

Emission of Pb and PAHs from thermally co-treated MSWI fly ash and bottom ash process

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Abstract

Municipal solid waste incinerator (MSWI) fly ash was regarded as a hazardous material because concentrations of TCLP leaching solution exceeded regulations. Previous studies have investigated the characteristics of thermally treated slag. However, the emissions of pollutant during the thermal treatment of MSWI fly ash have seldom been addressed. The main objective of this study was to evaluate the emission of Pb and PAHs from thermally co-treated MSWI fly and bottom ash process. The experimental parameters included the form of pretreatment, the proportion of bottom ash (bottom ash/fly ash, B/F=0, 0.1 and 1) and the retention time. The toxicity of thermally treated slag was also analyzed.

The results indicated that (1) Pb emission occurred only in the solid phase and that PAHs were emitted from both solid and gas phases during thermal treatment process. (2) Washing pretreatment reduced not only the TCLP leaching concentration of Pb (from 15.75 to 1.67 mg/L), but also the emission of PAHs from the solid phase during thermal treatment process. (3) Adding bottom ash reduced the TCLP leaching concentration of thermally treated slag. (4) The concentration of Pb emission increased with retention time. (5) The thermal treatment reduced the toxicity of raw fly ash effectively, the inhibition ratio of raw fly ash and thermal treated slag were 98.71 and 18.35%, respectively.

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Keywords: MSWI fly ash; PAHs; Emission; Thermally co-treated; Toxicity

1. Introduction

Incineration is a major government-approved method for treating waste material in Taiwan. The Taiwanese government introduces nearly 20 municipal solid waste incinerators (MSWI) to eliminate the waste. During incineration some pollutants are released, and MSWI fly ash is a major one. Since much waste is treated every day, municipal solid waste incinerators produce a great quantity of MSWI fly ash every year. Table 1 lists the total MSWI fly ash and bottom ash produced from 2001 to 2005. The amount of MSWI fly ash produced is approximately 0.83 million tonnes and MSWI bottom ash is about 4.2 million tonnes. In the combustion process, some metal compounds are vaporized at high temperature and condensed on MSWI fly ash at low temperature in an air pollution control

device [1–3]. The toxicity characteristic leaching procedure (TCLP) concentrations of MSWI fly ash are high, especially Pb concentration, that often exceed the levels allowed by Taiwan EPA. Therefore, MSWI fly ash is regarded as hazardous materials and must be treated to avoid damaging the environment.

The major methods of treating MSWI fly ash include melting, solidification/stabilization and sintering [4–8]. Solidification/stabilization often involves the addition of some additives to fix or encapsulate hazardous materials inside agglomerate. In sintering and melting, a high temperature is adopted to remove hazardous metals that are present in the MSWI fly ash. The ash obtained in this process can be used as additive in cement. The emission level of heavy metals depends on the composition of the MSWI fly ash and the thermal treatment conditions of the MSWI fly ash. If metal chlorides and sulfates are present in MSWI fly ash, then these also can be emitted during this process, because of their low boiling point [3,9–14]. The conditions of the thermal treatment also affect the levels of heavy metal emitted [15,16].

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Table 1
MSWI fly ash and bottom ash product of incinerators of Taiwan from 2001 to 2005

Incineration plant	2001		2002		2003		2004		2005	
	F ^a	B ^b	F	B	F	B	F	B	F	B
Neihu	1532.47	8667.86	3706.28	16315.81	3948.15	18739.6	2893.6	13250.37	4453.42	15892.92
Mucha	1471.37	22567.56	4022.58	29523.89	4062.4	25621.17	3658.22	27762.59	2263.71	25999.54
Peitou	0	79671.74	509.24	70510.85	8250.41	39800.93	8936.39	45341.42	6680.14	40503.32
Shulin	8961.94	61338.91	8897.52	57557.31	7829.35	51056.04	7401.58	51887.99	6576.3	48087.44
Hisntien	4505.69	35647.26	5013.9	37770.88	5031.77	38865.8	4693.95	36170.38	4606.54	33139.07
Bali	4926.38	31807.8	14290.14	73642.29	13542.14	70152.76	12516.48	66447.5	12063.7	63595.8
Taoyuan	4106.31	17497.93	21801.6	96505.01	19115.17	78696.03	14408.6	70988.61	14301.1	63681.25
Hsinchu	4757.29	26046.96	6308.5	37987.67	7545.14	39334.48	8238.42	39771.14	6601.46	31663.25
Taichung	6646.32	33612.52	8906.94	34302.84	9504.05	28303.66	7545.98	27699.34	7366.51	27269.57
Houli	11482.16	60497.02	13143.14	52770.24	11425.97	47365.88	8548.48	44958.44	7640.09	48562.09
Wujih	0	0	0	0	0	0	3301.22	15652.62	8906.42	47905.64
Hsichou	15530.67	60635.83	16464.7	46348.13	12915.5	42890.79	7513.19	39530.8	7999.99	42731.12
Lutsao	1320.52	6465.61	13386.57	52584.1	10889.04	50183.77	8751.41	46268.62	8820.23	48889.74
Chiayi	0	11620.1	0	13567.6	1709.11	10954.35	2132.81	9684.59	1783.44	8743.09
Tainan	6056.03	30935.01	7598.5	31488.87	7329.18	32443.44	7269.63	33549.74	5105.66	32339.17
Renwu	9718.04	50321.28	13536.96	70055.29	12766.06	64898.75	12610.2	68457.82	12234.82	67363.2
Kangshan	3776	13135	13564.04	54530.13	16193.32	69137.68	8760.66	52264.41	9493.76	56311.35
Kaohsiung	5479.5	29472.66	6151.38	27984.15	6458	30040.25	6996.95	29938.01	8244.57	31269.65
Kaohsiung South	18692.59	71699.6	20040.79	80438.6	18567.94	73018.16	20362.42	88024.83	17487.85	73903.48
Kandi	7451.47	31491.46	9832.37	36164.12	12511.27	48835.83	12409.95	45649.04	12172.23	56250.25

Source: collected from Taiwan EPA.

^a MSWI fly ash (tonnes/year).

^b MSWI bottom ash (tonnes/year).

In addition to heavy metals, polycyclic aromatic hydrocarbons (PAHs) are also present in MSWI fly ash. The main species of PAHs in MSWI fly ash are low-ring compounds such as naphthalene, acenaphthylene and phenanthrene. Most of PAHs are in the gas phase and very few are present in the slag during the thermal treatment process [17,18]. Some studies have focused on the TCLP concentration in thermally treated slag and evaluated the feasibility of its reuse [19–21]. Some other studies of the conditions of the thermal treatment of MSWI fly ash and heavy metal transformation have been performed. Although considerable research has been done on the reuse of MSWI fly ash. However, very few reports have addressed the emission of PAHs and heavy metals during the thermal treatment process.

The aim of this study is to evaluate the emission of Pb and PAHs from thermally co-treated MSWI fly ash and bottom ash process. Studies focus on the effect of such parameters as retention time, pre-treatment and co-treatment on the emission of Pb and PAHs. The results of Pb and PAHs emission with pre-treatment and without pre-treatment are compared. This study also compares the toxicity of raw fly ash and thermally treated slag.

2. Experiment

2.1. Materials

MSWI fly ash and bottom ash used in this study were collected from a mass-burning incinerator in Taiwan. MSWI fly ash and bottom ash were sieved to make sure that they contained particles of the same size.

2.2. Apparatus

The thermal treatment of fly ash was conducted in the laboratory-constructed apparatus shown in Fig. 1. This apparatus was a pilot-scale rotary kiln reactor whose major components are a thermal chamber (210 cm long with an internal diameter of 9 cm), a control system and a collection system. The thermal chamber was made of steel (AISI 316). The control system had two parts: the temperature control system has two thermocouples and a proportional integral derivative (PID) controller; the other was a rotary kiln speed controller. The thermal chamber used an electrical heater to achieve the desired temperature and the temperature control system adjusted the temperature. The exhaust gas was cleaned using an air pollution control device and released to the atmosphere.

2.3. Experimental procedure

The fly ash collected from MSWI was mixed well and some of the fly ash was washed with distilled water for 3 h with a solid/water ratio of 1/10. Following washing, the solid/water mixture was separated through a glass fiber filter, and the solid part was dried overnight in an oven at 105 °C. This part of the fly ash was classified as the washed fly ash and the remaining portion of the MSWI fly ash was regarded as raw fly ash. MSWI bottom ash was added to both washed and raw fly ash in various ratios which called mixed ashes. The sampling time was identified that ash was fed into the thermal chamber and the thermally treated slag dropped into the collection system completely. The sampling time depended on the speed of reactor and there are three different sampling time in this study. Table 2 lists the experimen-

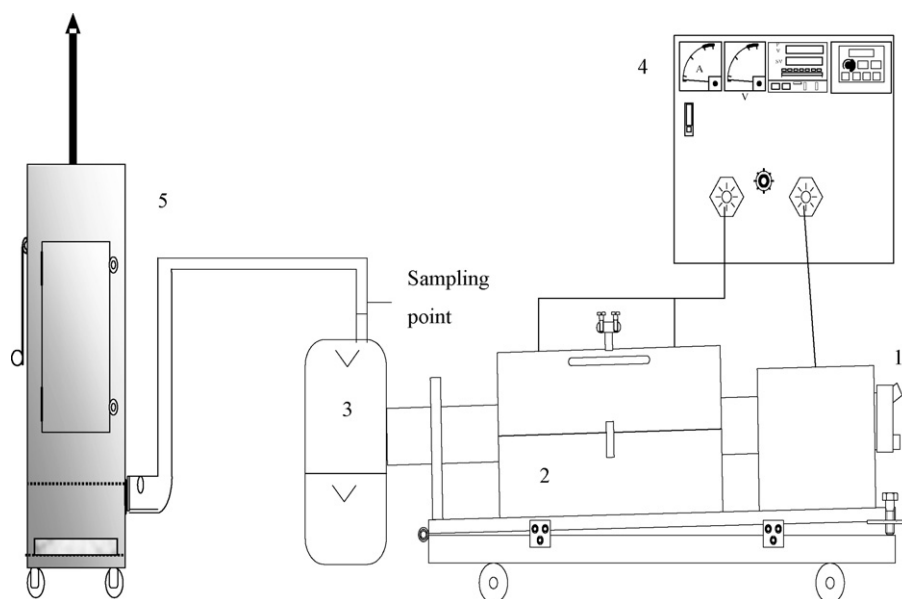


Fig. 1. Schematic representation of pilot-scale rotary kiln incinerator: (1) feeding hole; (2) rotary kiln incinerator; (3) collection system; (4) control system and (5) air pollution control system.

tal conditions of this study. The sampling procedure followed the standard method of Taiwan EPA (NIEA A302.72C). After the thermal treatment, the product was collected and the Pb concentration was analyzed according to TCLP method. PAHs and Pb concentration were also sampled during the thermal treatment process. In the PAHs section, gas-phase PAHs were sampled by XAD-4 and solid phase samples were sampled by filter, then treated by modified Soxhlet extraction and analyzed by GC-FID. In the lead section, amount of lead in the solid and gas phase were sampled during thermal treatment process. The concentration of Pb in the gas phase was sampled by using an adsorption

agent (an adsorption agent was HNO_3 (5%) + H_2O_2 (10%)), and the concentration of Pb in the solid phase was sampled by glass fiber filter; extracted by microwave digestion, and analyzed by flame atomic absorption spectroscopy (FAAS).

2.4. Toxicity test

Micortox was a bacterial method that uses luminescent bacteria developed by Beckman Instruments, Inc. This method was based on the reducing the bioluminescence of the marine bacterium *Vibrio fischeri* by toxicants. Previous researchers used

Table 2
Operating conditions of the experiment

Run	Temperature (°C)	Retention time	Speed (rpm)	Feed materials	Pre-treatment
1	700	t_1^a	0.89	Pure fly ash	None
2	700	t_1	0.89	Mix F ^d :B ^e = 1:1	None
3	700	t_1	0.89	Mix F:B = 10:1	None
4	700	t_2^b	1.39	Pure fly ash	None
5	700	t_2	1.39	Mix F:B = 1:1	None
6	700	t_2	1.39	Mix F:B = 10:1	None
7	700	t_3^c	2.0	Pure fly ash	None
8	700	t_3	2.0	Mix F:B = 1:1	None
9	700	t_3	2.0	Mix F:B = 10:1	None
10	700	t_1	0.89	Pure fly ash	Water
11	700	t_1	0.89	Mix F:B = 1:1	Water
12	700	t_1	0.89	Mix F:B = 10:1	Water
13	700	t_2	1.39	Pure fly ash	Water
14	700	t_2	1.39	Mix F:B = 1:1	Water
15	700	t_2	1.39	Mix F:B = 10:1	Water
16	700	t_3	2.0	Pure fly ash	Water
17	700	t_3	2.0	Mix F:B = 1:1	Water
18	700	t_3	2.0	Mix F:B = 10:1	Water

^a t_1 : 0–42, 44–86, 88–130, 132–174 and 176–218 min.

^b t_2 : 0–28, 30–58, 60–88, 90–118 and 120–148 min.

^c t_3 : 0–21, 23–44, 46–67, 69–90 and 92–113 min.

^d F: MSWI fly ash.

^e B: MSWI bottom ash.

this method to assay the toxicity ($EC_{50}\%$) of the bottom ash leachate [22]. In this study, *V. fischeri* (luminescent bacteria) was cultured by the ISO11348-1 standard method, and *V. fischeri* was used to evaluate the short-term toxicity of the raw fly ash extraction solution, the thermally treated slag extraction solution. Briefly, the sample was adjusted to pH 6–8 with either 0.1N HCl or 0.1N NaOH and without significantly affecting the luminescence. Sample was mixed with NaCl to achieve 2% NaCl. Then, 0.5 ml of sample and 0.5 ml *V. fischeri* were mixed thoroughly. Phenol was used as control chemical and its initial concentration was 45.5 mg/L. EC_{50} value for phenol ranged from 13 to 26 mg/L when each *V. fischeri* light inhibition test began doing [23,24].

3. Results and discussion

3.1. Emission of PAHs

3.1.1. Effect of pretreatment on PAHs emission

Fig. 2 shows the emission of PAHs in the gas phase and the solid phase during the thermal treatment of raw fly ash. In both of these phases, the dominant species was acenaphthene (3-ring

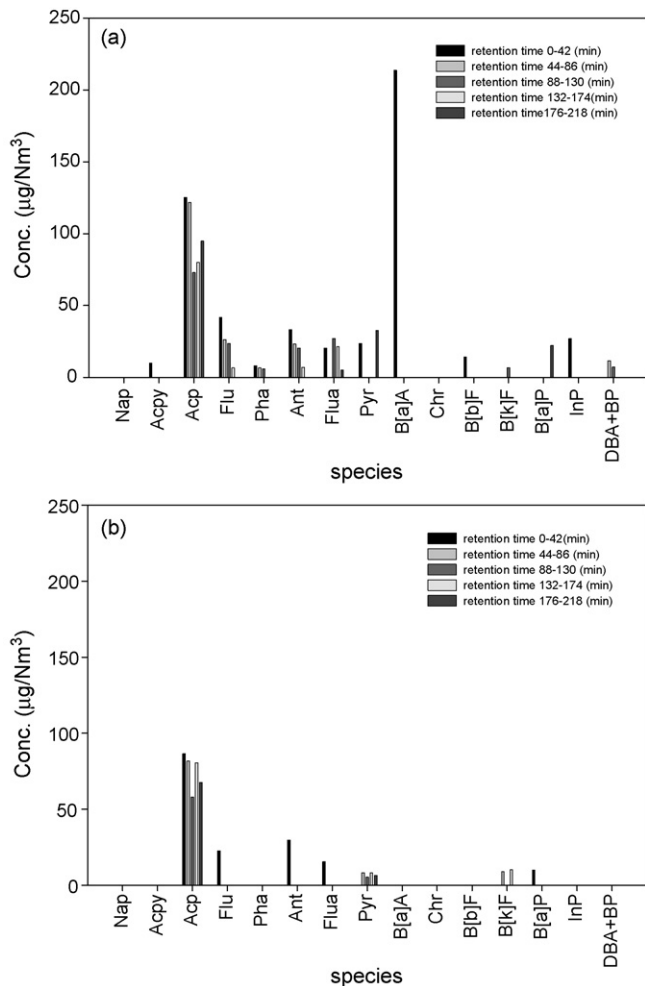


Fig. 2. PAHs emission during the thermal treatment of raw fly ash: (a) gas phase and (b) solid phase.

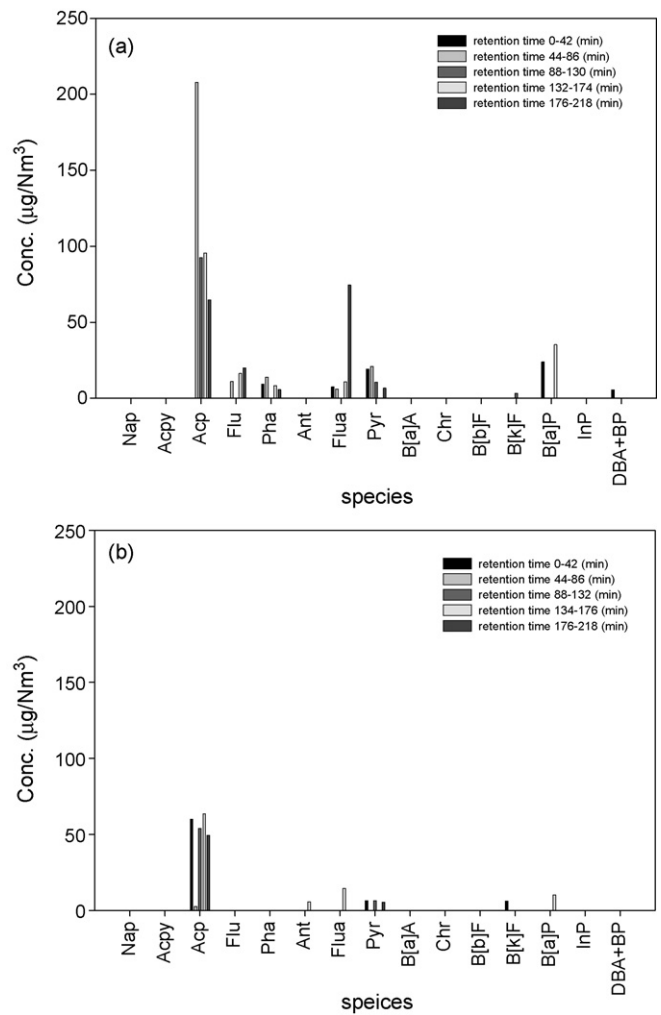


Fig. 3. PAHs emission during the thermal treatment of washed fly ash: (a) gas phase and (b) solid phase.

PAHs) and less carcinogenic 5- and 6-ring PAHs were present. As the retention time increased, the emission concentration of PAHs in the gas phase (from 516 to 154 $\mu\text{g}/\text{Nm}^3$) and in the solid phase (from 164 to 74 $\mu\text{g}/\text{Nm}^3$) became lower. This phenomenon was because PAHs were destroyed as the retention time increased. The variation of the PAHs species in the gas phase exceeded that in the solid phase, perhaps because 5- and 6-ring PAHs were destroyed and converted to 3- or 4-ring PAHs at high temperature. Fig. 3 illustrates the PAH emission in the gas phase and the solid phase during the thermal treatment of washed fly ash. The concentration of PAHs emission in the gas phase was higher than that in the solid phase and the species of PAHs emission in the gas phase was more than that in the solid phase. Acenaphthene (3-ring PAHs) was the dominant species in the gas phase and the solid phase. Figs. 2 and 3 indicated that the emission concentrations of PAHs in the gas phase were similar. However, in the solid phase, the concentrations differed significantly perhaps because pretreatment can washout fine particles that contained PAHs. However, the washing process did not significantly change the emission of PAHs in the gas phase but did influence in the solid phase.

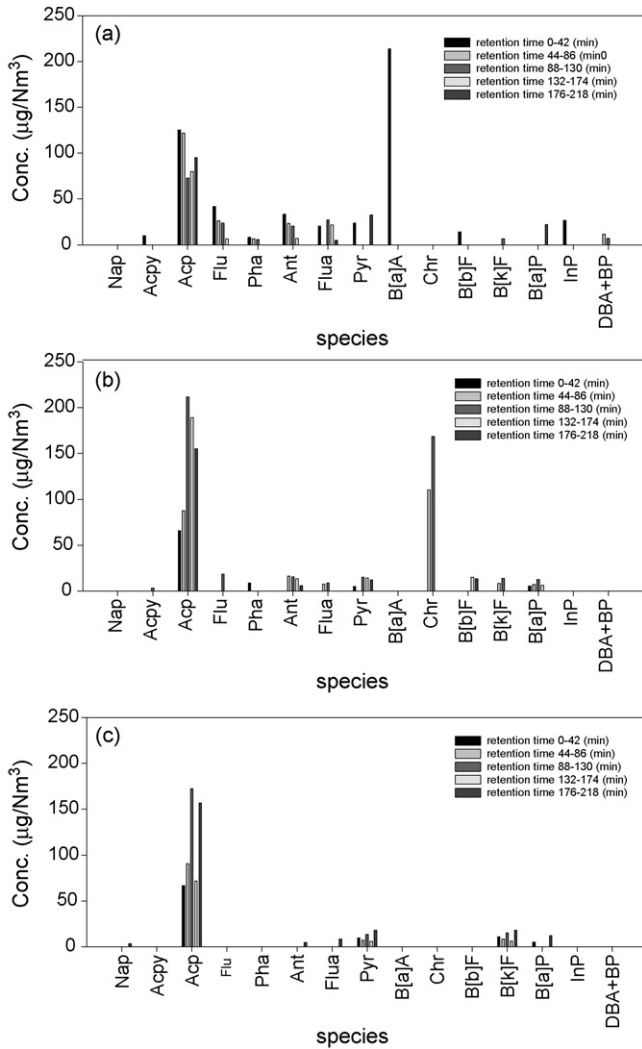


Fig. 4. PAHs emission in the gas phase during the thermal treatment process with adding different amount of bottom ash: (a) pure fly ash; (b) bottom ash/fly ash = 1:1 and (c) bottom ash/fly ash = 1:10.

3.1.2. Effect of additives ratio on PAHs emission

Fig. 4 displays the emission of PAHs in the gas phase during the thermal treatment process with adding different amount of bottom ash. Regardless of whether MSWI bottom ash was added, the dominant species of the gas phase was acenaphthene, and chrysene was present only when B:F = 1:1. The emission of 5- and 6-ring PAHs from co-treated raw fly ash declined as the retention time increased, because the retention time was long enough to destroy organic pollutants. Fig. 5 illustrates PAHs emission in the solid phase during the thermal treatment process with adding different amount of bottom ash. Acenaphthene was the dominant species in the thermal treatment process, but adding bottom ash had no significant influence on concentration of PAHs emission. As the retention time increased, 3-ring PAHs concentration increased and the 5- and 6-ring PAHs concentrations decreased. In conclusion, adding different amount of MSWI bottom ash did not affect the concentration of emitted PAHs in the gas phase, but reduced the PAHs concentration of emitted PAHs in the solid phase.

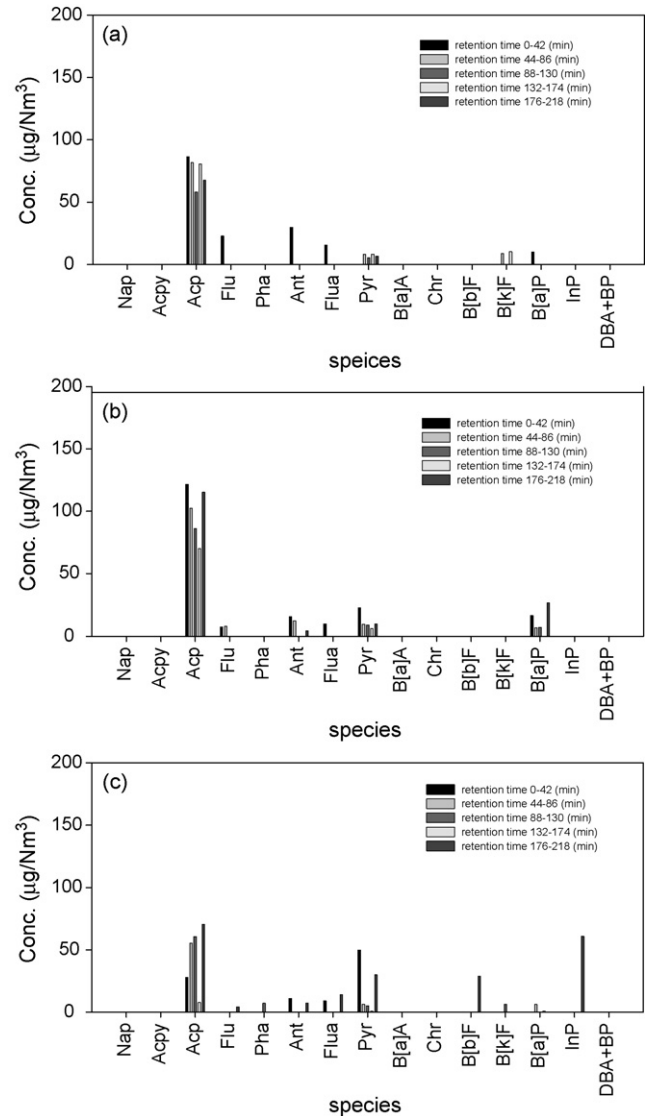


Fig. 5. PAHs emission in the solid phase during the thermal treatment process with adding different amount of bottom ash: (a) pure fly ash; (b) bottom ash/fly ash = 1:1 and (c) bottom ash/fly ash = 1:10.

3.1.3. Effect of retention time on emission of PAHs

Fig. 6 shows the emission of PAHs in the gas phase during the thermal treatment of raw fly ash with different retention time. The dominant species at three different retention time was acenaphthene. At the various retention times, the distribution of species in the emitted PAHs was quite similar. The difference was that benzo[k]fluoranthene was present at the shortest and moderate retention time, but did not in the longest retention time, perhaps because the retention time was sufficiently long to destroy benzo[k]fluoranthene. The retention time influenced the concentrations of 5-ring and 6-ring PAHs. As retention time increased, the concentrations of 5- and 6-ring PAHs decreased. Fig. 7 depicts PAHs emission in the solid phase during the thermal treatment of raw fly ash with different retention time. Acenaphthene was the major species at three different retention time and the PAHs emission concentration in the moderate retention time slightly exceeded that at other retention time. The

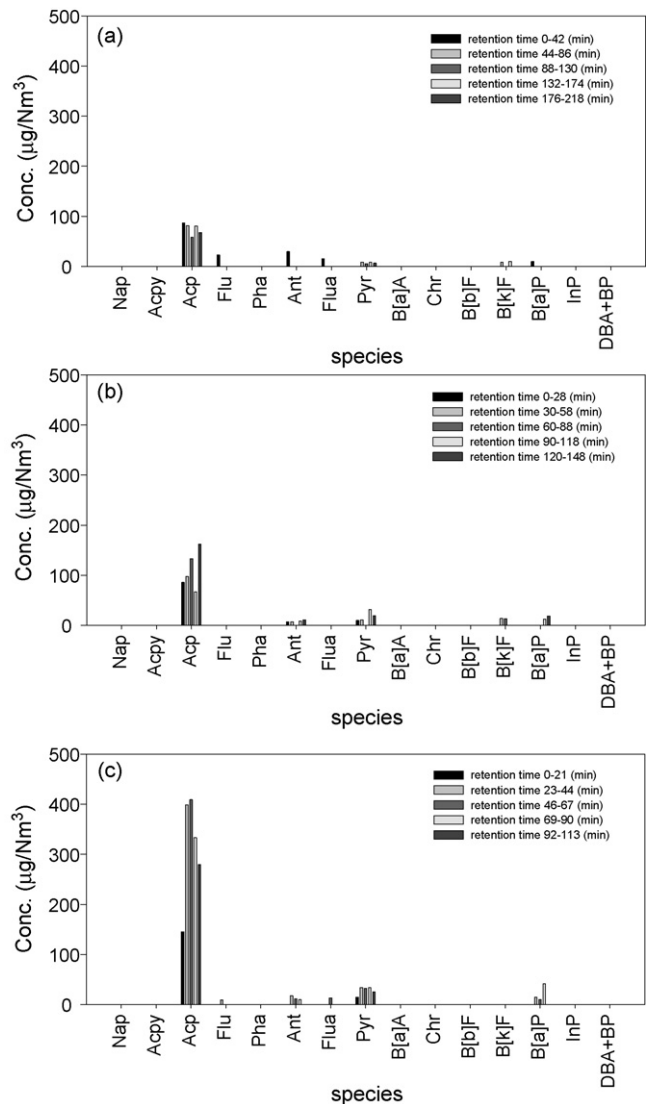
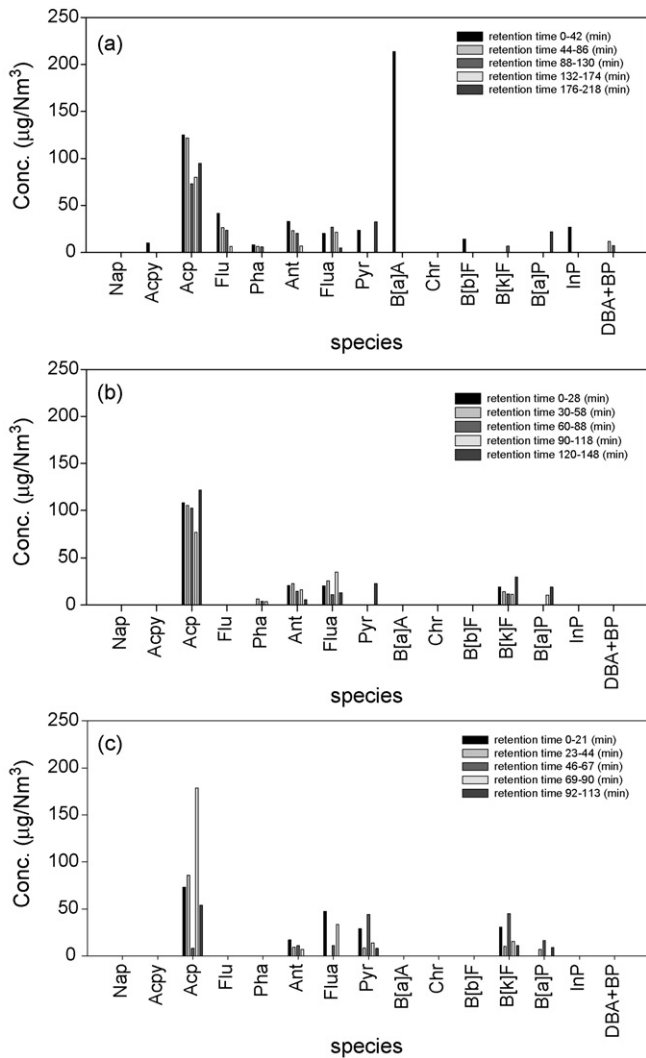


Fig. 6. PAHs emission in the gas phase during the thermal treatment of raw fly ash with different retention time: (a) speed = 0.89 rpm; (b) speed = 1.39 rpm and (c) speed = 2.0 rpm.

Fig. 7. PAHs emission in the solid phase during the thermal treatment of raw fly ash with different retention time: (a) speed = 0.89 rpm; (b) speed = 1.39 rpm and (c) speed = 2.0 rpm.

concentration of PAHs emission in the solid phase decreased as retention time increased. Comparing the solid phase emissions at the different retention time indicated no significant variation with retention time. However, the retention time did not significantly influence the gas phase or the solid phase.

3.2. Emission of Pb

3.2.1. Effect of pretreatment on Pb emission

When the fly ash was treated at high temperature the heavy metals may be encapsulated, vaporized or condensed [1]. Therefore, solid and gas-phase Pb emission had to be quantified. The concentration of Pb emission in the gas phase was too low to analyze, so only Pb in the solid phase was discussed. Fig. 8 plots the emission of Pb in the solid phase during the thermal treatment of raw fly ash and washed fly ash with different retention time. The concentration of solid phase Pb emission was increased with retention time and the trend was rapid from fourth to fifth retention time range. The Pb emission in the solid

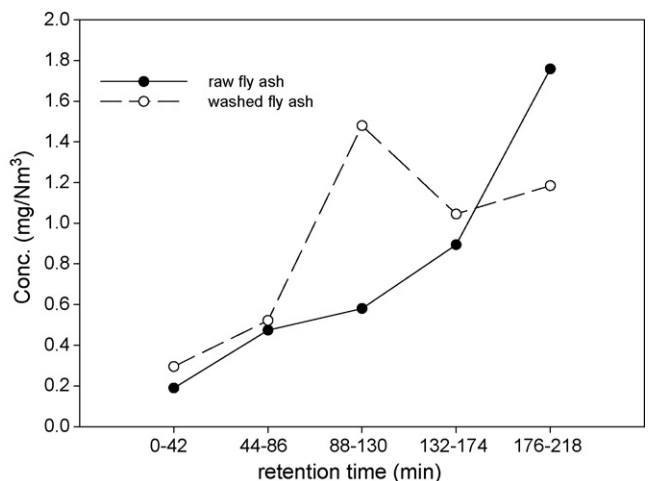


Fig. 8. Emission of Pb in the solid phase during the thermal treatment of raw fly ash and washed fly ash with different retention time.

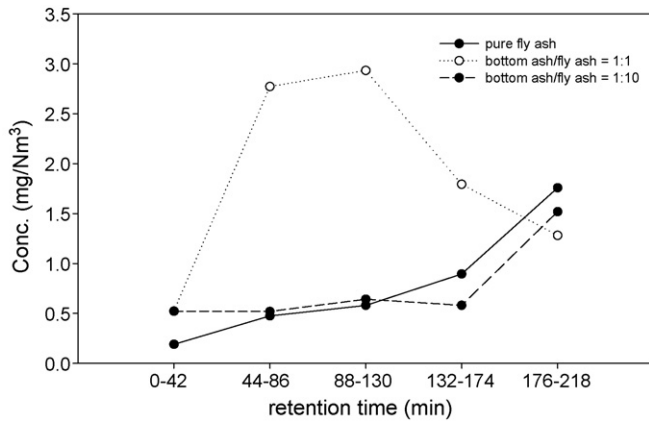


Fig. 9. Emission of Pb in the solid phase during the thermal treatment process with adding different amount of bottom ash.

phase from washed fly ash during the thermal treatment process exhibited a slightly increase in trend in the first two retention time ranges and achieved maximum in the third retention time range. After third retention time range, the Pb emission concentration was decreased. This may due to the change in properties of fly ash and reduced the degree of aggregation of washed fly ash during the thermal treatment process, as a result Pb vapor were condensed on fine particle of fly ash surface. As the retention time increased, the emission reaction achieved to finish and the concentration of Pb emission in the solid phase emission decreased.

3.2.2. Effect of additives on Pb emission

Fig. 9 shows the emission of Pb in the solid phase during the thermal treatment process with adding different amounts of bottom ash. During the thermal treatment process, pure ash and mixed ash ($B/F = 1$ and $B/F = 0.1$) were exhibited similar, but Pb emission in the solid phase from pure ash increased sooner than it did from mixed ash. The Pb concentration was the highest at the ratio ($B:F = 1:1$), because fly ash and bottom ash contains different particle size and the agglomeration was not evident in mixed ash. Then, the emission of Pb from mixed ash was higher in later retention time range. Comparing fly ash with different amounts of bottom ash, the emission of mixed ash was increased in trend and was prolonged until the amounts of added bottom were decreased. However, bottom ash influenced Pb emission during the thermal treatment process and the delay of Pb emission time.

3.2.3. Effect of retention time on Pb emission

Fig. 10 illustrates the concentration of Pb emission in the solid phase during the thermal treatment of raw fly ash with different retention time. The Pb emissions in the longest and moderate retention time were similar. The concentration of Pb emission was very low in the shortest retention time. In the longest and moderate retention time, concentration of Pb emitted in the first two retention time ranges was increased smoothly. The concentration of Pb emission achieved maximum in the third retention time range, perhaps the reaction time was sufficiently long to cause some of the Pb vaporized and condensed on surface of ash

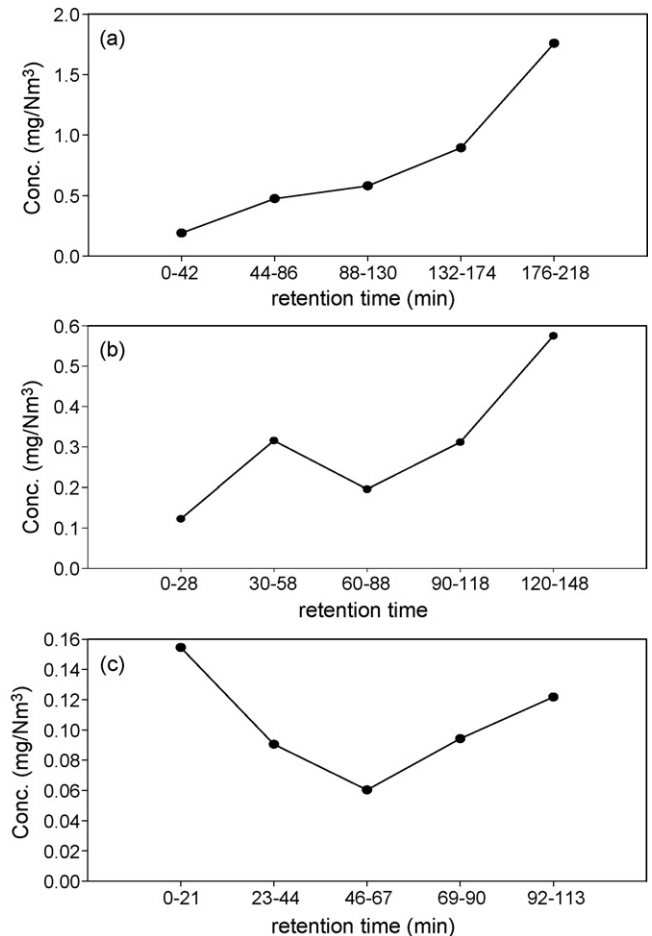


Fig. 10. Emission of Pb in the solid phase during the thermal treatment of raw fly ash with different retention time: (a) speed = 0.89 rpm; (b) speed = 1.39 rpm and (c) speed = 2.0 rpm.

particle. Since Pb vaporized and the ash aggregated at the same time, Pb was encapsulated in the aggregate as it formed and Pb emission was thus reduced. Comparing different retention time of fly ash indicated that the concentration of Pb emission during the thermal treatment process was increased slightly as the retention time increased.

3.3. TCLP leaching concentration

3.3.1. Effect of pretreatment of fly ash on Pb leaching

Fig. 11(a) plots the TCLP leaching concentration in Pb of raw fly ash and thermally treated raw fly ash slag. The TCLP leaching concentration of Pb in raw fly ash and thermally treated raw fly ash slag exceeded the allowed values. A high temperature could reduced the TCLP lead value, but sometime the TCLP leaching concentration of Pb of thermally treated raw fly ash slag exhibited potential over-regulation. Since encapsulation was incomplete as to result in this potential [4], the TCLP leaching concentration of Pb in thermally treated raw fly ash slag was high and the slag was classified as a hazardous material. Mangialarid [7] used water to wash fly ash and concluded that washing in water could improve the chemical and mechanical characteristics of sintering products. Wang et al. [25] utilized

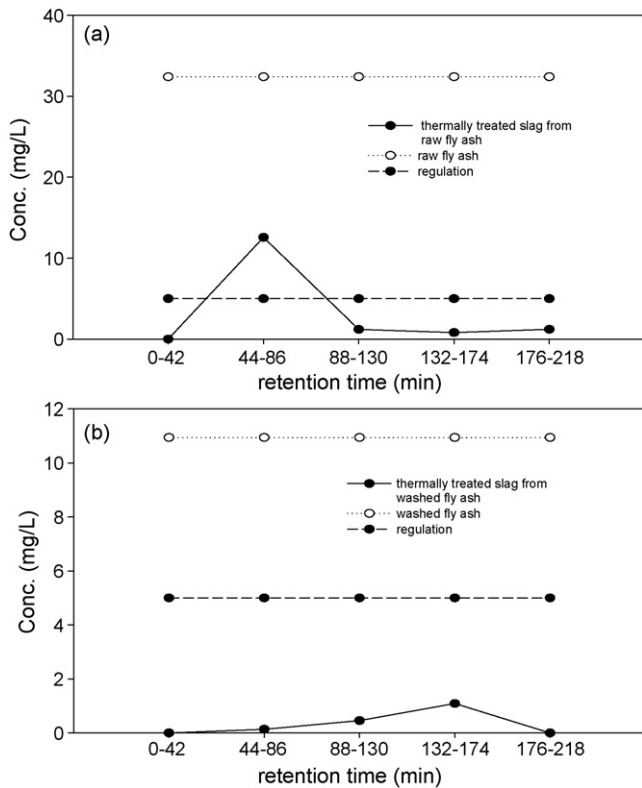


Fig. 11. (a) TCLP leaching concentration in raw fly ash and thermally treated raw fly ash slag and (b) TCLP leaching concentration in washed fly ash and thermally treated washed fly ash slag.

water-extraction to investigate the behavior of heavy metals in fly ash. They found the water-extraction could leach some elements and heavy metals such as Cl, K, Na, Pb and others. Therefore washing in water was the chosen pre-treatment in this study. Fig. 11(b) plots the TCLP concentration of Pb in washed fly ash and thermally treated slag from washed fly ash. A comparison of the TCLP concentration of raw fly ash and washed fly ash revealed that washing effectively reduced the TCLP concentration of Pb. However, the TCLP concentration of Pb in washed fly ash was still higher than that of Pb regulation. After thermal treatment, in thermally treated washed fly ash slag was lower than the allowed Pb concentration. However, washing reduced the TCLP concentration of Pb but the thermal treatment of the slag of washed fly ash was required to make it non-hazardous materials.

3.3.2. Effect of additive in fly ash on Pb leaching

Fig. 12(a) shows the TCLP leaching concentration in Pb of thermally treated slag with adding different amount of bottom ash. As expected, the TCLP leaching concentration in Pb of thermally treated slag was exceeded the regulation value at B/F = 0. The TCLP leaching concentration of thermally treated slag was lower than the regulation value at B/F = 1, because of the volume effect, which diluted the Pb concentration of the ash. The TCLP leaching concentration of thermally treated slag was higher than the regulation value when B/F = 0.1. The leaching concentration of thermally treated mixed ash slag could not reasonably be considered to exceed that of thermally treated pure ash slag.

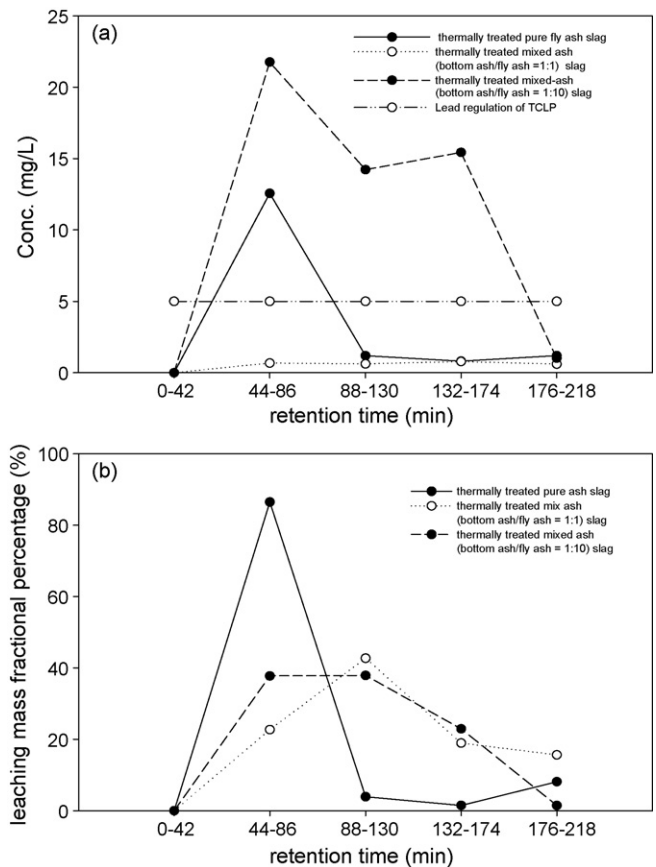


Fig. 12. (a) TCLP leaching concentration of thermally treated slag with adding different amount of bottom ash and (b) total mass percentage of TCLP leaching solution in adding different amount of bottom ash.

However, this phenomenon can be explained as a percentage of the total leaching mass. Fig. 12(b) shows the percentage of the total leaching mass with different amount of bottom ash. The results indicated that the percentage of total leaching mass in pure ash exceeded that of other ashes, because the retention time was too short to encapsulate Pb in thermally treated slag and most Pb in thermally treated slag of pure ash was leached in the forward period. However, adding bottom ash caused the structure of thermally treated slag to become loose and delay Pb leaching time.

3.3.3. Effect of retention time of fly ash on Pb leaching

TCLP leaching concentration of Pb in thermally treated raw fly ash slag with different retention time was shown in Fig. 13. At three different retention time, the TCLP leaching concentration increased in the second retention time range and decreased in the later retention time range, because the retention time did not suffice to encapsulate Pb in thermally treated raw fly ash slag. As retention was increased to allow the encapsulation of Pb in thermally treated raw fly ash slag, the TCLP leaching concentration of Pb in thermally treated raw fly ash slag decreased. The TCLP leaching concentration of thermally treated slag of washed fly ash followed the same trend. However, the TCLP leaching concentration of Pb did not vary with retention time.

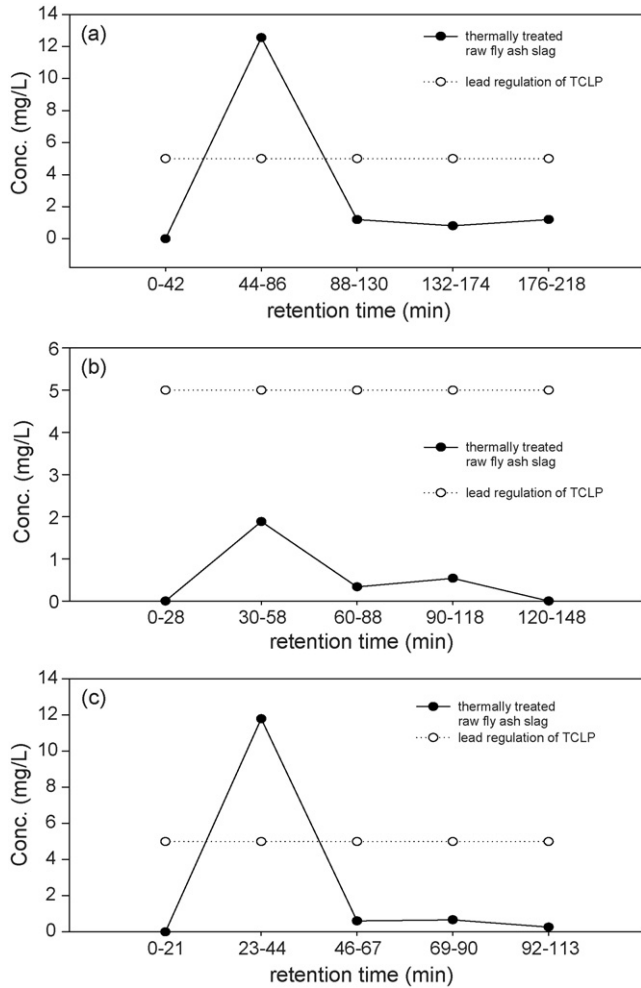


Fig. 13. TCLP leaching concentration of thermally treated raw fly ash slag with different retention time: (a) speed = 0.89 rpm; (b) speed = 1.39 rpm and (c) speed = 2.0 rpm.

3.4. Toxicity test

The inhibition rate represents short-term toxicity. Table 3 presents the inhibition rate of raw fly ash and the thermally treated slag. The inhibition rate of raw fly ash was approximately 98%, indicating that raw fly ash exhibited high short

Table 3
Inhibition rate of raw ash and thermally treated slag

Materials	Inhibition (%)	Materials	Inhibition (%)
Blank ^a	None	Raw fly ash ^b	98.71
Slag R1 ^b	18.35	Slag R10	26.73
Slag R2	15.02	Slag R11	23.25
Slag R3	31.59	Slag R12	34.14
Slag R4	34.00	Slag R13	25.83
Slag R5	27.99	Slag R14	36.33
Slag R6	25.34	Slag R15	24.07
Slag R7	6.80	Slag R16	34.47
Slag R8	36.59	Slag R17	38.06
Slag R9	21.41	Slag R18	30.81

^a Extraction solution was 0.1N HCl.

^b MSWI fly ash and thermally treated slag were extracted by 0.1N HCl.

term toxicity. After the thermal treatment, the rate of inhibition of thermally treated slag was substantially reduced. Comparing the inhibition rates of raw fly ash and thermally treated slag provides evidence that the thermal treatment reduces the toxicity of raw fly ash and thus reduces its impact on environment. A statistical test (SAS 8.02 version, *t*-test) was performed to determine which parameters had a significant effect. According to the statistical results, the statistical value was significant in inhibition rate of raw ash and thermally treated slag ($P=0.0017$). Other results demonstrated that pretreatment ($P=0.4008$), the amount of bottom ash ($P=0.2150$) and the retention time ($P=0.1265$) did not have significant influence. In conclusion, the statistical results indicate that only the thermal treatment had significant effect. No other parameters significantly affect the toxicity of thermally treated slag.

4. Conclusion

The MSWI fly ash and bottom ash were valuable materials that can be reused especially MSWI fly ash. The thermal treatment was a method by which fly ash was reused and detoxified. However, some air pollutants including organic and inorganic were emitted during the thermal treatment process. The emissions of Pb and PAHs from thermally co-treated MSWI fly ash and bottom ash process were evaluated. Different parameters were studied and the following conclusions drawn.

1. During the thermal treatment process, in the gas phase or in the solid phase, the dominant species was acenaphthene. The concentration PAHs decreased as the retention time increased.
2. Washing pretreatment effectively removed Pb (Pb concentration of TCLP was from 32.42 to 10.94 mg/L) and reduced the emission concentration of PAHs in the solid phase. However, the washing solutions still contained heavy metals, so further treatment was required.
3. Adding different amount of bottom ash reduced the concentration of Pb emission in the solid phase. The TCLP leaching concentration varied with amount of bottom ash. When B:F = 1:1, the volume effect reduces the TCLP leaching concentration which rose at a later retention time when B:F = 1:10.
4. The concentration of Pb emission increased with retention time as more Pb vaporized and condensed on the ash surface.
5. Comparing the toxicity of raw fly ash and thermally treated slag indicated that thermal treatment could decrease the inhibition rate and toxicity of raw fly ash. According to statistic results, washing ($P=0.4008$), adding bottom ash ($P=0.2150$) and the different retention time ($P=0.1265$) did not have significant effect on the toxicity of thermally treated slag. In this research, toxicity of TCLP solution also was analyzed, but TCLP solution would influence inhibition rate. Furthermore, the toxicity of TCLP should be analyzed and discussed.

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