

Utilization of Phuket Municipal Solid Waste Incinerator Fly Ash as a Partial Cement Replacement in Concrete

Pakawat Sancharoen¹, Manaskorn Rachakornkij¹, and Methi Wecharatana²

¹National Research Center for Environmental and Hazardous Waste Management, Chulalongkorn University, Bangkok, Thailand

²Department of Civil and Environmental Engineering, New Jersey Institute of Technology, New Jersey, USA

Abstract

This paper presents the results of a study carried out on sifted and washed samples of Phuket municipal solid waste incinerator fly ash (MSWIFA) collected from mass-burn incinerator in Phuket, Thailand to evaluate the possibility to utilize MSWIFA as a constituent in concrete. Physical and chemical properties of MSWIFA, including specific gravity, particle size distribution, specific surface area, moisture content, loss on ignition, absorption capacity, morphology, bulk chemical compositions, and mineralogical compositions were studied. Physical and mechanical properties of concrete within which Portland cement was partially replaced by MSWIFA at 0, 10, 15, and 25% and washed-MSWIFA 15% by weight were slump value, setting time, unit weight, development of compressive strength, and water-soluble chloride content.

Properties of MSWIFA did not meet most of the requirements for pozzolanic materials to be used as a mineral admixture in concrete (ASTM C618); however, it should be noted that ASTM C618 was designed mainly for coal fly ash (CFA) and natural pozzolan.

The setting time of MSWIFA concrete reduced with increasing MSWIFA content because of high content of chloride in MSWIFA. At replacement level of 10%, MSWIFA concrete showed the highest compressive strength that was 86% compared to that of control concrete; however, all compressive strengths of MSWIFA concrete specimens were lower than that of control concrete. Although MSWIFA highly consisted of chloride, the water-soluble chloride contents of MSWIFA concrete were

within the limit to prevent corrosion of reinforcing steel.

Finally, leachate extraction procedure was used to evaluate environmental safety of MSWIFA and concrete product. Results showed that concentrations of all regulated heavy metals were within the limits; however, concentrations of barium, lead, and chloride in wastewater from washing process exceeded the wastewater discharge standards.

1. Introduction

Thailand is one of the developing countries that are currently faced with problems regarding disposal of municipal solid waste (MSW) due to ever-increasing amount of MSW generated and depleting space of existing landfill disposal sites, especially provinces with limited space, such as Phuket. Since 1998, Phuket had completely constructed and operated the municipal solid waste incinerator (MSWI) to mainly reduce the volume of MSW prior to disposal in landfill.

The main advantage of MSWI is volume reduction up to 75% of the original volume of MSW prior to disposal. Pathogenic and organic fractions in MSW are destroyed by high combustion temperature. Moreover, heat energy can be recovered to produce electricity or steam. However, MSWI still leaves residues, bottom ash (MSWIBA) and fly ash (MSWIFA), which require further management, i.e., landfill disposal.

At the Phuket incineration facility, up to 250 tons of MSW have been incinerated daily since 1998, resulting in approximately 8.50 tons of MSWIFA everyday. MSWIFA captured by bag house filter is moistened prior to transportation

and disposal in the HDPE-lined landfill located close to the MSWI. Unfortunately, MSWIFA may be contaminated by vaporized heavy metals and chloride in MSW stream, thus making it a hazardous waste. Therefore, MSWIFA should be stabilized and solidified prior to disposal in the secure landfill. For that reason, excess amount of lime is injected into flue gas stream during air pollution control (APC) process.

Utilization of industrial byproducts, such as coal fly ash (CFA), and steel blast furnace slag as a mineral admixture in concrete material has been practiced for many decades. CFA and slag can enhance properties of concrete such as increase in workability; increase in latter strength; increase in sulfate resistance; reduction in alkali-aggregate reaction; reduction in permeability and chloride ion penetration; reduction in heat of hydration; and reduction in cost of concrete [1-3]. In contrast, there are only a few number of researches conducted on utilization of MSWIFA in construction materials, especially in Thailand [4-11]. Also physical and chemical characteristics of MSWIFA were merely studied by some researchers [12-15]. If it is found that Phuket MSWIFA can improve the properties of concrete and, at the same time, that its toxic elements can be stabilized and solidified, MSWIFA will possibly find its niche in the market for construction applications.

2. Research Significance

It is clearly realized that MSWI is not a complete solution for MSW disposal problem because of the toxic residues. This research presents the possibility of utilizing MSWIFA as a partial Portland cement replacement in concrete to completely solve the disposal problem of MSW.

3. Methodology

Approximately 500 kg of MSWIFA was sampled from the MSWIFA landfill near the Phuket MSW incineration facility in December 2001, prior to installation of MSW processing facility. The fly ash was sifted through an ASTM standard sieve No. 20 (0.84-mm open-

ings) before carrying out any tests to remove very large particles and then stored in a plastic-lined plastic container. This sifted MSWIFA was named "MSWIFA". A portion of sifted MSWIFA was simply washed twice by tap water in a mortar mixer with a liquid-to-solid ratio of 5 to remove soluble contents. Then it was dried in an oven over night. This MSWIFA was named "WMSWIFA". Both of MSWIFA and WMSWIFA were analyzed for physical and chemical characteristics and studied the effect on the properties of concrete products when used as a cement replacement throughout the study.

Specific gravity, moisture content, and loss on ignition (LOI) of MSWIFA and WMSWIFA as well as Portland cement were determined following the procedures described in ASTM C311. Particle size distribution (PSD) was determined by Particle Size Analyzer using air as a medium. Bulk chemical compositions were determined by x-ray fluorescence spectrometer (XRF). Mineralogical compositions were analyzed by x-ray diffraction spectrometer (XRD) with Cu K_α radiation ($\lambda = 1.5418\text{\AA}$) at 40 kV accelerating voltage, 40 mA current, 0.02 step time, and 5° to 70° 2θ scanning range.

Five mixture proportions of ordinary Portland cement (OPC) concrete and MSWIFA concretes were mixed in 0.15 m³ batches. The cement used was type I Portland cement. Replacement levels of MSWIFA were 0, 10, 15, and 25% by weight of OPC, while that of WMSWIFA was only 15% to study the effect of soluble fractions of MSWIFA. Water to binder ratio of 0.63 and other mixture proportions were kept constant for all mixes as shown in Table 1. According to ASTM C192, coarse aggregate, sand and approximately 70 % of total mixing water were added to the wetted mixer. Once the mixer was started, cement and MSWIFA was added simultaneously because they were considered insoluble material admixtures in the amount exceeding 10 % by weight of cement. The remaining mixing water was gradually added to ensure the uniform blending, while the total mixing time was kept lower

Table 1

Mix proportions for 1 m³ concrete and properties of fresh concrete

Mix No.	Mixture Proportion, kg						Slump, cm	Setting Time, min		Unit Weight, kg/m ³
	Cement	MSWIFA	WMSWIFA	Sand	Gravel	Water		Initial	Final	
F00	282	0	0	816	1098	178	9.9	175	211	2440
F10	254	28	0	816	1098	178	12.2	116	166	2414
F15	240	42	0	816	1098	178	12.9	113	159	2379
F25	212	71	0	816	1098	178	15.2	115	177	2379
WF15	240	0	42	816	1098	178	10.4	170	243	2397

than 10 minutes. Internal vibration was used to consolidate the concrete into the cylindrical mold (150mm × 300mm). All of the specimens were demolded after 24 hours of casting and cured in the moisture room until the time of testing.

Fresh concrete properties included slump, setting time and unit weight were measured after the mixing process following ASTM C143, C403 and C138, respectively. Compressive strength tests at the age of 3, 7, 14, 28, 56, and 90 days were conducted following ASTM C39. Samples collected from crushed specimens of compressive strength tests were used to determine water-soluble chloride content according to ASTM C1218.

MSWIFA, WMSWIFA, and crushed specimens of MSWIFA and WMSWIFA concrete at the age of 28 days were subjected to leachate extraction procedure as described in the Notification of Ministry of Industry No. 6, B.E. 2540 (1997) to ensure their environmental safety. Concentrations of Arsenic, Barium, Cadmium, Chromium, Lead, Selenium, and Silver were measured by ICP atomic emission spectrometer, while mercury was measured by cold vapor atomic absorption.

4. Results and Discussion

4.1. Characteristics of MSWIFA

Specific gravity (SG), moisture content (MC) and LOI of MSWIFA, WMSWIFA and OPC were shown in Table 2. SG of OPC was the highest as expected followed by those of WMSWIFA and MSWIFA. The lowest SG of MSWIFA may be due to porous structure of coarser particles [8]. The extremely high MC of MSWIFA was due to MSWIFA moistening process of MSWI at the facility, while that of

WMSWIFA was lower because it was dried in an oven after washing process. LOI of MSWIFA and WMSWIFA were incredibly high. This may be due to high carbon content in MSWIFA; however, it should be noted that water bound in hydration of excess lime in MSWIFA cannot be evaporated at 105°C in an oven but can be liberated after being ignited at 750°C. As a result, WMSWIFA showed the highest MC due to the fact that it was saturated with water during washing process. Therefore, other methods such as particulate carbon, total organic carbon, or total inorganic carbon should be used to determine the carbon content of MSWIFA.

Table 2

Specific gravity, moisture content and loss on ignition

Sample	Specific Gravity	Moisture Content, %	Loss on Ignition, %
MSWIFA	1.92	14.81	12.44
WMSWIFA	2.26	0.44	17.33
OPC	3.14	0.13	1.95

PSD curves of MSWIFA and WMSWIFA compared to those of OPC and sand are shown in Fig. 1. The curves of MSWIFA and WMSWIFA showed coarser distribution than that of OPC, but finer than that of sand because the moistening process causes agglomeration of very fine particle of MSWIFA.

Table 3 shows the chemical compositions of MSWIFA, WMSWIFA, and OPC in their oxide forms. The major elements found in MSWIFA were CaO and chloride since they are the main products of dry scrubber reagent of an APC system. Soluble fractions of MSWIFA such as NaCl and KCl were dissolved after washing process; therefore, amounts of Na₂O, K₂O, and Cl in WMSWIFA

were lower than those of MSWIFA while insoluble fractions of WMSWIFA increased; for example, Al_2O_3 , Fe_2O_3 and SiO_2 . Trace quantities of various metals were also detected in MSWIFA and WMSWIFA.

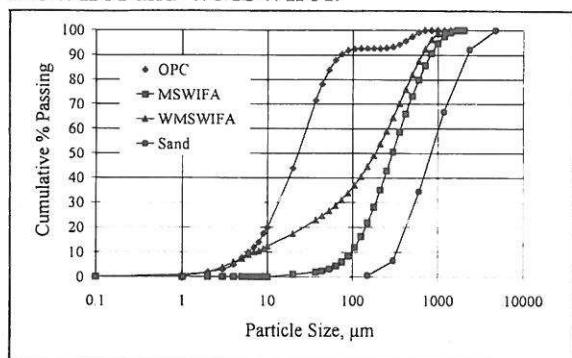


Fig.1. Particle size distribution curves of MSWIFA, WMSWIFA, OPC and sand.

Comparison between properties of MSWIFA and requirements of ASTM C618 is shown in Table 4. Most of properties of MSWIFA and WMSWIFA did not meet the requirements of ASTM C618, except SO_3 content of MSWIFA and MC of WMSWIFA.

The major crystalline phases of MSWIFA were KCl and $NaCl$, which were consistent with results of chemical compositions. Moreover, XRD spectrum of WMSWIFA showed disappearance of $NaCl$ and KCl and newly detected phase of $Ca(OH)_2$ supporting result of higher LOI of WMSWIFA due to loss of combined water.

4.2. Properties of MSWIFA Concrete

Slump, setting time and unit weight of MSWIFA and WMSWIFA concrete are shown in Table 1. MSWIFA showed higher slump values compared to that of OPC concrete. The higher replacement level, the higher slump value was observed. This result disagreed with all previous literatures [4,10]. It was believed that the characteristics of MSWIFA were not the cause of this unexpected phenomenon; however, the absorption capacity of MSWIFA used to correct the mixing water content was. The absorption capacity of MSWIFA was determined following ASTM C128 to determine

the absorption capacity of fine aggregate. Unfortunately, this standard method is mainly appropriate for inert materials like sand, while the MSWIFA is not. Immersing the MSWIFA in water overnight caused the extra amount of water to chemically combine in the newly formed products rather than to be physically absorbed. As a result, the corrected mixing water for MSWIFA concrete was overestimated. A different phenomenon was observed in case of washed MSWIFA, in which the reactive compositions were completely reacted. Initial and final setting times of concrete were accelerated due to replacement of MSWIFA. This result also contradicts to the literatures [4,8,10]. However, this result was reasonable because MSWIFA contains large amount of chloride known as setting accelerator of concrete. The reason that setting time of F15 was faster than that of F25 is the lower amount of OPC in its mixture. Unit weight of MSWIFA concrete was lower than that of OPC concrete because of lower SG of MSWIFA.

Fig. 2 shows development of compressive strength of OPC concrete and MSWIFA concrete from 3 to 91 days. All compressive strengths of MSWIFA and WMSWIFA concrete were lower than that of OPC concrete, even though at the longest curing period. This result contradicts to case of CFA concrete that its compressive strength is usually greater than that of OPC concrete at later age. The reduction of compressive strength was larger as the replacement level was increased. At 28 days, compressive strength of OPC concrete (F00) achieved 360 ksc, while those of F10, F15 and F25 were 310, 280, 187 ksc, respectively. WF15 showed lower compressive strength at all ages compared to same replacements level of MSWIFA (F15). This revealed the valuable effects of soluble fractions of MSWIFA similar to previous research [10]. Relative compressive strength of each mixture compared to its compressive strength at 90 days is shown in Fig. 3. This graph revealed almost similar trend of compressive strength development rate between OPC concrete and MSWIFA concrete in

contrast to CFA concrete that is retarded during

MSWIFA concrete became a concern. Maximum water-soluble chloride is limited to 0.15%

Table 3

Chemical composition of MSWIFA, WMSWIFA and OPC

Analyte	Chemical Composition, % by wt			Analyte	Chemical Composition, % by wt		
	MSWIFA	WMSWIFA	OPC		MSWIFA	WMSWIFA	OPC
Al ₂ O ₃	2.08	4.90	4.58	P ₂ O ₅	0.95	2.60	0.06
CaO	34.36	44.38	62.05	SiO ₂	5.88	8.55	21.33
Cr ₂ O ₃	0.00	0.03	0.00	SnO ₂	0.13	0.27	0.00
CuO	0.05	0.07	0.00	SO ₃	4.15	7.93	4.07
Fe ₂ O ₃	0.68	1.23	3.16	SrO	0.04	0.05	0.04
K ₂ O	5.27	0.65	0.39	TiO ₂	0.39	0.83	0.19
MgO	1.30	4.12	1.50	ZnO	0.58	0.76	0.00
MnO	0.03	0.08	0.05	Br	0.00	0.00	0.00
Na ₂ O	3.70	1.53	0.14	Cl	27.80	4.48	0.00
PbO	0.15	0.23	0.00	Rb	0.00	0.00	0.00

Table 4

Comparison between requirements of ASTM C618 and properties of MSWIFA and WMSWIFA

Requirement	ASTM C618		MSWIFA	WMSWIFA
	Class C	Class F		
Silicon dioxide (SiO ₂) plus aluminum oxide (Al ₂ O ₃) plus iron oxide (Fe ₂ O ₃), min, %	50.00	70.00	8.64	14.68
Sulfur trioxide (SO ₃), max, %	5.00	5.00	4.15	7.93
Moisture Content (MC), max, %	3.00	3.00	14.81	0.44
Loss on Ignition (LOI), max, %	6.00	6.00	12.44	17.33
Available alkalies, as equivalent, as Na ₂ O, max, %	1.50	1.50	7.17	1.96

the early hydration period.

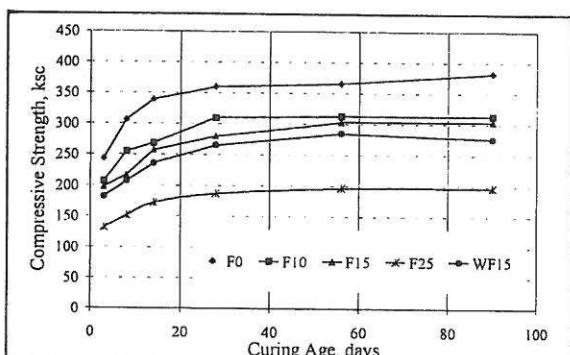


Fig.2. Compressive strengths of OPC, MSWIFA and WMSWIFA concrete.

Due to large amount of chloride in MSWIFA, corrosion of reinforcing steel in

by weight of cement for reinforced concrete structure [17]. Fig. 4 showed the results of water-soluble chloride contents of MSWIFA and WMSWIFA concrete. At the highest replacement level (F25), the content of water-soluble chloride was still lower than limitation in contrast to literature's result [5] that showed very high content of acid-soluble chloride. This may be due to chloride was bound in the chemical products such as Friedel's salt; therefore, it was not extracted by de-ionized water.

4.3. Leachate Characteristics

Table 5 shows concentrations of heavy metals in leachate of MSWIFA and WMSWIFA concrete according to the Notification of Ministry

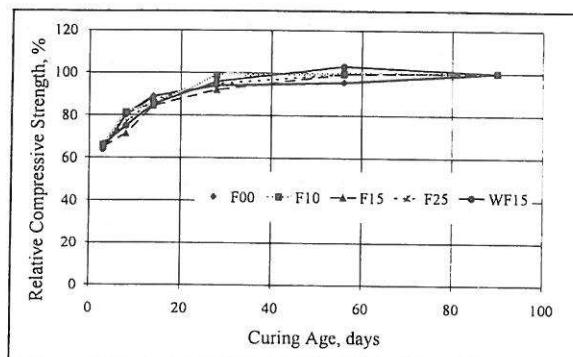


Fig.3. Relative compressive strengths normalized to the value at 90 days of each mixture.

of Industry No. 6, B.E. 2540 (1997). Most of concentrations of heavy metals were below the detection limits of the instruments, except those of barium, chromium and lead that were found in significant amounts. However, all concentrations of heavy metals were lower than the limits regulated in the Notification ensuring the environmental safety of MSWIFA to a significant level. Concentrations of three major heavy metals are presented in Fig. 5 to Fig. 7.

Fig. 5 shows the concentrations of barium increased as MSWIFA replacement levels were increased due to high concentration in MSWIFA. In contrast, Fig. 6 shows the concentrations of chromium decreased as MSWIFA replacement levels were increased. Fig. 6 also shows that content of chromium in MSWIFA was similar to that of MSWIFA concrete product. This revealed that OPC was a source of chromium contamination.

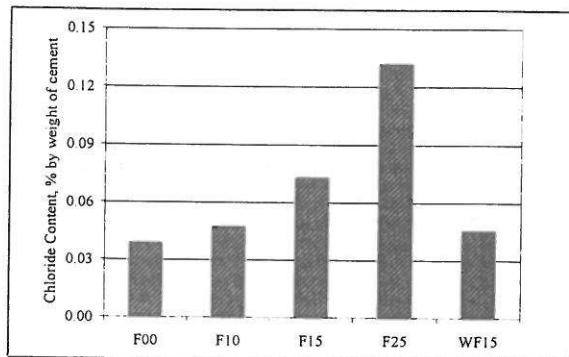


Fig.4. Water-soluble chloride content of OPC, MSWIFA and WMSWIFA concrete.

Fig. 7 shows the accomplishment of stabilization and solidification of lead by OPC because the graph shows almost 70 times reduction in concentrations of lead compared between MSWIFA and MSWIFA concrete. However, it should be noted that concentrations of barium, lead and chloride in wastewater from washing process of MSWIFA were extremely high. Actually, concentrations of lead and barium were approximately 1.6 and 26.5 times higher than the wastewater effluent standard, respectively.

5. Conclusions

The physical and chemical properties of Phuket MSWIFA and WMSWIFA were determined in this study. Specific gravity of MSWIFA was lower than that of OPC almost 40% that may be due to the coarser PSD of MSWIFA. Moisture content and LOI value of MSWIFA were extremely high and in excess of

Table 5

Concentrations of heavy metals in leachate of MSWIFA, WMSWIFA, MSWIFA concrete and WMSWIFA concrete

Metal	Limitation	Concentration, ppm						
		F00	F10	F15	F25	WF15	MSWIFA	WMSWIFA
Silver, Ag	5.000	< 0.007	< 0.007	< 0.007	< 0.007	< 0.007	< 0.007	< 0.007
Arsenic, As	5.000	< 0.100	< 0.100	< 0.100	< 0.100	< 0.100	< 0.100	< 0.100
Barium, Ba	100.000	0.267	0.233	0.244	0.367	0.300	0.956	0.322
Cadmium, Cd	1.000	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005
Cromium, Cr	5.000	0.069	0.064	0.052	0.034	0.053	0.062	0.043
Lead, Pb	5.000	< 0.050	0.078	< 0.050	0.067	< 0.050	3.344	2.033
Mercury, Hg	0.200	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005
Selenium, Se	1.000	< 0.100	< 0.100	< 0.100	< 0.100	< 0.100	< 0.100	< 0.100

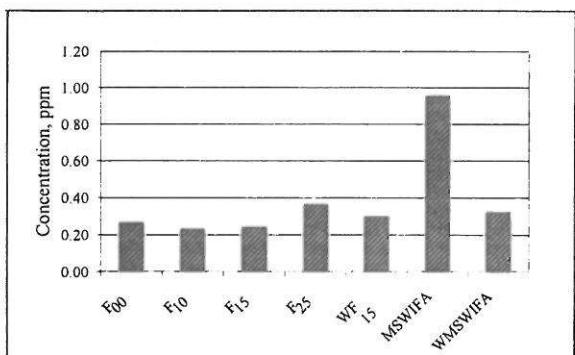


Fig.5. Concentrations of barium in leachates of OPC, MSWIFA and WMSWIFA concrete.

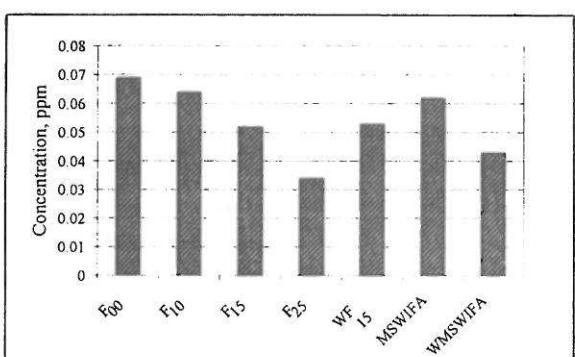


Fig.6. Concentrations of chromium in leachates of OPC, MSWIFA and WMSWIFA concrete.

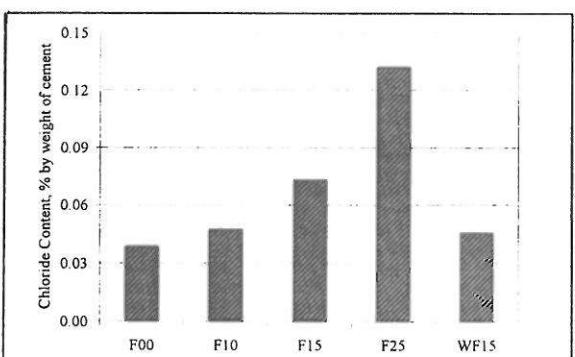


Fig.7. Concentrations of lead in leachates of OPC, MSWIFA and WMSWIFA concrete.

the ASTM C618 limits as well as contents of SO_3 and alkalis. However, it should be noted that ASTM C618 is generally designed for only CFA and natural pozzolans. Major chemical compositions in MSWIFA were CaO , NaCl and KCl as observed by XRF and XRD. Properties of WMSWIFA were almost similar to

those of MSWIFA, except moisture content and chemical compositions. Mainly, chloride and alkalis were dissolved after the washing process and $\text{Ca}(\text{OH})_2$ was newly formed.

Properties of MSWIFA and WMSWIFA concrete were also studied. Chloride present in MSWIFA significantly accelerated the setting time of MSWIFA concrete, by approximately 30%. Nevertheless, all compressive strengths of MSWIFA concrete were lower than that of OPC concrete even at the later age. The higher MSWIFA replacement levels, the greater reduction in compressive strength was observed. However, the rate of compressive strength development of OPC and MSWIFA concrete were similar. The maximum compressive strength of MSWIFA (F10) concrete at the age of 28 days was 310 ksc, which was 14% lower than that of OPC concrete at the same age. Water-soluble chloride contents of all concrete specimens, even the highest MSWIFA replacement level, were still within the limits to prevent corrosion of reinforcing steel.

Only concentrations of barium, chromium and lead were detected in significant amounts; however, all of them were well within the limits specified in the Notification. The results also revealed that MSWIFA was a source of barium contamination, while OPC was of chromium. Lead was effectively stabilized by high alkalinity of cement hydration products. It should be noted that high concentrations of barium, lead and chloride were measured in the wastewater from MSWIFA washing process.

From the results of this study, the possibility of MSWIFA utilization as a partial cement replacement in concrete was realized. However, similar to the beginning scenario of utilization of CFA in concrete, further researches should be conducted to clearly understand the effects of MSWIFA on the properties of concrete as well as the environmental safety of the products. This may include quality control of MSWIFA, durability aspects and other mechanical properties of MSWIFA concrete, and long-term environmental monitoring of MSWIFA products. It is expected that the fur-

ther researches related to the above topics concerning both of civil and environmental engineering aspects will lead to the most valuable and safest final destination for MSWIFA, instead of landfill disposal.

6. Acknowledgement

The authors would like to thank the National Research Center for Environmental and Hazardous Waste Management, Department of Environmental Engineering, and Department of Civil Engineering, Chulalongkorn University for the valuable supports.

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