thresholds for leaching toxicity of zinc, cadmium, lead, and copper are 25.0, 0.5, 5.0, and 15.0 mg/l, respectively. The MSW incinerator fly ash studied in this work is thus identified as a hazardous waste. This finding is in good agreement with previous studies [4, 5]. Solidification or other treatment of this waste is inevitably needed before its final disposal.

3.2. Unconfined compressive strengths (UCS) of solidified specimens

3.2.1. Replacement of cement by slag

Results of UCS measurements are shown in Table 3. In this table, the term "sample group" denotes the solidified specimens with partial replacements of portland cement

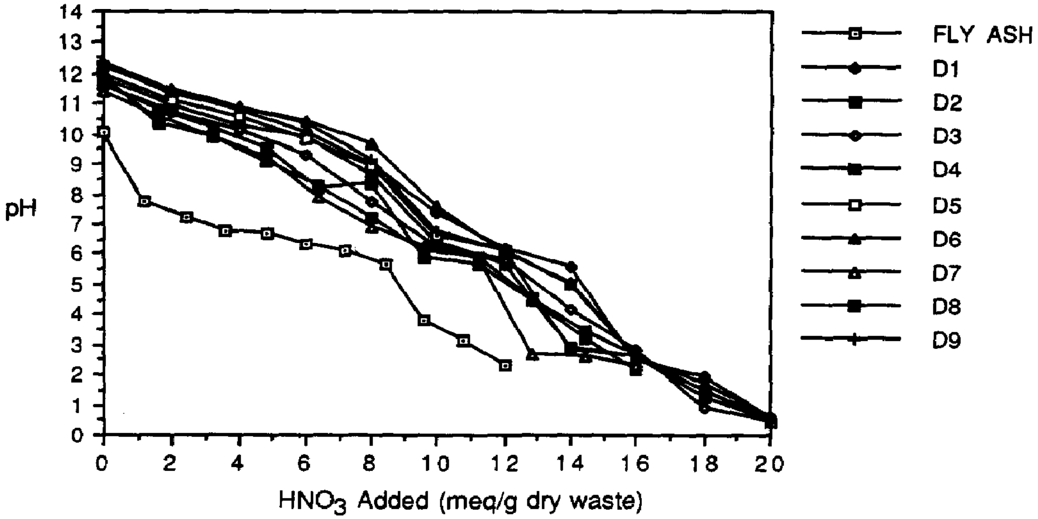

Fig. 1. Comparison of acid neutralization capacity for untreated MSW incinerator fly ash and solidified specimens (D*n*) in control group.

Table 3
Unconfined compressive strengths of solidified 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 (D*n*)[a]	Sample group (C*n*)[b]	Difference[c]
1	154.15	191.63	37.48
2	199.47	265.43	65.96
3	238.43	249.83	10.95
4	109.92	185.13	75.21
5	41.93	53.65	11.72
6	155.59	173.08	17.49
7	48.64	55.85	7.21
8	163.99	193.87	29.88
9	67.87	71.47	3.60

[a] Control group denotes specimens solidified only by Type I portland cement.
[b] Sample group denotes specimens solidified by cement with a partial replacement by water-quenched blast furnace slag.
[c] Difference = C*n* − D*n*.

by slag; whereas "control group" denotes the specimens solidified solely by portland cement. It was found that UCS values of specimens in sample group were greater than UCS values of corresponding specimens in control group. Besides, all UCS values in control group and sample group were found to be greater than the current ROC EPA regulatory requirement for landfilling solidified wastes (i.e. 10 kg/cm^2).

Table 4
Degrees of contribution and response values for unconfined compressive strengths of solidified incinerator fly ash specimens at an age of 28 days (replacement of cement by slag)

UCS values of sample group				UCS differences between sample group and control group			
A	B	C	D	A	B	C	D
a	49.75	1	235.63	a	7.17	1	38.13
		2	137.29			2	34.81
		3	107.06			3	13.56
b	6.79	1	144.20	b	15.28	1	40.00
		2	170.98			2	35.85
		3	164.79			3	10.68
c	14.39	1	186.19	c	28.00	1	28.28
		2	174.01			2	48.26
		3	119.78			3	9.96
d	29.07	1	105.58	d	49.55	1	17.60
		2	164.79			2	30.22
		3	209.61			3	38.68

A denotes the experimental factor; B denotes the degree of contribution (%); C denotes the level of variation; D denotes the response value; a denotes water-quenched blast furnace slag; b denotes ASTM Type I portland cement; c denotes mixing water; d denotes MSW incinerator fly ash.

Table 4 shows the results of statistical analyses of UCS values of sample group with respect to each experimental factor. In this table, degrees of contribution were determined by the variance analysis, whereas response values by the regular analysis. From Table 4, it is clear that water-quenched BF slag has the largest degree of contribution (49.75%) for UCS values among the sample group. The response values for slag indicate that (variation level 1) > (variation level 2) > (variation level 3). That is, under the experimental conditions used in this study, the greater the amount of cement replacement by slag, the greater the response value. More specifically, the more the cement is replaced by slag, the greater will be the UCS value. A similar observation was also found for incinerator fly ash, which yielded a degree of contribution of 29.07%. The greater the amount of incinerator fly ash solidified, the greater the response value, and in turn, the greater the UCS value, provided that other experimental factors are kept constant.

Also shown in Table 4 are the results of statistical analyses of UCS differences between sample group and control group with respect to each experimental factor. Here, incinerator fly ash was found to have the greatest degree of contribution (49.55%). The greater the amount of incinerator fly ash in a solidified monolith, the greater the positive effect of UCS enhancement. The reason for this finding is not clear at this point. In this study, however, it was observed that incinerator fly ash had a great capacity of water adsorption during the mixing stage of preparing the

Table 5
Unconfined compressive strengths of solidified incinerator fly ash specimens at an age of 28 days (addition of polymer to cement)

Solidified monolith No.	Unconfined compressive strength (kg/cm^2)		
	Control group (H*n*)[a]	Sample group (E*n*)[b]	Difference[c]
1	48.64	58.23	9.59
2	102.11	130.97	28.86
3	122.10	169.51	47.41
4	100.60	111.54	10.94
5	34.89	51.10	16.21
6	167.43	216.71	49.28
7	51.69	54.66	2.97
8	167.43	204.65	37.22
9	82.76	101.77	19.01

[a] Control group denotes specimens solidified only by Type I portland cement.
[b] Sample group denotes specimens solidified by cement with an addition of Polymer SP to cement paste.
[c] Difference = E*n* − H*n*.

solidified monoliths. Whether this phenomenon of water adsorption would lower the water- to-binders ratio and result in a greater UCS (i.e. Abrams' law) is worth studying further. As for slag, it gave rise to the smallest degree of contribution. This may be due to the fact that normally slag has a much longer UCS development time (ca. 90 d or even longer) versus 28 for ordinary portland cement. Therefore, replacement of cement by slag did not give rise to a significant contribution to the UCS differences. However, this negative effect of slow UCS development has been largely cancelled out in the case of UCS values among the sample group.

3.2.2. Addition of Polymer SP to cement

Results of UCS measurements of solidified monoliths modified by Polymer SP are shown in Table 5. Like in the case of cement replacement by slag, the UCS values of sample group are greater than that of control group. In other words, an addition of Polymer SP to cement paste would yield a greater UCS for a solidified monolith.

Like Table 4, Table 6 shows the results of statistical analyses of UCS values of sample group with respect to each experimental factor. Incinerator fly ash was found to have the greatest degree of contribution (40.67%) for UCS values among the sample group. The response values for incinerator fly ash indicate that (variation level 3) > (variation level 2) > (variation level 1). Namely, under the experimental conditions employed, the greater the amount of incinerator fly ash treated, the greater the UCS value of a solidified monolith. Among the sample group, Polymer SP has the least degree of contribution (i.e., 1.05%) for UCS values. This is understandable because the weight percentage of Polymer SP added in this study is very small, ranging from 0.10 wt% to 0.57 wt% of total mix. Any positive effect on UCS due to

Table 6
Degrees of contribution and response values for unconfined compressive strengths of solidified incinerator fly ash specimens at an age of 28 days (addition of polymer to cement)

UCS values of sample group				UCS differences between sample group and control group			
A	B	C	D	A	B	C	D
a	1.05	1	119.57	a	21.30	1	28.62
		2	126.45			2	25.48
		3	120.36			3	19.73
b	36.24	1	74.81	b	58.16	1	7.83
		2	128.91			2	27.43
		3	162.66			3	38.57
c	22.04	1	159.86	c	5.94	1	32.03
		2	114.76			2	19.60
		3	91.76			3	22.60
d	40.67	1	70.37	d	14.60	1	14.94
		2	134.11			2	27.04
		3	161.90			3	31.86

A denotes the experimental factor; B denotes the degree of contribution (%); C denotes the level of variation; D denotes the response value; a denotes Polymer SP; b denotes ASTM Type I portland cement; c denotes mixing water; d denotes MSW incinerator fly ash.

the addition of Polymer SP has been largely cancelled out among the sample group. The reason for the large degree of contribution resulting from incinerator fly ash, as indicated above, remains uncertain.

Table 6 also shows the results of statistical analyses of UCS differences between sample group and control group with respect to each experimental factor. Here, degrees of contribution for all experimental factors are: portland cement (58.16%) > polymer SP (21.30%) > incinerator fly ash (14.60%) > mixing water (5.94%). Accordingly, addition of Polymer SP to cement paste would give rise to a positive effect on UCS development. Results of response values also indicate that the greater amount the Polymer SP added to the cement paste is, the greater the positive effect will be. We also noted that the more the cement is used, the greater is the UCS value for a solidified monolith.

3.3. TCLP leaching toxicity of solidified specimens

3.3.1. Replacement of cement by slag

Concentrations of zinc and cadmium and pH values for TCLP leachates of solidified specimens listed in Table 2 are shown in Table 7. It is clear that all leached concentrations for regulated heavy metals are below the current ROC EPA regulatory thresholds. It was noted that solidification treatment of incinerator fly ash by portland cement alone would be good enough to reduce the leaching of heavy metals. Effects of

Table 7
Heavy-metal concentrations and pHs of TCLP leachates of solidified incinerator fly ash specimens at an age of 28 days (replacement of cement by slag)

Solidified monolith No.	Control group (D*n*)[a]			Sample group (C*n*)[b]		
	Zn conc. (mg/l)	Cd conc. (mg/l)	pH	Zn conc. (mg/l)	Cd conc. (mg/l)	pH
1	0.105	0.005	11.91	0.077	0.006	10.34
2	0.089	0.009	11.53	0.183	0.012	9.93
3	0.110	0.009	11.29	0.154	0.014	10.05
4	0.089	0.007	11.07	0.078	0.011	9.86
5	0.070	0.020	11.65	0.083	0.006	11.05
6	0.090	0.011	11.42	0.070	0.014	10.96
7	0.302	0.017	11.35	0.127	0.008	10.97
8	0.056	0.010	10.04	0.167	0.016	10.71
9	0.233	0.026	11.46	0.144	0.012	11.53

[a] Control group denotes specimens solidified only by Type I portland cement.
[b] Sample group denotes specimens solidified by cement with a partial replacement of cement by water-quenched blast furnace slag.

cement replacement by slag may not necessarily be noticeable. As indicated above, the loss on ignition (LOI) of incinerator fly ash is as high as 24.01%. (Normally, an acceptable level of LOI for incinerator fly ash is less than 5%.) In other words, about one-quarter of the materials within incinerator fly ash is not burnt out during the combustion process. That is, the incinerator fly ash studied contains a high content of carbonaceous materials. Previous investigations have shown that the pore structure of incinerator fly ash provides many good surface sites for physical adsorption and chemisorption of polycyclic aromatic hydrocarbons (PAHs). Besides, extents of physicochemical sorption of PAHs on incinerator fly ash are highly dependent upon the content of elemental carbon [11–13]. It is speculated that carbonaceous materials within incinerator fly ash might have adsorption/absorption effects on heavy metals as well. If that is the case, it would explain why portland cement alone is able to stabilize heavy metals of concern in a satisfactory manner. pH values of leachates for sample group were found to be lower than that of control group. This may be due to that the pH value of slag (i.e. 11.14) is lower than that of cement (i.e. pH = 12.53).

Table 8 shows the results of the variance analysis and the regular analysis for zinc and cadmium concentrations and pH values of TCLP leachates among the sample group. It was noted that cement replacement by slag gave rise to the greatest contribution for leached concentrations of zinc. The reason is not known. As for leached concentrations of cadmium, only incinerator fly ash was controlling. Response values also show that the greater the amount of incinerator fly ash in a solidified monolith, the greater the leached concentration of cadmium. Among the experimental factors of concern, the amount of cement replacement by slag was found

Table 8
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 sample group (replacement of cement by slag)

Zinc concentration				Cadmium concentration				pH			
A	B	C	D	A	B	C	D	A	B	C	D
a	46.38	1	0.138	a	0	1	0.011	a	47.14	1	10.11
		2	0.077			2	0.010			2	10.62
		3	0.146			3	0.012			3	11.07
b	15.80	1	0.094	b	0	1	0.008	b	7.49	1	10.39
		2	0.144			2	0.011			2	10.56
		3	0.123			3	0.013			3	10.85
c	35.87	1	0.105	c	0	1	0.012	c	17.08	1	10.67
		2	0.135			2	0.012			2	10.44
		3	0.121			3	0.009			3	10.69
d	1.94	1	0.101	d	100	1	0.008	d	28.30	1	10.97
		2	0.127			2	0.011			2	10.62
		3	0.133			3	0.013			3	10.21

A denotes the experimental factor; B denotes the degree of contribution (%); C denotes the level of variation; D denotes the response value; a denotes water-quenched blast furnace slag; b denotes ASTM Type I portland cement; c denotes mixing water; d denotes MSW incinerator fly ash.

to have the greatest degree of contribution for pH values of TCLP leachates. Response values indicate that the lesser the amount of cement replacement by slag is, the higher will be the pH of TCLP leachate. This finding is in good agreement with the fact that the pH of slag is lower than that of cement. Since the differences of leaching toxicity between sample group and control group are trivial (see Table 7), they are not subjected to further analysis.

3.3.2. *Addition of Polymer SP to cement*

Like in the case of cement replacement by slag, an addition of Polymer SP would not yield pronounced effects on leaching toxicity of solidified monoliths and pH values of TCLP leachates (see Table 9). Again, this might be due to the fact that solidification of incinerator fly ash by portland cement alone would be more than satisfactory in this regard. Results of statistical analyses of leaching toxicity of sample group with respect to each experimental factor are shown in Table 10. Due to the fact that the error term plays a significant role in degree of contribution (see Table 10), it is not possible to determine which experimental factor is controlling the leaching toxicity. As for pH values of TCLP leachates, incinerator fly ash has the greatest degree of contribution. The reasoning is not known. Like in the case of replacement of cement by slag, the differences of leaching toxicity between sample group and control group are not worth analyzing.

Table 9
Heavy-metal concentrations and pHs of TCLP leachates of solidified incinerator fly ash specimens at an age of 28 days (addition of polymer to cement)

Solidified monolith No.	Control group (H*n*)[a]			Sample group (E*n*)[b]		
	Zn conc. (mg/l)	Cd conc. (mg/l)	pH	Zn conc. (mg/l)	Cd conc. (mg/l)	pH
1	0.070	0.011	11.57	0.073	0.013	11.86
2	0.062	0.002	11.47	0.053	0.014	11.73
3	0.053	0.025	10.95	0.062	0.011	11.65
4	0.151	0.013	11.03	0.047	0.007	11.39
5	0.055	0.011	11.75	0.065	0.014	11.96
6	0.054	0.013	11.38	0.086	0.011	11.82
7	0.026	0.018	11.40	0.082	0.005	11.53
8	0.048	0.015	10.74	0.061	0.016	11.32
9	0.057	0.010	11.83	0.061	0.013	11.90

[a] Control group denotes specimens solidified only by Type I portland cement.
[b] Sample group denotes specimens solidified by cement with an addition of polymer SP to cement paste.

Table 10
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 sample group (addition of polymer to cement)

Zinc concentration				Cadmium concentration				pH			
A	B[a]	C	D	A	B[b]	C	D	A	B	C	D
a	0	1	0.063	a	0	1	0.013	a	10.28	1	11.75
		2	0.066			2	0.011			2	11.72
		3	0.068			3	0.011			3	11.58
b	0	1	0.067	b	36.95	1	0.008	b	13.18	1	11.59
		2	0.060			2	0.015			2	11.67
		3	0.070			3	0.013			3	11.79
c	42.48	1	0.073	c	0	1	0.013	c	3.66	1	11.67
		2	0.054			2	0.011			2	11.67
		3	0.070			3	0.010			3	11.71
d	25.56	1	0.066	d	0	1	0.013	d	72.88	1	11.91
		2	0.074			2	0.010			2	11.69
		3	0.057			3	0.011			3	11.45

A denotes the experimental factor; B denotes the degree of contribution (%); C denotes the level of variation; D denotes the response value; a denotes Polymer SP; b denotes ASTM Type I portland cement; c denotes mixing water; d denotes MSW incinerator fly ash;
[a] Degree of contribution for the error term is 31.96%.
[b] Degree of contribution for the error term is 63.05%.

Table 11
Acid neutralization capacities of solidified incinerator fly ash specimens at an age of 28 days (replacement of cement by slag)

Solidified monolith No.	Acid neutralization capacity[a] (2 N HNO_3 added, milliequivalent/g dry waste)		
	Control group (D*n*)[b]	Sample group (C*n*)[c]	Difference[d]
1	10.65	8.44	− 2.21
2	9.47	7.57	− 1.90
3	9.00	8.56	− 0.44
4	8.89	7.89	− 1.00
5	9.66	7.74	− 1.92
6	10.76	8.66	− 2.10
7	7.92	7.73	− 0.19
8	8.31	7.76	− 0.55
9	9.78	9.41	− 0.37

[a] pH = 7 is the basis for ANC comparison.
[b] Control group denotes specimens solidified only by Type I portland cement.
[c] Sample group denotes specimens solidified by cement with a partial replacement by water-quenched blast furnace slag.
[d] Difference = C*n* − D*n*.

3.4. *Acid neutralization capacities (ANC) of solidified specimens*

ANC test, generally, is used for determining the buffering capacity of a waste or its solidified specimen under the attack of an acidic solution. pH value of 7 is commonly used as a basis for determining the amount of a specific acid (e.g., nitric acid) required to lower the pH of a test specimen to pH = 7 [14]. Fig. 1 shows a comparison of ANC for untreated incinerator fly ash and specimens of incinerator fly ash solidified with portland cement alone using various solidification recipes (control group D*n*). It is obvious that solidified specimens have higher acid neutralization capacities than does untreated incinerator fly ash. This is an expected result because ordinary portland cement has a pH of 12.53, while incinerator fly ash has a lower pH of 9.85, as reported above.

3.4.1. *Replacement of cement by slag*

Results of ANC test show that specimens in sample group have lower ANC values than that of control group, as evidenced by the negative values of ANC difference shown in Table 11. This is ascribed to the fact that portland cement is partly replaced by slag resulting in lower pH and ANC values for specimens in sample group. However, any solidified specimen in sample group still has a greater acid neutralization capacity than does untreated incinerator fly ash, as shown in Fig. 2.

Table 12 shows the results of statistical analyses of ANC values of sample group with respect to each experimental factor. It is not surprising to find that ordinary

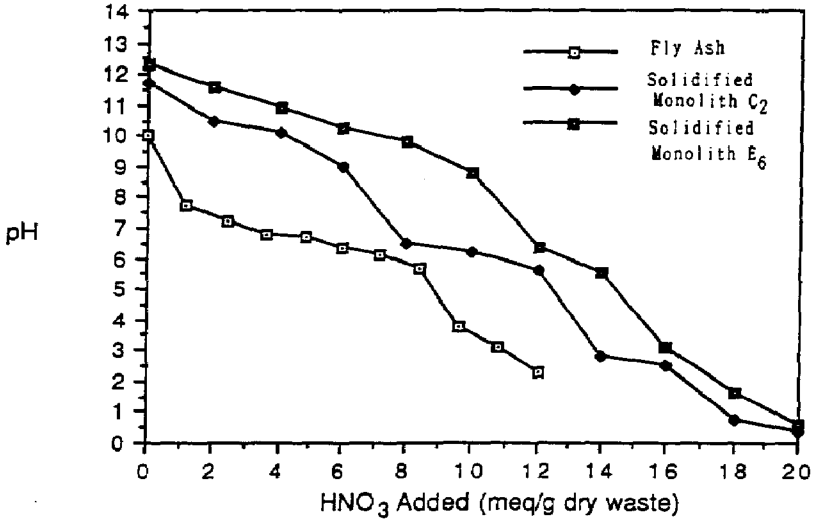

Fig. 2. Comparison of acid neutralization capacity for untreated MSW incinerator fly ash and solidified specimens (C_2 and E_6) in sample group.

Table 12
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 sample group				ANC differences between sample group and control group			
A	B	C	D	A	B	C	D
a	8.34	1	8.19	a	47.80	1	– 1.52
		2	8.10			2	– 1.67
		3	8.30			3	– 0.37
b	73.40	1	8.02	b	26.36	1	– 1.13
		2	7.69			2	– 1.46
		3	8.88			3	– 0.97
c	3.11	1	8.29	c	10.08	1	– 1.62
		2	8.29			2	– 1.09
		3	8.01			3	– 0.85
d	15.15	1	8.53	d	15.76	1	– 1.50
		2	7.99			2	– 1.40
		3	8.07			3	– 0.66

A denotes the experimental factor; B denotes the degree of contribution (%); C denotes the level of variation; D denotes the response value; a denotes water-quenched blast furnace slag; b denotes ASTM Type I portland cement; c denotes mixing water; d denotes MSW incinerator fly ash.

Table 13
Acid neutralization capacities of solidified incinerator fly ash specimens at an age of 28 days (addition of polymer to cement)

Solidified monolith No.	Acid neutralization capacity[a] (2 N HNO_3 added, milliequivalent/g dry waste)		
	Control group (Hn)[b]	Sample group (En)[c]	Difference[d]
1	9.34	11.18	1.84
2	9.42	9.62	0.20
3	9.16	9.32	0.16
4	10.07	7.75	− 2.32
5	11.58	11.50	− 0.08
6	11.28	11.46	0.18
7	9.60	9.60	0.00
8	9.57	10.56	0.99
9	12.92	10.69	− 2.23

[a] pH = 7 is the basis for ANC comparison.
[b] Control group denotes specimens solidified only by Type I portland cement.
[c] Sample group denotes specimens solidified by cement with an addition of Polymer SP to cement paste.
[d] Difference = En − Hn.

portland cement has the highest contribution (73.40%), followed by a figure of 15.15% for incinerator fly ash. As for ANC differences between sample group and control group, slag has the greatest contribution. Again, this finding points out that cement replacement by slag would lower the ANC of the solidified specimen. Results of response values show that (variation level 3) > (variation level 2) $\approx$ (variation level 1). Namely, the greater the amount of cement replaced by slag is, the lower will be the ANC of the solidified specimen. This is in good agreement with the fact that slag has a lower pH than cement.

3.4.2. Addition of Polymer SP to cement

From Table 13, it was found that addition of Polymer SP to cement paste would not give rise to a markedly positive effect on ANC. Some values of ANC differences between sample group and control group are positive and some are negative. Therefore, it is not appropriate to conduct statistical analyses based on ANC differences, particularly based on negative values. Consequently, Table 14 shows only the results of the variance analysis and the regular analysis for ANC values among the sample group with respect to each experimental factor. Incinerator fly ash was found to have the greatest contribution (44.69%), whereas polymer addition has the smallest (3.31%). Results of response values also indicate that the smaller the treated amount of incinerator fly ash is, the greater will be the ANC of the solidified specimen. This should be related to the fact that ordinary portland cement has a higher pH than that of incinerator fly ash.

Table 14
Degrees of contribution and response values for acid neutralization capacities (ANC) of solidified incinerator fly ash specimens at an age of 28 days for sample group (addition of polymer to cement)

ANC values of sample group			
A	B	C	D
a	3.31	1	10.04
		2	10.04
		3	10.28
b	16.29	1	9.51
		2	10.56
		3	10.49
c	35.71	1	11.07
		2	9.35
		3	10.14
d	44.69	1	11.12
		2	10.23
		3	9.21

A denotes the experimental factor; B denotes the degree of contribution (%); C denotes the level of variation; D denotes the response value; a denotes Polymer SP; b denotes ASTM Type I portland cement; c denotes mixing water; d denotes MSW incinerator fly ash.

4. Conclusions

In this work, statistical analyses of control parameters for various physical and chemical properties of solidified incinerator fly ash of municipal solid wastes were carried out. Solidification recipes are based on the L_9 orthogonal arrays of the Taguchi method using amounts of ordinary portland cement, mixing water, incinerator fly ash, and cement replacement by water-quenched blast furnace slag or addition of Polymer SP to cement as experimental factors. Three levels of variation are associated with each experimental factor. Physicochemical properties investigated include unconfined compressive strength (UCS), TCLP leaching toxicity, and acid neutralization capacity (ANC). Based on the results obtained above, the following conclusions may be drawn:

(1) Replacement of cement by slag or addition of Polymer SP to cement paste would give rise to pronounced, positive effects on unconfined compressive strengths of solidified monoliths of incinerator fly ash, whereas no effect or negative effects on TCLP leaching toxicity and acid neutralization capacity.

(2) Regarding UCS, the most important control parameters are: (i) slag for those among the sample group and incinerator fly ash for differences between sample group and control group in the case of cement replacement by slag; (ii) incinerator fly ash for those among the sample group and portland cement for

differences between sample group and control group in the case of polymer addition to cement paste.

(3) Regarding TCLP leaching toxicity, the most important control parameters among the sample group are: (i) slag for leached zinc concentrations, incinerator fly ash for leached cadmium concentrations, and slag for leachate pHs in the case of cement replacement by slag; (ii) no identified control parameter for leached zinc and cadmium concentrations, but incinerator fly ash for leachate pHs in the case of polymer addition to cement paste.

(4) Regarding ANC, the most important control parameters are: (i) portland cement for those among the sample group and slag for differences between sample group and control group in the case of cement replacement by slag; (ii) incinerator fly ash for those among the sample group and no identified control parameter for differences between sample group and control group in the case of polymer addition to cement paste.

Acknowledgement

This investigation was supported by ROC National Science Council under the Project No. NSC 82-0421-E110-021-Z.

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