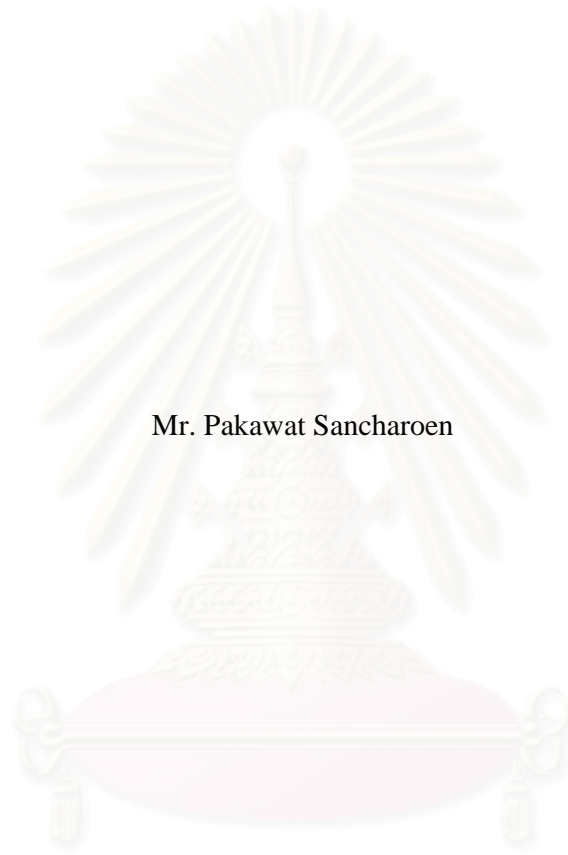


UTILIZATION OF MUNICIPAL SOLID WASTE INCINERATOR
FLY ASH AS A PARTIAL CEMENT REPLACEMENT IN CONCRETE



Mr. Pakawat Sancharoen

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การประยุกต์ใช้เก้าอี้จากเตาเผาขยะชุมชนทดแทนปูนซีเมนต์บางส่วนในคอนกรีต



นายภัควัฒน์ แสนเจริญ

สถาบันวิทยบริการ

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 จากเตาเผาขยะชุมชน จังหวัดภูเก็ต การทดสอบรวมถึงค่าความถ่วงจำเพาะ ขนาดอนุภาค พื้นที่
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 เกณฑ์ต่ำกว่าความต้องการของมาตรฐาน ASTM C618

นอกจากนี้ผลการทดลองของคุณสมบัติของคอนกรีตสด การพัฒนากำลังอัด และปริมาณ
 คลอไรด์ที่ละลายน้ำ ของคอนกรีตที่มีการประยุกต์ใช้เถ้าลอยจากเตาเผาขยะชุมชนแทนปูนซีเมนต์
 บางส่วนระบุว่า กำลังอัดของคอนกรีตผสมเถ้าลอยจากเตาเผาขยะชุมชนมีค่าต่ำกว่าค่าของ
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 อยู่ในเกณฑ์ที่ยอมรับได้ตามข้อกำหนดของวิศวกรรมสถานแห่งประเทศไทยเพื่อป้องกันการกัดกร่อน
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ลักษณะของน้ำชะจากเถ้าลอยจากเตาเผาขยะชุมชน และคอนกรีตผสมเถ้าลอยจาก
 เตาเผาขยะชุมชนถูกวิเคราะห์ตามข้อกำหนดในประกาศกระทรวงอุตสาหกรรม ฉบับที่ 6 พ.ศ.
 2540 เพื่อศึกษาความปลอดภัยต่อสิ่งแวดล้อมในการนำเถ้าลอยมาใช้ประโยชน์ ผลการทดสอบ
 ระบุว่าความเข้มข้นของโลหะหนักมีค่าต่ำกว่าข้อกำหนดตามประกาศกระทรวง แต่อย่างไรก็ตาม
 น้ำเสียที่เกิดจากการล้างเถ้าลอยจากเตาเผาขยะชุมชนมีค่าความเข้มข้นของ แปรเปี่ยม
 ตะกั่ว และคลอไรด์สูงเกินมาตรฐานน้ำเสีย

สหสาขาวิชา...การจัดการสิ่งแวดล้อม...ลายมือชื่อผู้นิสิต.....
 สาขาวิชา.....การจัดการสิ่งแวดล้อม...ลายมือชื่ออาจารย์ที่ปรึกษา.....
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PAKAWAT SANCHAROEN : UTILIZATION OF MUNICIPAL SOLID WASTE INCINERATOR FLY ASH AS A PARTIAL CEMENT REPLACEMENT IN CONCRETE. THESIS ADVISOR : MANASKORN RACHAKORNKIJ, Ph.D., THESIS COADVISOR : PROF. METHI WECHARATANA, Ph.D., 99 pp. ISBN 974-17-3544-8.

The physical and chemical properties of sifted and washed samples of municipal solid waste incinerator fly ash (MSWIFA) collected from mass-burn incinerator in Phuket, Thailand were determined. Tests included specific gravity, particle size distribution, specific surface area, moisture content, loss on ignition, absorption capacity, morphology, bulk chemical compositions, and mineralogical compositions. Results showed that properties of MSWIFA did not meet most of the requirements of ASTM C618.

MSWIFA was used to directly replace cement by up to 25 percent for making MSWIFA concrete. Parameters under investigation included properties of fresh concrete, development of compressive strength from 3 to 90 days, and water-soluble chloride content. The results showed that compressive strengths of all MSWIFA concrete specimens were lower than those of control concrete. It was found that chloride, a soluble fraction of MSWIFA, accelerated setting time of concrete and improved compressive strength compared to that of washed MSWIFA concrete. Fortunately, water-soluble chloride contents of all samples were within the limits set by the Engineering Institute of Thailand to prevent corrosion of reinforced steel.

Leachate extraction procedure described in the Notification of Ministry of Industry No.6 (1997) was used to evaluate environmental safety of MSWIFA and concrete products. Results showed that concentrations of all regulated metals were within the limits. However, it should be noted that concentrations of barium, lead, and chloride in wastewater from washing process were higher than effluent standards.

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NOMENCLATURES

APC	=	air pollution control
ASTM	=	American Society for Testing of Materials
C ₂ S	=	2CaO·SiO ₂ , dicalcium silicate
C ₃ A	=	3CaO·Al ₂ O ₃ , tricalcium aluminate
C ₃ S	=	3CaO·SiO ₂ , tricalcium silicate
CH	=	Ca(OH) ₂ , calcium hydroxide
C-S-H	=	calcium silicate hydrate
CClOHHyd	=	calcium chloride hydroxide hydrate
d _{50%}	=	mean particle size
ESP	=	electrostatic precipitator
Fly Ash	=	particulate matters captured from flue gas by APC systems
ksc	=	kilogram per square centimeter
LOI	=	loss on ignition (%) defined by ASTM C311 as the weight fraction of material that is lost by heating the oven dried sample at 750°C
MSW	=	municipal solid waste
MSWI	=	municipal solid waste incineration
MSWIFA	=	municipal solid waste incinerator fly ash sampled from ash pit and then sifted passed through a standard sieve No. 20
SEM	=	scanning electron microscope
TCLP	=	Toxicity Characteristic Leaching Procedure
w/(c+fa)	=	water-to-binder ratio, the weight ratio of water to cement and fly ash
w/c	=	water-to-cement ratio
XRD	=	X-ray diffraction spectrometer
XRF	=	X-ray fluorescence spectroscopy

CHAPTER 1

INTRODUCTION

1.1 General

Thailand is one of the developing countries that are currently faced with the problem regarding disposal of municipal solid waste (MSW) due to two reasons. Firstly, the increase in population in each city causes higher amount of MSW that is required to be disposed of. The amount of MSW generated has been increasing every year; for example, from 29,540 tons/day in 1992 to 37,879 tons/day in 1999. Most of it (72%) was disposed of by open dumping and burning. Other methods were landfill (27%) and incineration (1%). Secondly, direct landfill disposal of MSW requires a large area of landfill space, which leads to rapid depletion of the existing landfill space. A new landfill construction proposal may not be an attractive alternative anymore because of rising costs associated with landfill construction and operations.

The biggest island city of Thailand Phuket is located in the southern part of Thailand. Phuket has very limited space to build a new landfill because almost 70 percent of the total area (570 sq.km.) is mountainous. Approximately 202 tons of MSW was generated daily in 1997. In 1994, sanitary landfill with the capacity of 370,000 tons of MSW was constructed, but its capacity was reached in 1998. Therefore, a construction of a MSW incinerator was completed in 1997 and operated in 1998 to reduce the volume of MSW prior to landfill disposal.

The main advantage of incineration is that it can reduce the volume of MSW up to 90 percent and the weight up to 75 percent of the original. Therefore, an amount of MSW that required further management such as transportation can be reduced. Moreover, high temperature in combustion chamber can destroy pathogenic and organic fractions in MSW. Heat that is released from combustion can be

recovered by the energy recovery system and converted to electricity or steam. This recovered energy can offset the capital and operation costs of the incinerator.

Although incinerator can effectively reduce the volume and weight of MSW, incinerator still leaves two major types of residue: bottom ash and fly ash. Bottom ash (BA) is a principal residue from incineration. Its amount is between 20 to 25 percent by weight of the original waste or around 80 to 95 percent of total residue. It is collected from bottom of combustion chamber. Normally, it is safe for landfill disposal. It is possible to recover and utilize the iron component in BA. Modified BA has a potential for use as a concrete aggregate (Berg and Neal, 1998) or road base material. Recovery and utilization of these fractions can reduce the capacity of landfill required for disposal. In contrast, fly ash (FA) is a particulate matter that is captured from exhausted gases by air pollution control device prior to emission into the atmosphere. FA may be collected alone or together with products from flue gas treatment processes. Its amount is between 2 to 3 percent by weight of the original waste. Due to very high temperature in combustion chamber, many gaseous compounds, including vapors of heavy metals, are produced and presence in the flue gas. When the flue gas is cooled these evaporated heavy metals and other gaseous compounds will condense and deposit on the surfaces of fly ash particles. In contrast to BA, FA may be considered as hazardous waste because of high content of heavy metals such as arsenic, lead, and, cadmium that may be leached out from the landfill and contaminate the environment. Residues are normally subjected to test for leachable substance by leaching extraction procedure that is described in the Notification of Ministry of Industry No.6, B.E. 2540 (1997), issued under Factory Act, B.E. 2539 (1996). Residues having concentrations of heavy metal or toxic substances in the extract in excess of the limit contaminants listed in the Notification, will be classified as hazardous waste. Therefore, prevention techniques such as solidification and stabilization are used prior to disposal in the HDPE-lined landfill. One of the additive reagents that can stabilize heavy metals is Portland cement.

There are many researches that succeeded in utilizing coal fly ash (CFA) in concrete. It is directly used as a partial cement replacement or a mineral admixture to Portland cement concrete. CFA may be grounded and blended with Portland cement to produce blended cement. Due to physical properties and chemical

characteristics of CFA, it is classified as pozzolanic material. We have realized that CFA can enhance properties of concrete such as increase in workability; increase in ultimate 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. In contrast to CFA, there are a few researches that were conducted on utilization of MSWIFA in Portland cement concrete. If it is found that MSWIFA can improve the properties of concrete and, at the same time, its toxic elements can be stabilized and solidified, MSWIFA products may find their niche in the market for construction applications. If this is so, disposal cost of MSWIFA that involves high-capital investment, operation, and environmental control and monitoring can be minimized or offset by the revenue generated from the sale of MSWIFA.

1.2 Objectives

The main objective of the study is to investigate the properties of concrete incorporating municipal solid waste incinerator fly ash (MSWIFA). The specific objectives are as follow:

1. To determine the physical and chemical characterization of MSWIFA
2. To determine the properties of concrete that uses MSWIFA as a cement replacement
3. To determine the potential environmental impact as a result of MSWIFA solidification in product

1.3 Scopes of Study

This research was conducted to determine the compressive strength development and leachate characteristics of concrete containing MSWIFA. The fly ash was obtained from mass burn incinerator in Phuket, Thailand. The following works of the research were studied.

1. The physical characteristics and chemical composition of MSWIFA were studied including particle size distribution, specific surface area, bulk specific gravity, moisture content, loss on ignition, morphology, chemical compositions, and mineralogical compositions.

2. The Portland cement was directly replaced by MSWIFA 0, 10, 15, and 25 percent and washed MSWIFA 15 percent by weight of Portland cement. Therefore, totally five batches of concrete were mixed. Soon after mixing, fresh concrete properties such as slump, unit weight, and setting time were determined. To determine development and ultimate compressive strength of the concrete products, the concrete products were subjected to compressive strength test at the age of 3, 7, 14, 28, 56, and 90 days.
3. Both of MSWIFA and concrete product were analyzed for the presence of heavy metals according to the leachate extraction procedure described in the Notification of Ministry of Industry No. 6, B.E. 2540.
4. Social, economical, and environmental benefits from concrete products were discussed.



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CHAPTER 2

LITERATURE REVIEW

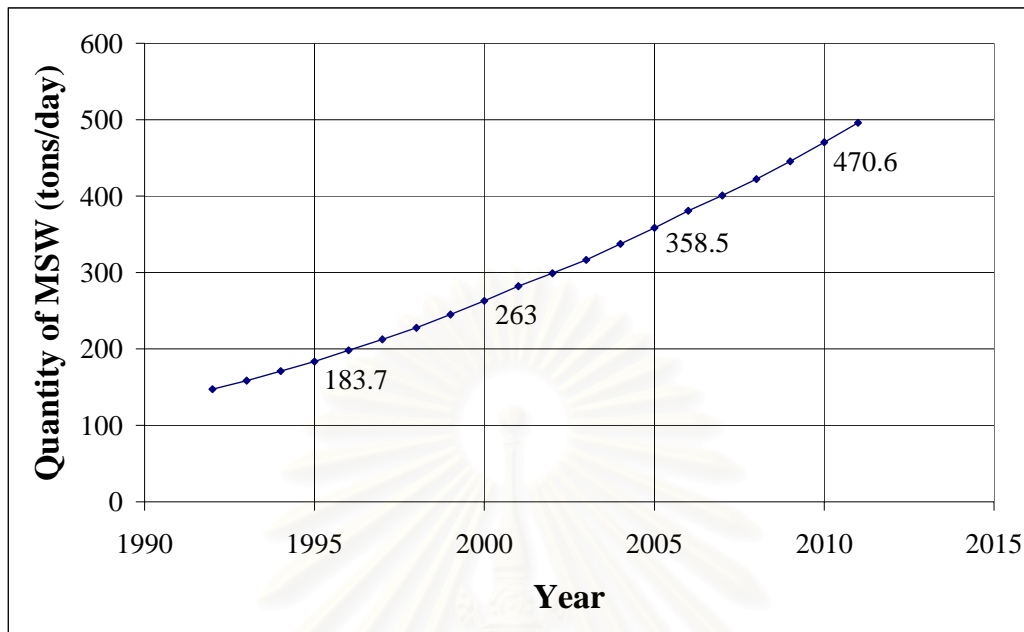
2.1 Municipal Solid Waste (MSW)

Pollution Control Department (PCD) gives the definition of municipal solid waste (MSW) in the Regulation and Guideline for Solid Waste Management. It says “any solid waste generated from community activities, e.g. residential household, commercial and business establishments, fresh market, institutional facilities and construction and demolition activities, excluding hazardous and infectious wastes”.

Phuket, Thailand’s biggest island, is located in the southern part of Thailand. Total area of Phuket is 570 sq.km; however, 70 percent of it is mountainous. In 1997, the total amount of MSW generated in Phuket was around 202 tons/day. In 1994, five sanitary landfills, with the total area of 192,793 sq.m, had already been in operation, but their total design capacity of 370,000 tons was reached in 1998. However, as estimation of an amount of MSW will increase to 496.1 tons/day in 2011 as shown in Figure 2.1.

Due to the fact that direct landfill disposal of MSW causes rapid depletion of existing landfill space, it is not suitable for a city with limited space such as Phuket. The most effective solution to manage MSW is integrated solid waste management. The management hierarchy of source reduction, recycling, transformation, and landfill disposal. As a result, the final amount of MSW to be disposed of in landfill can be minimized. The construction of the incinerator in Phuket was completed in 1998 in order to minimize the waste requiring disposal.

Figure 2.1 Estimation of the Quantity of MSW Generated in Phuket



Source: Pal Consultant, 1998

2.2 *Municipal Solid Waste Incinerator (MSWI)*

Rapid increase in landfill investment cost from higher value of land property, operation and maintenance cost, and difficulties in proposing a new sanitary landfill made construction of a new landfill less attractive. Countries with limited land space such as Japan and Switzerland realized the problems and chose MSWI over landfill as their solid waste management means. Approximately 63 percent of generated MSW was incinerated in Japan. Japan also has the highest number of MSW incinerator that is 1,850 incinerators. In Asia, there is limited experience about MSW incinerator except industrialized countries such as Japan, Singapore, and Taiwan. In Thailand, there are only 7 proposed incinerator projects; however, only 2 of them are have been in operation as shown in Table 2.1.

Table 2.1 MSW Incinerator Projects in Thailand

Name	Status	Capacity (Tons/Day)	Cost
Phuket Municipal Waste Incineration Plant	Operational	250	\$25,000,000
Samui Municipal Solid Waste Incineration Plant	Operational	140	\$3,500,000
Waste-to-Energy Plant in Chiang Mai	Canceled (because of local protest)	300	\$50,000,000
On Nut Waste-to Energy Plant Phase I (Bangkok)	Proposed	1,350	\$125,000,000
On Nut Waste-to Energy Plant Phase II (Bangkok)	Proposed	1,350	\$125,000,000
Nongkhaem Waste-to-Energy Plant (Bangkok)	Proposed	1,350	\$125,000,000
Tha Reang Waste-to-Energy Plant (Bangkok)	Proposed	1,350	\$125,000,000

Source: Greenpeace, 1996

2.2.1 Process and Air Emission Control of MSWI

MSWI is a combustion system that transforms solid wastes by chemical oxidation in an excess air atmosphere to mainly carbon dioxide and water. There are two broad categories of MSWI that are in operation nowadays: mass-burn and refuse-derived fuel (RDF). However, most of MSWI are mass-burn type that allows as-received and non-homogeneous MSW to be fed into the incinerator. Processing of MSW such as removal of glass or ferrous materials is required for RDF incinerator type. The main advantage of MSWI is a reduction in volume of waste. MSWI can reduce approximately 90 percent by volume and 75 percent by weight of the original MSW. This can effectively reduce the space that is required for landfill disposal. Approximately 80-95 percent by weight of total residue is a bottom ash (BA) that is residues collected from bottom of the combustion chamber. Remainder is a fly ash (FA) that is a residue captured by the air pollution control device. MSWI also destroys organic and pathogenic fractions in MSW by very high temperature (more than 870 °c) in combustion process. To offset very high capital and operation cost of the incinerator, heat from combustion is recovered by energy recovery system in the form of electricity or hot water and sold to the market.

Although the main products of combustion process are carbon dioxide and water, many kinds of air pollutant may be emitted from MSWI. Nitrogen oxides (NO_x) are formed during combustion process in presence of nitrogen in air and fuel.

Sulfur dioxide (SO₂) is formed by the combustion of sulfurous compounds. Acid gases such as hydrogen chloride (HCl) and hydrogen fluoride (HF) are formed during the combustion of the MSW contained chlorine and fluorine such as PVC, and other plastics. Due to very high temperature in combustion process, heavy metals contained in MSW are vaporized and may be emitted in the form of vapor. More than the gaseous emissions, and particulate matter carried over in flue gases is also emitted. To protect the environment, air emissions from the incinerator are regulated as shown in Table 2.2. Therefore, modern MSWI will be installed with very high-cost and high-technology air pollution control (APC) devices.

Table 2.2 Standard of Air Emissions from the MSW Incinerator

Pollutant	Standard of the incinerator's capacity	
	1-50 (tons/day)	More than 50 (tons/day)
1. Particulate Matter, PM (mg/m ³)	Less than 400	Less than 120
2. Sulfurdioxide, SO ₂ (ppm)	Less than 30	Less than 30
3. Nitrogen oxides, NO _{xs} (ppm)	Less than 250	Less than 180
4. Opacity (%)	Less than 20	Less than 10
5. Hydrochloric, HCl (ppm)	Less than 136	Less than 25
6. Dioxins, (ng/m ³)	Less than 30	Less than 30

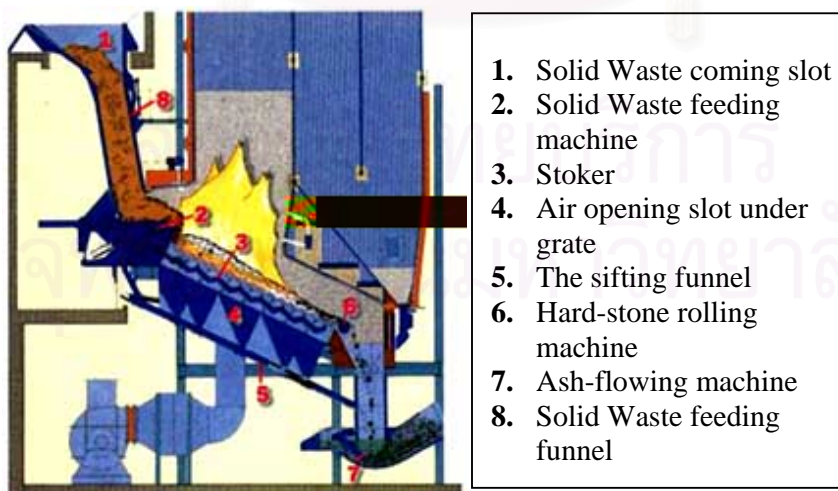
Source: Ministry of Science and Technology, 2003

Combination of various APC devices is installed in MSWI. Nitrogen oxides are normally minimized by controlling the burning condition or using flue gas treatment. Mostly selective non-catalytic reduction is used to minimize the formation of nitrogen oxides. This process injects ammonia (NH₃) to the hot flue gases to produce nitrogen and water. Flue gases are cooled down by heat recovery unit or spray cooler. Acid gases such as sulfur dioxide or hydrochloric acid can be neutralized by dry, semi-dry, or wet scrubber processes. Vapors of heavy metals condensed and deposited on the surface of particulate matters and scrubber residues. Both of particulate matters and scrubber residues, which are fly ash, will be captured together or separately by fabric filters or electrostatic precipitators.

Phuket MSWI was completely constructed in 1997 and has began in operation since 1998. It is a mass-burn incinerator with moving grate that allows 250 tons/day as-received MSW to be fed. Table 2.3 shows the amount of MSW that are fed to the incinerator since the beginning. Heat from combustion is used to produce steam. Steam turbine is used to generate 2,500 kW of electricity. Figure-1A shows

burning process of the Phuket incinerator. This process can be simply explained as 1. Collected MSW are weighed and stored in the refuse pit. 2. Operator of refuse crane removes bulky items (larger than 50 cm.), then homogenizes, picks, and feeds the MSW to a hopper. 3. MSW flows through refuse feeder and mixed with ignited MSW by moving grate in the furnace as shown in Figure 2.2. Mostly MSW incinerator is equipped with the moving grate because it can accommodate large variations in waste composition and heating value. The grate will transport, mix and level the waste and also supplies and distributes air for the combustion process. 4. Heated air is forced up to furnace through the bottom of grate. 5. MSW is dried, ignited, combusted, and final burned out together with flowing down along the grate. 6. Completely burned MSW that is bottom ash is cooled down by quenching in the water bath before stored in ash pit and transferred to landfill. 7. Flue gases are cooled down to 230-300 °C by passing through the boiler that produces steam and electricity. More than generating the electricity, cooling the flue gases is necessary to improve efficiency of the followed air pollution control devices such as a bag filter. 8. Flue gases are injected with dry lime powder to neutralize acid gases such as HCl and SO₂. Products of this process are calcium chloride, calcium sulfite, calcium sulfate, and calcium fluoride. 9. Scrubber products and fly ash are captured together by bag filter before be moistened and transferred to HDPE lined landfill. 10. Finally the clean gases are emitted through the stack to the atmosphere.

Figure 2.2 Martin Stoker Grate



Source: Phuket Municipality, 2003

2.2.2 Residues from MSWI

Although MSWI can significantly reduce the volume of MSW up to 90 percent of the original, MSWI still leaves two major types of residue, Bottom ash and Fly ash that require proper management. Figure 2.3 shows the approximate amount of residues generated from the incinerator. As discussed earlier, bottom ash accounts for approximately 80 to 95 percent by weight of total residue or 20 to 25 percent by weight of the combusted waste. Bottom ash is a noncombustible material that remains on a grate at the end of the combustion cycle. It consists basically of glass, ceramics, ferrous, and non-ferrous metals. Bottom ash is collected in an ash pit and cooled down by water. Normally, bottom ash passes the leaching test, so it can be transferred and disposed of in sanitary landfill. Recovery and utilization of this residue is possible.

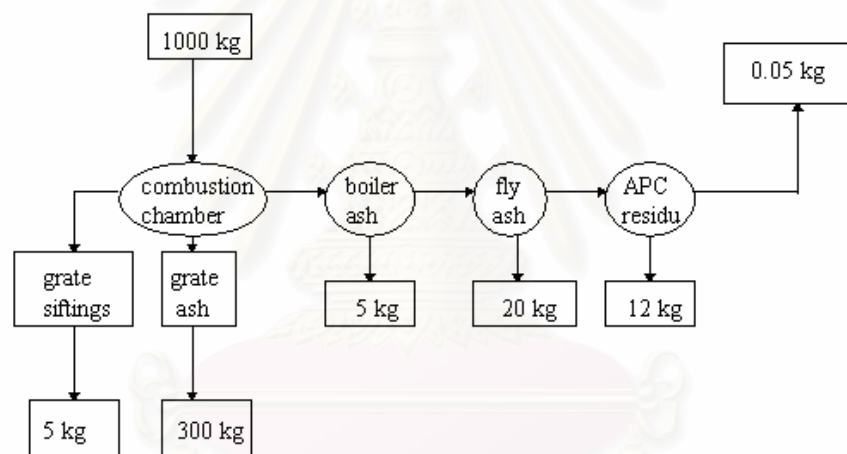


Figure 2.3 Amount of Residues Generated from the Incineration

Source: Vandecasteele et al., 2003

Fly ash is defined as particulate matters that are captured from the flue gases by the air pollution control device such as bag filter. At Phuket incinerator, both of fly ash and scrubber products are captured together by bag filter. Fly ash is recovered from bag filter and moistened before being transported and disposed of in HDPE-lined landfill. Table 2.3 shows total amounts of residue from the Phuket incinerator. Approximately 23 percent by weight of incinerated MSW is bottom ash, while fly ash accounts for only 3.5 percent by weight.

Table 2.3 Quantity of Incinerated MSW and Residues of Phuket MSWI

Operation period	Average quantity of MSW, excluding moisture (tons/day)	Average quantity of residues (tons/days)	
		Bottom Ash	Fly Ash
23 June 1999 - 22 July 1999	161	43.00	11.09
23 July 1999 - 21 Aug. 1999	196	65.55	8.38
22 Aug. 1999 - 20 Sept. 1999	225	42.53	5.47
21 Sept. 1999 - 20 Oct. 1999	215	43.42	4.46
21 Oct. 1999 - 19 Nov. 1999	225	52.60	5.90
20 Nov. 1999 - 19 Dec. 1999	235	50.87	11.70
20 Dec. 1999 - 18 Jan. 2000	256	83.45	18.45
19 Jan. 2000 - 17 Feb. 2000	241	42.33	4.63
18 Feb. 2000 - 18 Mar. 2000	251	73.40	9.23
19 Mar. 2000 - 17 Apr. 2000	246	53.23	5.40
18 Apr. 2000 - 17 May 2000	230	60.55	7.86
18 May 2000 - 16 June 2000	240	61.97	10.20
17 June 2000 - 16 July 2000	240	74.00	5.70
17 July 2000 - 15 Aug. 2000	239	55.63	6.50
16 Aug. 2000 - 14 Sept. 2000	227	53.90	6.40
15 Sept. 2000 - 14 Oct. 2000	223	54.80	5.83
15 Oct. 2000 - 13 Nov. 2000	232	55.77	7.08
14 Nov. 2000 - 13 Dec. 2000	233	49.76	6.14
14 Dec. 2000 - 12 Jan. 2001	252	57.23	4.87
13 Jan. 2001 - 11 Feb. 2001	254	57.70	6.03
12 Feb. 2001 - 13 Mar. 2001	256	56.73	4.67
14 Mar. 2001 - 12 Apr. 2001	260	55.27	5.77
13 Apr. 2001 - 12 May 2001	259	64.13	4.97
13 May 2001 - 11 June 2001	267	57.75	6.15
12 June 2001 - 2 July 2001	162	36.07	4.79
3 July 2001 - 1 Aug. 2001	258	49.10	4.77
2 Aug. 2001 - 31 Aug. 2001	263	54.07	54.07
1 Sept. 2001 - 30 Sept. 2001	272	58.17	5.73
1 Oct. 2001 - 30 Oct. 2001	257	59.43	6.27
Average (tons/day)	237.07	55.95	8.57

Source: Department of Public Work, 2001

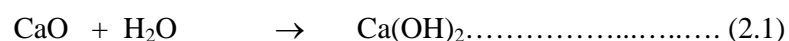
2.2.3 Contaminants in MSWIFA

Due to the nature of MSW that consists of various kinds of waste, residues from MSW incinerator are contaminated with both of organic and inorganic compounds. However, under well-controlled burning condition, the organic pollutants

can be minimized. Therefore, in this study the pollutants of interest are inorganic pollutants such as heavy metals and salts.

Although there are many kinds of metals in MSW stream, there are only eight metals regulated in the TCLP test; namely, arsenic, barium, cadmium, chromium, lead, mercury, silver, and selenium, because there are evidences that they can cause cancer, birth defect, nervous disorders, and etc. For example, storage batteries, newspaper, plastics, pigments, paints, and electronics equipment contain most of those metals. It is interesting because not only clearly realized metallic waste such as batteries or electrical equipment, but also easy combustible waste such as paper and plastics are also significant sources of heavy metals. It should be made clear that an incinerator cannot destroy the metals, but it can only change their physical and chemical forms. Due to very high temperature in combustion process, heavy metals are vaporized and entrained in the flue gases. When the flue gases are cooled down, vapors of metals condense and attach to the surface of fly ash particles and scrubber residues. Therefore, when they are disposed in landfill, heavy metals may be leached out and contaminate the environment. In order to assess the leaching characteristic of the fly ash, it is subjected to the leaching test such as the U.S. TCLP (Toxicity Characteristics Leaching Procedure) that is explained later in section 3.2.4.

Chloride and sulfate salts are easily soluble in water; therefore they can also easily be leached out from the landfill and contaminate the environment. These salts are the final products from a scrubber process of an air pollution control system designed to neutralize the acid gases, hydrochloric (HCl) and sulfur dioxide (SO₂). As discussed earlier, HCl is converted from the combustion of organic chlorine found in plastics and solvent. And SO₂ comes from combustion of sulfurous compounds. There are 3 types of scrubber process: dry, semi-dry, and wet. However Phuket incinerator is equipped with dry scrubber system. In this process, dry lime powder is injected to the cooled flue gases to neutralize acid gases and produces chloride and sulfate salts as shown in the equation 2.1 to 2.3.



2.3 Physical and Chemical Characteristics of MSWIFA

2.3.1 Bulk Specific Gravity

Hamernik and Frantz (1991a) studied the physical properties of fly ashes from different MSW incinerators in the US. They reported that specific gravity of MSWIFA was in the range of 2.22 – 2.51 that is close to value obtained from CFA.

Mangialardi et al. (1998) also studied the characteristics of MSWIFA from the mass-burn incinerator in Italy for using in concrete. The specific gravity of MSWIFA determined by the pycnometer method was 2.39.

Rachakornkij (2000) studied the utilization of MSWIFA as a cement replacement in mortar. He concluded that bulk specific gravity of MSWIFA was lower than cement by about 20-35%. Results showed that the finer MSWIFA particles had higher bulk specific gravity than the coarser MSWIFA.

2.3.2 Particle Size Distribution and Specific Surface Area

Mangialardi et al. (1998) used combination of two methods to find particle size distribution of MSWIFA. They used standard sieving method for particle size ranging 63 to 1000 μm and particle size analyzer for particle size ranging 0.9 to 63 μm . Their results showed that 80 percent of the material was smaller than 250 μm . Specific surface of particle finer than 63 μm also determined by particle size analyzer was 0.1539 m^2/cm^3 .

Remond et al. (2002) studied the characteristics of MSWIFA from MSW incinerator equipped with wet scrubber process in France. They sieved MSWIFA through 630 μm sieve before testing. Using laser diffraction particle size analyzer, particle size distribution of MSWIFA can be determined. They reported that particle size of MSWIFA was coarser than cement (determined by particle size analyzer) and finer than sand (determined by sieving). Mostly the particle sizes were between 50 and 500 μm .

2.3.3 Moisture Content and Loss on Ignition (LOI)

Hamernik and Frantz (1991a) reported that the moisture content of MSWIFA was in the range of 1.2 to 5.2 percent while LOI was in the range of 4.90 to 13.40 percent. This variation may be due to the nature of MSW, pre-combustion process, combustion condition, and air pollution control system. Moisture content and LOI of MSWIFA collected from mass-burn incinerator were lower than that collected from RDF. They also reported that MSWIFA could absorb moisture from the atmosphere approximately 20 percent by weight if it was sufficiently exposed to the atmosphere. This is probably due to high surface areas and high LOI values.

Mangialardi et al. (1998) determined LOI of MSWIFA that was classified into 3 groups depending on its particle size: bigger than 500 μm , between 125 to 250 μm , and smaller than 63 μm . The coarsest also had the highest LOI (16.27 percent); however, LOI value of the finest was higher than the middle size.

Rachakornkij (2000) showed very high values of LOI (12.63-17.94%). He believed that MSWIFA contained the particles of unburned carbon or charred. LOI value of washed MSWIFA was higher than raw MSWIFA, because bound water in hydrated compounds was driven off by very high temperature in the furnace.

2.3.4 Morphology

In contrast to CFA that has generally smooth-surfaced and spherical particles, Hamernik and Frantz (1991a), Rachakornkij (2000), and Remond et al. (2002) found that MSWIFA had a variety of shapes and surface textures including full or hollow spherical particles, long or flat particles, very porous particles, etc.

2.3.5 Bulk Chemical Compositions

According to ASTM C618, fly ash is classified into 2 classes depending on the summation of oxides of silica, alumina, and iron: class C (minimum 50 percent) and class F (greater than 70 percent). The x-ray fluorescence (XRF) spectrometry can be efficiently used to measure oxide contents of the sample. Mangialardi et al. (1998), and Remond et al. (2002) reported that the most abundant oxides found in MSWIFA were SiO_2 , CaO , Al_2O_3 . Moreover, alkalies, chlorides, and

sulfates were also relatively high. Hamernik and Frantz (1991a) concluded that the summation of SiO_2 , Al_2O_3 , and Fe_2O_3 of the RDF fly ash met class C requirements while mass-burn fly ash did not meet the requirements for both classes. These findings were also confirmed by Mangialardi et al. (1998), Rachakornkij (2000), and Remond et al. (2002). However, after washed by water, Mangialardi et al. (1998) found that the MSWIFA met the limit of three oxides summation of class C. Remond et al. (2002) also reported that heavy metals were mainly zinc and lead. The total amount of heavy metals in MSWIFA represented approximately 2 % by weight of MSWIFA. Effect of particle size on chemical composition was determined by Mangialardi et al. (1998). Their results showed that most of chemical compositions depended on particle sizes of MSWIFA. In contrast, Rachakornkij (2000) concluded that fractionation did not affect the chemical compositions. He also concluded that washing by water significantly reduced Na and Cl contents that may be in the form of NaCl.

Rand et al. (2000) reported the chemical compositions of incinerator residues. They found that heavy metals, that had high boiling point such as Fe, Cu, and Ni, were present in bottom ash more than in fly ash. In contrast, lower boiling point metals, Al, Zn, Pb, Cr, As, Cd, and Hg, were present in higher amount in fly ash.

Fermo et al. (1999), studied the MSWIFA in Italy, used TXRF and ICP (inductively coupled argon plasma spectrometry) analysis to determine total composition of MSWIFA after total digestion. They found that results from both methods showed good agreement. The major constituents ($\geq 10000 \mu\text{g/g}$) were Cl, Si, S, Ca, Na, Al, K, Zn, P, Pb, and Mg. Minor constituents ($1000 - 10000 \mu\text{g/g}$) were Fe, Ti, Sn, Cu, Ba, and Sb. Trace elements ($\leq 1000 \mu\text{g/g}$) were Cr, Cd, Mn, Sr, Ag, Zr, Ni, Se, Mo, Tl, Th, and U.

2.3.6 Mineralogical Compositions

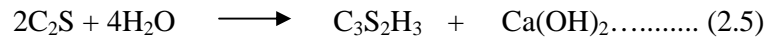
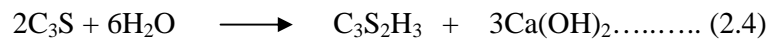
Remond et al. (2002) used X-ray powder diffraction spectrometry (XRD) to detect the main crystalline compounds present in MSWIFA. They found that major phases are quartz (SiO_2), sylvite (KCl), halite (NaCl), anhydrite (CaSO_4), calcite (CaCO_3), and lime (CaO) respectively. Mangialardi et al. (1998) reported the presence of anhydrite (CaSO_4), and gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) that can form the

ettringite ($\text{CaSO}_4 \cdot 32\text{H}_2\text{O}$), which causes expansion of concrete. However, quartz, gehlenite ($\text{Ca}_2\text{Al}_2\text{SiO}_7$), belite (Ca_2SiO_4), calcite, Ca_3SiO_3 , and albite ($\text{NaAlSi}_3\text{O}_8$) were also detected. After the MSWI was leached in solution at pH 4.8, they found that the peak intensities of belite, gehlenite, and calcite decreased, while that of gypsum increased. Fermo et al. (1999) reported that the presence of crystalline phases was difficult to be detected in the raw MSWIFA, because of great complexity of the patterns and numerous peaks overlapping. However, halite (NaCl), sylvite (KCl), bassanite, anhydrite, and gypsum could be identified. They also detected leached MSWIFA with water or acid; therefore, main crystalline components that are silicates can be easier identified. If MSWIFA was leached by water, they found the presence of gehlenite, gypsum, anhydrite, calcite, and syngenite ($\text{K}_2\text{Ca}(\text{SO}_4)_2 \cdot \text{H}_2\text{O}$). If they leached with HCl and H_2O_2 , they found gehlenite, gismondine ($\text{CaAl}_2\text{SiO}_8 \cdot 4\text{H}_2\text{O}$), and ettringite. Moreover, Rachakornkij (2000) found calcium aluminum oxide ($\text{Ca}_2\text{Al}(\text{OH})_7 \cdot 3\text{H}_2\text{O}$), calcium chloride hydroxide (CaClOH), calcium chloride hydroxide hydrate ($\text{CaCl}_2 \cdot \text{Ca}(\text{OH})_2 \cdot \text{H}_2\text{O}$), indialite ($\text{Mg}_2\text{Al}_4\text{Si}_5\text{O}_8$), revdite ($\text{Na}_2\text{SiO}_6 \cdot 5\text{H}_2\text{O}$), and ZnCl_2 . Hydrated compounds such as portlandite ($\text{Ca}(\text{OH})_2$), calcium aluminum oxide, calcium aluminum hydroxide ($\text{Ca}_2\text{Al}(\text{OH})_6\text{Cl} \cdot 2\text{H}_2\text{O}$), and hydrocalumite ($\text{Ca}_4\text{Al}_2\text{O}_6\text{Cl}_2 \cdot 10\text{H}_2\text{O}$) were detected in washed MSWIFA, while soluble salts such as halite were removed.

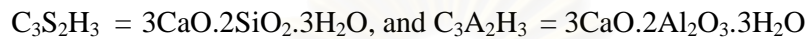
2.4 Properties of MSWIFA concrete

Typically, concrete is a mixture of cement, aggregate, and water. Also other materials such as mineral or chemical admixtures and pozzolanic materials may be added to improve specific properties of concrete. Due to the presence of the major compositions of cement, calcium silicates (C_3S and C_2S), and water, hydration reaction can occur. In the hydration reactions as shown in the equation 2.4 to 2.6, calcium silicate oxides react with water and produce microcrystalline hydrated product, calcium silicate hydrate ($\text{C}_3\text{S}_2\text{H}_3$), and crystalline product, calcium hydroxide ($\text{Ca}(\text{OH})_2$). Calcium silicate hydrate is a cementitious material that causes concrete to firm, set and harden, while calcium hydroxide causes an alkaline condition that can protect corrosion of reinforcing steel. Also tricalcium aluminate (C_3A) is one of the cement compositions; however, it is present in comparatively small amount. Its hydration reaction is very rapid and undesirable because its reaction causes the flash

set of concrete and also produces high heat of hydration. Therefore, gypsum is added to the cement clinker to reduce the rate of this reaction.



when, $C_3S = 3CaO.SiO_2$, $C_2S = 2CaO.SiO_2$, $C_3A = 3CaO.Al_2O_3$



There are numerous properties of concrete of concern. Fresh concrete properties such as workability, setting time, bleeding, unit weight, and air content have significant effects on the long-term properties of hardened concrete such as strength and durability. There are many factors that can affect both of fresh and hardened concrete properties. One of the major factors is the property of concrete ingredients, which include admixtures and pozzolanic material. Therefore, all of major concrete ingredients have specific standards such as cement (ASTM C150), and aggregates (ASTM C33) that control their properties to ensure that the final concrete product will have satisfactory properties. Also coal fly ash and natural pozzolanic material for use as a mineral admixture in concrete has its specific standard (ASTM C618). Pozzolanic material, a siliceous or siliceous aluminous material, which by itself possesses little cementitious properties, can react with calcium hydroxide in the presence of moisture to form calcium silicate hydrate, a cementitious compound, also product from hydration reaction of Portland cement. This reaction is called pozzolanic reaction and shown in the equation 2.7 to 2.8.



ASTM standard C618, standard specification for coal fly ash and raw or natural pozzolan for use as a mineral admixture in concrete, set the requirements of many parameters that can affect the properties of concrete. For example, chemical compositions and physical properties, effects of these parameters on concrete properties are discussed later in sect 3.2.1. Although this specification is mainly

applicable for coal fly ash, it is used as a guideline to evaluate MSWIFA because there is no particular standard for MSWIFA.

For decades, CFA have been successfully used as a partial cement replacement or as a mineral admixture for Portland cement concrete. CFA is also grounded and blended with Portland cement to produce blended cement. Due to physical properties and chemical characteristics of CFA, it is classified as pozzolanic material. CFA can improve properties of concrete such as increase in workability; increase in ultimate strength; increase in sulfate resistance; reduce in alkali-aggregate reaction; reduce in permeability and chloride ion penetration; reduce in heat of hydration; and reduce in cost of concrete. In contrast, there have been few researches that conducted on MSWIFA utilization in concrete.

Hamernik and Frantz (1991b) studied the properties of concrete in which cement was replaced by MSWIFA up to 60% by weight. They reported that MSWIFA itself did not show the cementitious properties and did not set after 72 hrs when mixed with only water. MSWIFA also increased the water requirement and the initial and final setting time of concrete. Up to 30 percent of cement replacement MSWIFA concrete showed better compressive strength or comparable to that of the control concrete. However, the initial development of compressive strength in MSWIFA concrete was slower than the control concrete similar to case of CFA concrete. They also concluded that the strength of MSWIFA concrete was contrary to the results predicted by the pozzolanic test in mortars.

Triano et al. (1992) studied the durability of MSWIFA concrete. They concluded that both strength and durability of concrete are varied significantly depending on the type of MSWIFA used. For example, concrete containing MSWIFA from RDF incinerator showed better compressive strength than control concrete, while the lower compressive strength was obtained in case of mass-burn MSWIFA concrete.

Ali and Chang (1994) studied the properties of masonry brick that contained MSWIFA. They reported that the compressive strength of MSWIFA brick increased with up to 40 percent replacement.

Pera et al. (1997) studied the potential of using MSWIBA as a concrete aggregate. Their results revealed that raw MSWIBA could cause the problems of swelling, and cracking of concrete because of the reaction between metallic aluminum, that presence in MSWIBA and cement. However, a simply process, that MSWIBA is immersed in sodium hydroxide solution, can eliminates those problems.

Mangialardi et al. (1998) studied the properties of mortars that cement was replaced by raw MSWIFA and washed MSWIFA up to 35 percent by weight of cement. The compressive strength and flexural strength decreased as the ash content increased. However, washed MSWIFA showed better results than raw MSWIFA.

Berg et al. (1998) evaluated the potential of using MSWI bottom ash as a concrete ingredient. They concluded that the angularity, chloride, and sulfate content of raw MSWIBA could cause the problems in application in concrete. However, by using simply processes such as sieving, rinsing, or blending for uniformity, most of those problems can be eliminated.

Rachakornkij (2000) concluded that MSWIFA retarded the hydration process of cement because intensity of XRD peaks of calcium silicate hydrate and calcium hydroxide detected in MSWIFA cement paste were lower than control paste at the same ages. However, the compressive strengths of MSWIFA cement mortars at the replacement level 15% were higher than the control mortars.

Wang et al. (2001) studied the properties of cement paste that used MSWIFA slag as a cement replacement ranging from 0% to 60%. Their results showed that the early compressive strengths (3 to 28 days) of slag-blended pastes were lower than the control pastes. However, after 28 days, the compressive strength of 10% and 20% slag-blended pastes were higher than the plain pastes. Dilution effect, due to the fact that cement was replaced by slag, caused the reduction of the hydration reaction in the early ages. However, at later ages, the delaying pozzolanic reaction, which had to wait for breaking down and dissolving the glassy structure of the slag by calcium hydroxide, enhanced the later compressive strength. However, with the higher percent cement replacement, both of early and later compressive strengths were lower than those of the control pastes, because the mixes did not have enough calcium hydroxide to enhance the pozzolanic reaction.

Remond et al. (2002) determined the hydrated compounds formed in MSWIFA-cement paste by XRD analysis. They showed that the major crystalline compounds formed due to the addition of MSWIFA were ettringite, Friedel's salt, and thenardite. They also studied the properties of mortars in which sand was replaced by MSWIFA by up to 20 percent by weight of cement. Their results revealed that the presence of MSWIFA caused retardation of the initial and final setting time. They believed that zinc and lead, the most abundant metals found in MSWIFA, were the setting retards. However, incorporating MSWIFA up to 15 percent replacement, the compressive strengths of MSWIFA mortars increased. The optimum replacement was found at 10 percent. They also conducted the test on specimens that used MSWIFA-washed water as mixing water. Their results showed that soluble fractions of MSWIFA, chlorides, significantly increased the compressive strength. While the specimens that used washed-MSWIFA instead of raw MSWIFA showed the lower compressive strength because of weak bond between the cement paste and the MSWIFA.

From previous discussion that MSWIFA contains a significant level of chloride content, which has a negative effect on durability of concrete. Normally uncarbonated concrete can protect corrosion of reinforcing steel because its network of pores contains highly alkaline solution ($\text{pH}=13.5$) that produces the passivating ferric oxide film around the reinforced steel. This film can protect steel from corrosion. However, when chloride is present in sufficient concentration, it will destroy the protection film and lead to corrosion. To prevent this problem, the Engineering Institute of Thailand (E.I.T.) (1991) established the guideline, "Building Code Requirements for Reinforced Concrete and Commentary", that specify maximum contents of water-soluble chloride present in concrete to prevent the possibility of reinforcing steel corrosion as shown in Table 2.4. Chloride can contaminate concrete from the two major sources: external and internal. External source is chloride that permeates into the concrete during the service life such as chloride permeation from seawater, while internal source is chloride that is present in concrete ingredients such as aggregate or chemical admixture. Chloride in MSWIFA is categorized as internal source, because scrubber process as a part of the air pollution control system injected lime to react with acid gases containing sulfur, and chlorine compounds. Therefore, chloride can deposit on the fly ash. Some of chloride

in the concrete is fixed in the hydration products such as Friedel's salt or fixed by the surface force on the surface of hydration products. The remaining chloride, or "free chloride", in the pore solution can destroy the protection film. Addition of pozzolanic material can reduce permeation of concrete and increase fraction of fixed-chloride. (E.I.T., 2000). Same conclusion was reached by Hussain et al. (1994) and Haque et al. (1995) that the unbound chloride in the pore solution decreased with the replacement of cement by coal fly ash that means the CFA itself can bind the free chloride in concrete. However, the total chloride content of 15 percent replacement MSWIFA concrete to be at less 15 times higher than control concrete was reported by Triano et al. (1992). Therefore, there is possibility of corrosion of the reinforced steel. Rachakornkij (2000) found that chloride in MSWIFA was involved in the formation of the new phase, hydrocalumite, detected by XRD after the ages of 7 days. He believed that hydrocalumite responses for the improvement of compressive strength of MSWIFA mortar.

Table 2.4 Maximum Water-Soluble Chloride Content

TYPE OF MEMBER	LIMIT*
1. Prestressed concrete	0.06
2. Reinforced concrete	0.15
3. Reinforced concrete that will be dry or protected from moisture in service	1.00
4. Other reinforced concrete constructio	0.30

* as percent of cement by weight

Source: Engineering Institute of Thailand, 1991

2.5 *Solidification and Stabilization*

Aside from, the improvement of concrete performance by addition of MSWIFA, this study expected that alkalinity of cement hydration product can stabilize the heavy metals presented in MSWIFA. Due to air pollution control devices, most of vapors of heavy metals are condensed and attached to the MSWIFA particles. Therefore, MSWIFA is normally considered as hazardous waste that requires special treatment and disposal. There are many treatment techniques that can be categorized into 3 major groups: physical processes such as air stripping, chemical processes such

as oxidation, and biological processes such as composting. Depending on specific characteristics of the waste and field condition, the most suitable method or combination of them is chosen. However, in this study solidification and stabilization (S/S) method are mainly concerned.

In general, solidification means “a process by which sufficient quantities of solidifying material, including solids, are added to the hazardous materials to result in a solidified mass of material”. In contrast, stabilization means “a process where additives are mixed with waste to minimize the rate of contaminant migration from the waste and to reduce the toxicity of the waste” (Lagrega, 2001). Normally, these two methods are used together in the treatment of waste. Resulting improves handling capability, decrease the contact area, limit the rate of migration, and reduce toxicity of the waste. Cement, lime, pozzolan, thermoplastic, and organic polymer or combinations are successful in utilized as additive of solidification and stabilization process. However, in this study the cement-based stabilization is the major mechanism.

Due to high alkalinity of cement hydration product, calcium hydroxide, heavy metals are fixed within stabilization product in the form of hydroxide or carbonate salts. Therefore, reduce the leachability of the heavy metals. Also cementitious properties of cement also solidify the waste; therefore, reduction in contact area. However, some constituents of the waste, especially organic compounds, may affect the hydration process of the cement causing retardation of setting time or reduce the compressive strength.

Wang and Vipulanandan (1996) studied the leachability of lead from fly ash cement products. They used lead nitrate mixed with mixing water. They found that lead nitrate caused higher amount of Ca and Si released in the pore solution, which means that lead possesses a deleterious effect on cement paste and affects the hydration of calcium silicates. Lead also retarded the initial and final setting time of Pb-cement pastes; therefore the strengths at later ages were lower than control paste. However, addition of fly ash can reduce both of initial and final setting times and also increase leached resistance of lead.

Hamilton and Sammes (1999) studied the stabilization of steel foundry bag house dusts in cement mortar. They concluded that zinc oxide retarded the hydration reaction of concrete in the first two weeks; however, it accelerated the strengths at later ages (after 28 days). Cement was successful to stabilize zinc and lead by using 10% cement replaced due to low concentration of leached metals and good compressive strength.

Wang and Vipulanandan (2000) studied the stabilization of Cr(VI) by cement. The hexavalent chromium used was potassium chromate (K_2CrO_4) and added to mixing water. It appeared that Cr(VI) retarded the setting times of cement which depended on initial Cr(VI) concentrations. Also presence of Cr(VI) had negative effect on the compressive strength. They found that reaction between calcium hydroxide and CrO_4^{2-} produced calcium chromate ($CaCrO_4$) during hydration of Cr(VI)-cement paste. However, original potassium chromate can be observed too. Immobilizing of Cr(VI) was successful because the solubility of calcium chromate is very low. Cr(VI) presented in S/S products in form of CrO_4^{2-} because of high alkaline condition ($pH > 12$).

Olmo et al. (2001) studied the effects of several kinds of heavy metals oxide on the setting time and strength of cement paste. Their results revealed that zinc, lead, and chromium oxide retarded the setting time. However, only zinc oxide affected the compressive strength of the paste.

2.6 Leaching Procedure

The potential for contaminant loss from a stabilized mass is usually determined by leaching tests. Leaching test means “the process by which contaminants are transferred from a stabilize matrix to a liquid medium such as water” (Lagrega, 2001). There are 2 major categories of the leaching test: batch test and column test. In the batch test, the waste is continuously contacted with the same leachant in the extraction vessel. This test is reproducible, simple to perform, and it simulates the worst-case scenario. Therefore, the current regulations such as TCLP (Toxicity Characteristic Leaching Procedure) specify batch test as a standard method. In case of the column-leaching test, leachant is continuously or intermittently renewed and flowed through a column packed with waste. Therefore, it is considered as a

representative of the field conditions. In Thailand, According to the notification of Ministry of Industry No.6, B.E. 2540 (1997), issued under Factory Act, B.E. 2539 (1996), residues from MSWI are considered as a leachable substances that must be tested for the leachate characteristics by leachate extraction procedure prior to disposal. Concentration of heavy metals and toxicological substances in leachate, specified in the notification, will be determined. Residue will be managed as non-hazardous waste if the concentration of toxic substance in extracted from residue is below the limit. On the contrary, residue that fails the test will be managed as hazardous waste and is required special treatment or disposal. Although very high temperature in combustion process of the incinerator can effectively destroy the organic compounds that presence in MSW, it cannot destroy the heavy metals. Moreover, the high temperature will vaporize the heavy metals and release contaminants into the flue gases. When the flue gases are cooled down, the vapors of heavy metal will condense and deposit on the surface of the particulate matters. Therefore fly ash has relatively high content of heavy metals and also soluble salts from scrubber process; it is normally categorized as hazardous waste and requires prevention techniques such as stabilization and solidification before disposed in sanitary landfill.

Hamernik and Frantz (1991a) studied the leachate of MSWIFA using TCLP and EPTOX. They concluded that the leachate showed high concentrations of heavy metals, especially lead and cadmium, which were substantially higher than the toxicity limits. There are significant variations in an amount of leachable metals between different types of the incinerator. This variation is probably due to the different in content of MSW fed to the incinerator or processing of MSW before feeding. They also concluded that the amount of heavy metals by leaching test and X-ray fluorescence analysis were significantly different in result.

Wang and Vipulanandan (1996) used extended TCLP to evaluate leached lead from cement-coal fly ash stabilized products. They found that addition of fly ash reduced the concentration of leached lead by 10% to 30% compared to only cement paste. However, as initial concentration of lead was greater than 10%, leached concentration of lead from all of stabilized products exceeded the regulatory limit.

Webster et al. (1996) studied the long-term leaching characteristics of Cd, Cr, and Pb from the concrete products. Results showed the alkalinity of cement was decreased over time in the sequential leaching test. Therefore, metals fixed in the concrete matrix were more soluble. Leached chromium concentrations were high when pH of the leachant was relatively high ($\text{pH} > 6$). For leached cadmium, its concentrations were very low when $\text{pH} > 8$. At $\text{pH} < 6$, leached lead concentrations were significantly increased from the level lower than detection limit.

Mangialardi et al. (1998) carried out the leaching test by two leachant: acetic acid/sodium acetate ($\text{pH} = 4.8$) and distilled water ($\text{pH} = 7$). They found that the most leachable metals were cadmium, lead, chromium, and arsenic, respectively. Due to the fact that pH has no effect in the leaching of chromium, they believed that chromium was present in form of Cr^{+6} .

Rachakornkij (2000) found that concentration of leached lead from raw MSWIFA failed to meet the TCLP limits. However, after stabilized in cement mortars, concentrations of all regulated metals passed the test.

Wang and Vipulanandan (2000) also used extended TCLP to evaluate the leaching of Cr(VI) from cement-stabilized products. Results showed leached chromium was in the form of Cr(VI) and was depended on initial concentration and leaching time. Efficiency of this treatment was higher than 80 percent.

Zhang et al. (2001) discussed the concentration of leached metals from coal fly ash concrete by three different methods: TCLP (18 hrs.), batch leaching test (24 weeks), and column leaching test. They concluded that concentrations of leached metals from all of the methods were below the regulatory levels. They commented using buffer solution and crushing of sample in TCLP method caused overestimation of the leached concentration relative to actual field condition. Using batch test or column leaching test was a better representative of the actual field conditions. Concentrations of leached Se by any methods were lower than the detection limit. Most of leached concentrations of heavy metals did not show any correlation to metals content in the fly ash or fly ash content in the paste.

Wang et al. (2001) reported that although Pb, Zn, and Cu were major components found in the MSWIFA, only TCLP leaching concentration of Cd exceeded the regulatory thresholds.



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CHAPTER 3

METHODOLOGY

3.1 Materials

3.1.1 Municipal Solid Waste Incinerator Fly Ash (MSWIFA)

Approximately 500 kg of raw MSWIFA was sampled from the ash pit of the Phuket MSW incinerator under the normal plant operation. This dumped MSWIFA was moistened after it was recovered from the bag filter. MSWIFA was collected and transported in double plastic bags. After MSWIFA was delivered to the laboratory, it was stored in a plastic lined plastic container. Stored raw MSWIFA was sifted through an ASTM standard sieve No. 20 (0.84-mm openings) before carried out any tests to remove very large particles and to preserve amount of MSWIFA. Approximately 25 % by weight of raw MSWIFA was passed through standard sieve No. 20. This sifted MSWIFA was named “MSWIFA”.

Moreover, a portion of sifted MSWIFA was simply washed in a blender with tap water to remove its soluble contents. Then it was dried in an oven over night. Details are given in section 3.2.3. This MSWIFA was named “washed-MSWIFA”. Both of MSWIFA and washed-MSWIFA was 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.

3.1.2 Portland Cement

Ordinary Portland cement type I according to ASTM C150, Mountain brand manufactured in Thailand by Asia Cement Public Company Limited, was used throughout the study.

3.1.3 Fine Aggregate

Natural river sand sieved pass through an ASTM standard sieve No. 4 (4.75-mm openings) was used as a fine aggregate for all concrete mixes. The particle size distribution was graded within the ASTM C33 limits as shown in Figure 3.1.

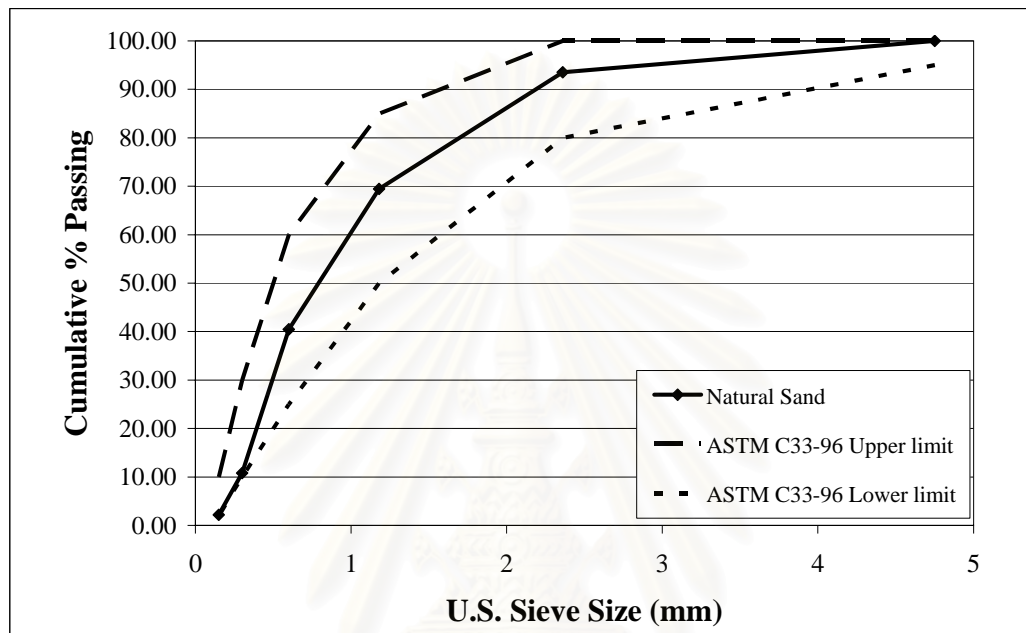


Figure 3.1 Grain Size Distribution of Fine Aggregate

3.1.4 Coarse Aggregate

The crushed limestone was used as a coarse aggregate. In this research two nominal sizes of coarse aggregates: 0.75 in. and 1 in. were mixed in the ratio of 47:53 by weight to achieve the gradation limits according to ASTM C33 as shown in Figure 3.2.

3.1.5 Mixing Water

Ordinary tap water supplied at Concrete laboratory, Chulalongkorn University was used for all concrete mixes.

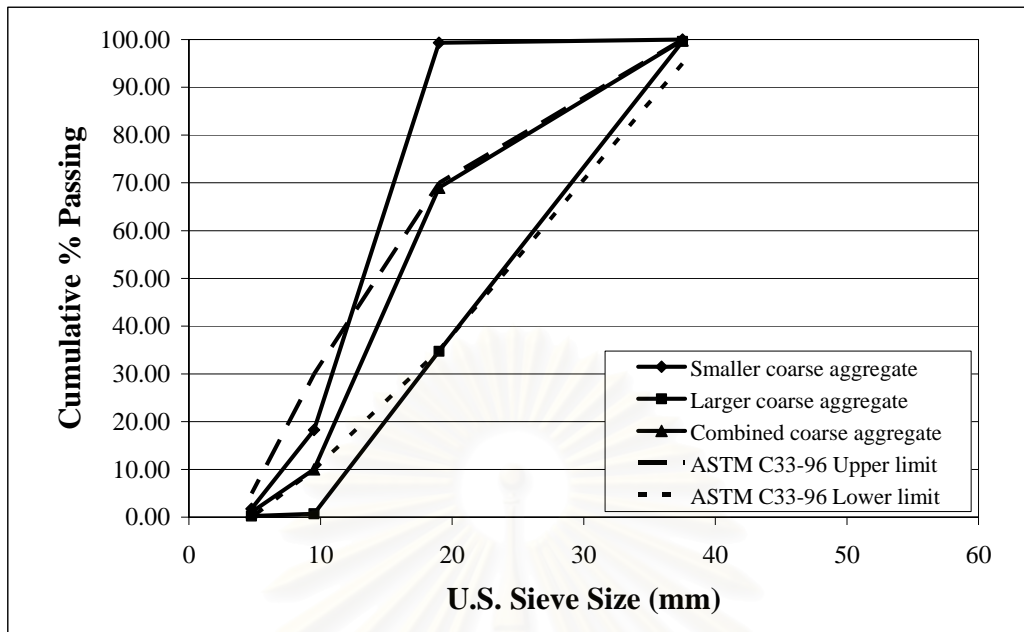


Figure 3.2 Grain Size Distribution of Coarse Aggregate

3.1.6 Trial Mixing

Firstly, approximate concrete mixture proportion was designed following the recommendation of ACI committee 211 (Chovichien, 1996) to achieve compressive strength of 250 ksc. at 28 days and slump 10 ± 2 cm. This designed proportion was used as the basic control mix. However, trial mixing was used to determine the actual water to cement ratio which produced for the workability equivalent to the designed slump.

3.1.7 Mix Proportions

Resulted water to cement ratio was used to produce five mix proportions. All mix proportions were shown in Table 3.1. All of the ingredients, except cement, were remained constant, while cement was directly replaced by MSWIFA at the ratio of 0, 10, 15, and 25 percent by weight of cement in the mix No. F00, F10, F15, and F25 respectively. Washed-MSWIFA replaced at the only 15 percent replacement in the mix No. WF15. Water to binder ratio was kept constant aiming to determine the effect of MSWIFA on the compressive strength of concrete.

Table 3.1 Mix Proportions of MSWIFA-Cement Concrete

Mix No.	% Replacement	Ingredients (kg/m ³)					
		Cement	MSWIFA	Sand	Water	Smaller coarse aggregate	Larger coarse aggregate
F00	0	282	0	816	178	582	516
F10	10	254	28	816	178	582	516
F15	15	240	42	816	178	582	516
F25	25	212	71	816	178	582	516
WF15	15	240	42	816	178	582	516

3.1.8 Mixing Procedure

According to ASTM C192, coarse aggregate, sand and approximately 70 % of total mixing water were added to the wetted mixer. Then start the mixer; cement was added simultaneously with the MSWIFA because it was considered as insoluble material admixture that had an 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 than 10 minutes.

3.1.9 Casting and Curing of Specimens

After mixing, internal vibration was used to consolidate the concrete into the cylindrical (150x300 mm) molds. Cylinder specimens were cast for compressive strength test at the age of 3, 7, 14, 28, 56, and 90 days for all test mixtures in accordance with ASTM C192. Triplicates of sample were used in the all of the strength test. After 24 hours, all of the specimens were demolded and cured in the moisture room until the time of testing.

3.2 Experimental Program

3.2.1 Characteristics of MSWIFA

Physical and chemical properties of MSWIFA can have influence on the properties of fresh and hardened concrete product. Therefore, clear understanding of the characteristics of MSWIFA can help to explain results in this study. All of MSWIFA, washed MSWIFA and cement were subjected to the following tests.

3.2.1.1 Bulk Specific Gravity

Bulk specific gravity is defined as the ratio of the weight of a given volume of a sample, including all pores, to the weight of the same volume of water. Bulk specific gravity of the material is depended on its physical properties and chemical compositions. We use bulk specific gravity to design the mixture proportion of concrete. Unit weight of concrete product is also depended on the specific gravity of its mixture.

According to standard method ASTM C188, bulk specific gravity of Portland cement can be measured. In this method, pycnometer was partially filled with kerosene instead of water to ensure that all grains of sample were wetted and that hydration of cement was prevented. Then, approximately 64 g. of cement was placed into the pycnometer. All types of MSWIFA were also subjected to this method except only 50 g. of MSWIFA was used instead of 64 g. of cement as recommended by ASTM C311.

3.2.1.2 Particle Size Distribution and Specific Surface Area

Particle size of cement has a significant effect on the rate of its hydration reaction. Finer cement particles cause reduction in the setting time and increase the strength development because it has more specific surface area to react with the water than coarser particles.

The Malvern Particle Size Analyzer model Mastersizer 2000 equipped with the Scirocco 2000 was used to determine the particle size distribution of the samples. The size distribution of dry powder samples, like cement and MSWIFA, can be directly measured in the range of 0.02 – 2000 μm . with using air as a medium. Approximately 10 g. of sample was placed on the tray then vibration and air pressure fed the sample to the measurement unit. Air pressure was varied between 0 to 4 bars until consistent result was obtained from each sample. Because air pressure can break the agglomerate particles and change their particle size distribution. The Malvern Particle Size Analyzer model Mastersizer 2000 uses the technique called Low Angle Laser Light scattering (LALLS). This technique assumes that the particle is

homogeneous and spherical. The obtained distribution result is the average value of three measurements.

Specific surface area is used to represent the fineness of the sample and relate to the rate of interaction with the surrounding. There are several methods to determine the specific surface area such as air permeametry, or gas adsorption; however, cement is normally measured by the Blaine air permeability method according to ASTM C204. It is a comparison between a powder of known surface area and the sample by using the time consumed for a fixed quantity of air to permeate through the packed bed. This standard may be applied to MSWIFA. Specific surface area can be also calculated from particle size distribution data and specific gravity value. By assuming the shape of the particles spherical, the specific surface area can be calculated as expressed in the following equations.

$$S_0 = \frac{\pi \times D_{av}^2}{w} \dots\dots\dots (3.1)$$

$$D_{av} = \frac{\sum D_i M_i}{\sum M_i} \dots\dots\dots (3.2)$$

$$V_{av} = \frac{\pi \times D_{av}^3}{6} \dots\dots\dots (3.3)$$

where S_0 is the specific surface area of the particles on spherical basis, cm^2/g
 D_{av} is the average diameter of the particles, cm
 w is the average weight of the particles = ρV_{av} , g
 D_i is the average opening sieve size between the upper sieve and the sieve i which particles retained, cm
 M_i is the mass (volume) fraction retained on sieve i , %
 ρ is the specific gravity of the particles, g/cm^3
 V_{av} is the average volume of the particles, cm^3

3.2.1.3 Moisture Content and Loss on Ignition (LOI)

ASTM C618 specifies the moisture content in fly ash to less than 3 percent because it will affect the water content of the concrete and may cause the hydration reaction in fly ash. The method described in standard ASTM C311 was used to determine the moisture content of the sample. Approximately 50 g. of sample

was dried in a ceramic cup to a constant weight in the oven at the temperature of 105 – 110 °C. Then, it was placed in the dessicator to prevent absorption of moisture from the atmosphere during the cooling down to room temperature before final weighing. The weight loss is assumed to be the evaporation of the absorbed water.

Loss on ignition (LOI) is normally used to represent the carbon content in the sample. Because carbon content will reduce the air entrainment presented in the concrete that effect the workablity, strength, and durability of concrete. Therefore ASTM C618 specifies the loss on ignition value (LOI) to less than 6 percent. However hydrated and carbonate compounds, presented in sample, may be also ignited and converted to water and carbon dioxide. According to ASTM C 114, LOI value of cement can be determined by igniting 1 g. of cement in the porcelain crucible to a constant weight in a muffle furnace at a temperature of 950 ± 50 °C. While LOI value of MSWIFA was determined by ignited 1 g. of sample, remained from the determination of moisture content, at only 750 ± 50 °C as recommended by ASTM C311. The weight loss after ignited was assumed to be the carbon content present in the sample.

3.2.1.4 Absorption Capacity

Absorption values are used to calculate the change in the weight of the sample due to water absorbed in the pore spaces compared to the dry condition. It may indicate how much the sample would consume the water in the mixes. Then, amount of mixing water is adjusted accordingly. Absorption capacity of the MSWIFA was determined by adapting ASTM C128. Firstly, dried specimen is immersed in water for 24 hrs. to ensure that all pore spaces are filled by water. Then the saturated specimen is gradually dried to saturated surface-dry condition before dried in the oven at a temperature of 110 ± 5 °C. Different in weight between saturated surface-dry condition and oven dry is assumed to be an amount of absorbed water.

3.2.1.5 Morphology

Scanning electron microscopes (SEMs) can be used to understand the particle shape, surface texture, or morphology of the sample. Magnification of SEMs can be varied from 20x to 100,000x, almost 300 times higher than optical instruments,

yielding the resolutions of approximately 5 nm. SEMs use electrons beam to produce secondary electrons emission (SSE), back-scattered electrons (BSE), light cathodoluminescent, and x-rays (Allen, 1997). These signals are detected and displayed on the screen. A SSE image shows particles in only 2 dimensional, which has little indication of height or depth. While the BSE mode, the shadows of the particles, indicating the height, can be identified. In this experiment, the external feature of MSWIFA was investigated by a JEOL JSM-6400 scanning electron microscope (SEM). The fly ash was initially glued on an aluminum stub and coated with gold-palladium alloy so that it was not electrically conductive.

3.2.1.6 Bulk Chemical Compositions

According to ASTM C618, the significant chemical compositions of fly ash such as oxides of silica, aluminum, iron, sulfur, and alkalis, are specified. Silica and alumino silicate are the major composition in the pozzolanic reaction, while sulfur and alkali content have the negative effect on the durability of concrete.

X-ray fluorescence is a mean of identification of elemental presented in the materials. Two major methods are wavelength dispersive spectroscopy (WDS) and energy dispersive spectroscopy (EDS). In the first method, X-rays is used to excite the transition of the electrons of the samples. When excited electrons return to the Ground State, they will emit the fluorescent radiation. This fluorescent radiation from the sample is used as a source of the incident beam instead of x-rays or other particle waves like in XRD. The known analyzer crystal is used as a target for the incident beam. Then the scattered beams from the analyzer are detected. In EDS, they detect and analyze the energy distribution on the produced fluorescence radiation from the sample directly. Mostly detector is a solid state detector such as a Si(Li) or Ge(Li).

In this study, Philips X-ray Fluorescence Spectrometer model 2400, WDS type, was used to determine the elemental composition of the sample. Firstly, sample was ground to homogeneously fine powder because the X-ray only penetrates up to a few millimeters from surface of a sample. Then 1.5 grams of the binder, H_3BO_3 (2.5% by weight), was added to the approximate 4.5 grams of the ground sample before being pressed into a pellet for convenient handling and measurement.

Before running, the pillled sample was put in a sample cup and loaded on a feeder tray of the instrument.

3.2.1.7 Mineralogical Compositions

X-ray diffraction can effectively be used to determine the crystalline structure of the materials; however, particle waves such as neutrons or electrons can also be used. X-rays are produced by interaction between accelerated electrons and metal target. When the accelerated electrons approach the metal target, they are decelerated and rid of the energy in form of X-rays and heat. Before incident of x-rays to the materials, x-ray radiation is passed through the monochromator to produce same wavelength and energy beam. Absorption, fluorescence, scattering, and attenuation (scattering with absorption) occur after the incident of beam. However, only scattered and attenuated beams are the principal of the diffraction technique. Positions and intensities of the measured peaks are related to the crystalline structure, while shapes are related to physical state of the materials. Powder diffraction pattern is produced and used in many applications such as qualitative-quantitative phase analysis, and determination of crystal structures. In this study, only qualitative phase analysis, identification of phases presented in materials, is interested. Identification of phases can be accomplished by compared detected powder diffraction patterns to the Powder Diffraction File (PDF), a database of more than 60,000 phases, developed by the International Center for Diffraction Data (ICDD) (Krawitz, 2001).

In this study, the powder X-ray diffraction (XRD) spectrometer, Bruker model D8 Advance equipped with copper X-ray tube radiation ($\lambda = 1.5418$ °A), was used to identify the crystalline phases of the MSWIFA and cement. Sample was prepared by drying in an oven and grinding in a ceramic mortar until it was homogeneous with particle size of below 45 μm . Operating conditions of the instrument were set at 40 kV accelerating voltage, 40 mA current, 0.02 step time, and 5° to 70° 2 θ scanning range.

3.2.2 Effect of MSWIFA on Properties of Concrete

3.2.2.1 Slump Test

Workability is one of the significant properties of fresh concrete to form and compact without the presence of voids. There are many factors affecting workability such as water content, grading of aggregate, and fineness of cement. The direct method to measure workability is not present. Therefore, the slump test, only an approximate measure of the workability, is accepted worldwide. According to ASTM C143, the freshly mixed concrete was placed and compacted to three layers into the wetted mold. The mold is a cone shape, 300-mm high by 200-mm of base diameter and 100-mm of top diameter. When the mold was filled with the compacted concrete, the mold was slowly raising in the vertical direction. The slump was measured immediately by determining the difference between the height of the mold and the height of the specimen.

3.2.2.2 Unit Weight of Concrete

The unit weight of freshly mixed concrete is important for design of the mixture proportion and quality control. Unit weight depends on specific gravity and proportion of the concrete ingredients. The procedure to determine the unit weight of concrete is described in ASTM C138. Calibrated container of known volume and mass was filled and compacted by freshly mixed concrete. The concrete weight and volume were determined and used to calculate the unit weight.

3.2.2.3 Setting Time of Concrete

Before hardening, concrete will gradually stiffen and set in order to provide sufficient time for placing and finishing the concrete. Normally, concrete should be in plastic condition for at least half an hour. Due to the setting of the concrete is a gradual process, the recognized definition of the setting time should be made. ASTM C403 defines the setting time as “the times required for the mortar to reach specified values of resistance to penetration”.

In ASTM C403, freshly mixed concrete was sieved through a sieve No.4 (4.75 mm.) to obtain the sample of mortar. Then the mortar was homogenized,

placed, and compacted into a container. The compacted mortar was subjected to penetration tests to a depth of 1 in. by a flat-ended plunger over a period of time. The face areas of the plungers were in the ranging of 1 to 0.025 sq. in. The resistance per square inch of face was calculated and plotted with the time when the test was made by the time was begun since the addition of water to the concrete mixer. The initial setting time is the time that a penetration resistance equals to 500 psi; while of the final setting time is 4000 psi.

3.2.2.4 Compressive Strength Test

The most important property of hardened concrete commonly concerned is compressive strength. This is because other properties such as strength properties, bonding, and durability of hardened concrete are related to the compressive strength. The concrete specimens were suddenly measured its dimensions and capped after being removed from the curing room. Therefore, all of specimens were tested in the moist condition as recommended by ASTM C39. The specimens were loaded continuously at constant rate of 0.14-0.34 Mpa/sec. In this study the development of the compressive strength at the age of 3, 7, 14, 28, 56, and 90 days for all test mixtures were determined. Triplicate samples were used in the all of the strength test.

3.2.2.5 Water-Soluble Chloride Content

Chloride presented in concrete from both of internal and external sources can cause corrosion of reinforced steel. There are three major methods to determine the chloride content in the concrete. First, the acid-soluble chloride is used to determine the total chloride content in the concrete because the acid will digest all of the compounds. Second, the water-soluble chloride is used to determine only water-soluble chloride such as sodium chloride. The last, free chloride ion is determined chloride that soluble in the extracted pore solution. However, Engineering Institute of Thailand (E.I.T.) (1991) uses water-soluble chloride as a limitation to prevent the corrosion of the reinforced steel. Therefore, this study determined the water-soluble chloride content to compare against the limitation.

According to ASTM C1218, the sample, obtained from remained concrete cylinder specimens at the age of 28 days, was crushed by hammering until passing the sieve No.20 (850 μm .). Approximately 10 g. of crushed sample was added to 50 mL of reagent water and boiled for 5 min. After standing for 24 hrs and filtration, filtrate was added with nitric acid and hydrogen peroxide and boiled. The chloride content was determined by titration with silver nitrate. Percent of chloride by weight of cement can be calculated.

3.2.3 Effect of Washed MSWIFA on Properties of Concrete

We are realized that chlorides can cause corrosion of the reinforced steel. Due to expectation that MSWIFA contains a significant amount of soluble compounds such as chlorides, the effect of washed MSWIFA on the properties of concrete was investigated. Moreover, calcium chloride, product from air scrubbing process, is expected to be present in the MSWIFA. Addition of calcium chloride more than 2 percent by weight would accelerate the setting time of concrete, while the amount of less than 1 percent would retard the setting. However, the water-soluble chloride level in concrete is limited to protect the reinforced steel from corrosion. Therefore, washed MSWIFA was used to partially replace cement the concrete mixture and subjected to the same series of tests as MSWIFA.

MSWIFA was washed two times by tap water in a mortar mixer with a liquid-to-solid ratio (L/S) equal to 5. The mixer was let to run for 10 minutes and rest for 5 minutes. Then supernatant was removed and replaced with fresh water in the same L/S ratio. Care must be taken in order to avoid loss of fine particles during removal of supernatant. The completely decanted MSWIFA was dried in an oven at 110 °C until fully dried. However, the dried MSWIFA formed cake which needed to be simply crushed by hand to make it into powder form.

Moreover, the supernatant from the washing process was analyzed for chloride ion and heavy metal concentrations. Chloride ion content was analyzed in the same method as mention in section 3.2.2.5. Methods to analyze heavy metals were described in the section 3.2.4.

3.2.4 Leachate Characteristics

Due to expected high content of heavy metals in MSWIFA, both of MSWIFA and MSWIFA-concrete products were subjected to heavy metal analysis in leachate before disposal of MSWIFA or application of MSWIFA-concrete products. The Notification of Ministry of Industry No. 6, B.E. 2540 (1997) describes the method for leachate extraction procedure. This test does not determine the total elemental contents of the samples, but it indicates the leaching potential of eight elements; namely, Arsenic (As), Barium (Ba), Cadmium (Cd), Chromium (Cr), Lead (Pb), Mercury (Hg), Selenium (Se), and Silver (Ag).

Approximately 100 g. of MSWIFA was added with an extraction fluid at a liquid-to-solid ratio equal to 20. The extraction fluid was prepared by adding 80% of sulfuric acid solution and 20% of nitric acid solution in the deionized water until its pH reached 5. The rotary agitator agitated the HDPE bottle, filled with sample and extraction fluid, for 18 hrs at 30rpm. After agitation was finished, the extract was filtrated through an acid-washed 0.6-0.8 μm glass fiber filter. Other sets of the extract was also collected and concentrated by evaporation on the hotplate before analyzed.

Before heavy metal analysis, the extract was subjected to microwave-assisted acid digestion according to U.S. EPA SW-846 Method 3015. In this method, 45 mL of the extract was added with 5 mL of concentrated nitric acid solution. The microwave digester was programmed to reach a temperature of 160 °C in the first 10 minutes and 170 °C in the followed 10 minutes. The digested extract was kept in the HDPE bottle and cooled at 4 °C until analyzed. The heavy metals were analyzed according to the method specified in the Notification of Ministry of Industry No. 2, B.E. 2539 (1996). Mercury (Hg) was analyzed by Varian Atomic Absorption Spectrophotometer model Spectra AA-300 with manual cold vapor generation technique. Other seven metals, silver (Ag), arsenic (As), barium (Ba), cadmium (Cd), chromium (Cr), lead (Pb), and selenium (Se) were analyzed by Perkin-Elmer ICP Atomic Emission Spectrometer model PLASMA-1000.

In case of MSWIFA-concrete product, the samples were obtained from the remained concrete cylinder specimen at the later age then they were crushed until

their particle sizes were less than 9.5 mm. Other procedures were the same as of the MSWIFA.

Concentrations of some heavy metals are lower than detection limit of instruments; therefore, extracted of MSWIFA, washed MSWIFA, and MSWIFA concrete were concentrated by an evaporator before analysis. MSWIFA and washed MSWIFA concrete were concentrated 20 times, while MSWIFA and washed MSWIFA was 5 times. Wastewater from the washing process was also concentrated 2 times.



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CHAPTER 4

RESULTS AND DISCUSSIONS

4.1 Characteristics of MSWIFA

The physical and chemical characteristics of MSWIFA should be evaluated to determine proper management strategy including the possibility of utilization. Many key parameters were determined in this study using samples from an MSW incineration facility in Phuket, Thailand. However, comparison of MSWIFA characteristics obtained from different incinerators should be dealt with discretion since there are many factors that influence the characteristics of MSWIFA. For example, air pollution control technology, feeding waste composition, and type of incineration.

4.1.1 Bulk Specific Gravity

Bulk specific gravity of Portland cement and MSWIFA can be used to preliminary evaluate the chemical compositions, voids, noncombustible material and fineness of the sample. Moreover, bulk specific gravity is significant in designing the mix proportion and unit weight of concrete. Therefore, bulk specific gravity of Portland cement and MSWIFA were determined according to standard method of ASTM C188. The results of bulk specific gravity are shown in Table 4.1 and also compared to NJIT MSWIFA and Mae-Moh CFA.

Table 4.1 Physical Properties of MSWIFA, Mae-Moh CFA, and Portland Cement

Sample	Specific Gravity	Moisture Content, %	Loss on Ignition, %	Absorption, %
MSWIFA	1.92	14.81	12.44	21.01
Washed MSWIFA	2.26	0.44	17.33	10.32
NJIT MSWIFA¹	2.26	2.83	12.94	NR
Mae-Moh CFA²	2.02	0.09	0.23	NR
Portland Cement	3.14	0.13	1.95	NR

Note: from (1) Rachakornkij (2000); (2) Jaturapitakkul et al. (2001); “NR”

means does not be reported.

As shown in Table 4.1, bulk specific gravity of MSWIFA, washed MSWIFA, and Portland cement were 1.92, 2.26, and 3.14, respectively. The bulk specific gravity of MSWIFA was quite less than those of other samples. Approximately, the specific gravity of MSWIFA was 39% lower than that of Portland cement. While value of washed-MSWIFA was comparable to NJIT MSWIFA, it was still lower than Portland cement.

The bulk specific gravity of MSWIFA was lower than others because of particle size and porosity. Kiattikomol et al. (1999) and Rachakornkij (2000) revealed that the finer particle size of fly ash showed higher bulk specific gravity than the one with larger particle size. This was due to the fact that larger-size fly ash had a higher porosity than smaller one. Results obtained from particle size analyzer, shown later, revealed that the average particle size of MSWIFA was larger than of washed MSWIFA. Therefore bulk specific gravity of MSWIFA was the lowest.

As discussed earlier, the bulk specific gravity of sample effects the unit weight of concrete when it is used as one of the concrete ingredients. Lower specific gravity of the material results in lower unit weight of concrete product that is discussed in the section 4.2.2.

4.1.2 Particle Size Distribution and Specific Surface Area

Particle size of Portland cement is related to its rate of reaction and also properties of concrete, water demand, pore structure, and strength development.

Also particle size of MSWIFA can affect the properties of concrete. Particle size distribution can be used to assess other physical properties of sample such as permeability and workability. Moreover, contents of heavy metals presented in MSWIFA depend on the particle size distribution of MSWIFA. Rebeiz and Mielich (1995) revealed that higher heavy metals content were found in the fine particles of MSWIFA due to their higher surface areas. Particle size distribution of the incineration residue greatly depends on the waste feed composition, incinerator type, operational condition, heat recovery system, and installed air pollution control devices. Therefore, Portland cement, MSWIFA and washed MSWIFA were determined their particle size distributions by a laser scattering particle size analyzer. Figure 4.1 shows the particle size distribution of MSWIFA, washed MSWIFA, and Portland cement.

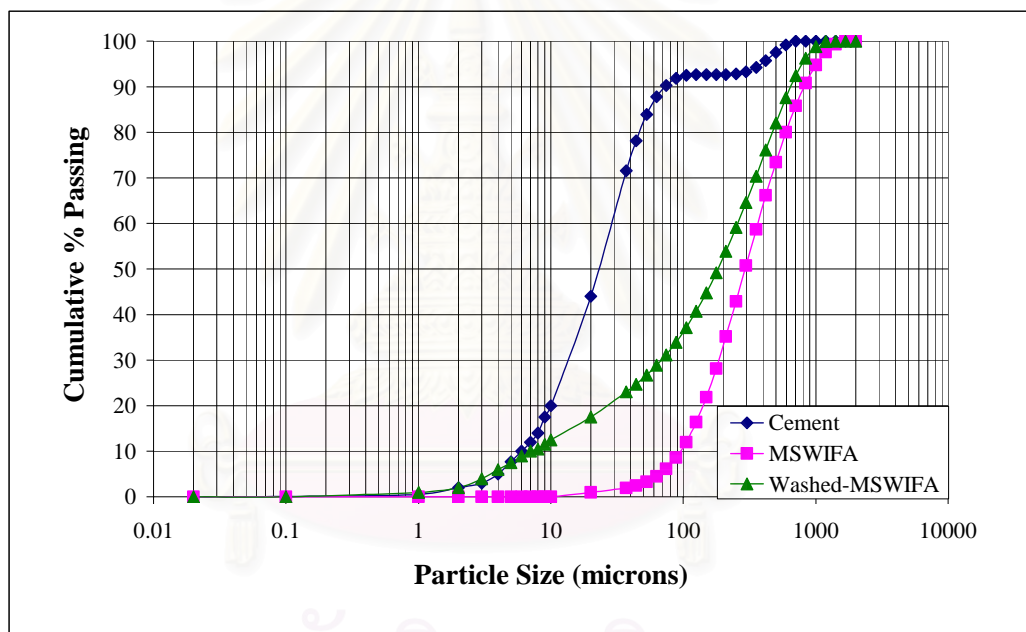


Figure 4.1 Cumulative Particle Size Distributions of MSWIFA, and Portland Cement

As shown in Figure 4.1, both of the particle size distribution curves of MSWIFA and washed MSWIFA showed that their sizes were coarser than those of Portland cement. However, particle sizes of washed MSWIFA were slightly finer than those of MSWIFA. The result also showed that washed MSWIFA had higher amount of fine particles than MSWIFA. This may be due to the fact that washing process to remove the soluble fractions from the surface of MSWIFA particles. Because washed MSWIFA formed a cake after MSWIFA was dried in an oven overnight, it needed to

be pushed through the sieve No.20 (0.84 mm). The slope of the particle size distribution curve is used to indicate gradation of the sample. The steep slope shows a poor gradation; in contrast, the gentle slope indicates a good gradation. Washed MSWIFA showed a better gradation, which is favorable for most engineering purposes, than cement and MSWIFA.

Table 4.2 shows specific surface area and particle sizes at different cumulative percent passing. Unfortunately, only specific surface of Portland cement can be measured by Blaine air-permeability method (ASTM C204), while the specific surface of MSWIFA and washed MSWIFA could not be determined by this method. Since their particle sizes and porosities were too large, air can easily diffused through the compacted bed. It was therefore impossible to accurately and precisely measure the time for a fixed volume of air passing through the compacted sample. However, the particle size analyzer can simply calculate specific surface area of sample by assuming that particle shape is spherical as discussed in section 3.2.1.2. The result is also shown in Table 4.2. Although the specific surface of Portland cement determined by this method decreased from 3120 cm²/g to 1672 cm²/g due to the fact that cement shape is not really spherical, it was used as a comparison. From the result, specific surface area of washed MSWIFA was slightly lower than that of cement. However, specific surface area of MSWIFA was obviously low compared to others due to the bigger particle size. Inthasaro (2002) recommended that other methods to determine specific surface of MSWIFA such as Brunauer, Emmett, and Teller (BET) adsorption technique should be used instead of the current methods, because of high porosity and irregular surface texture.

Table 4.2 Specific Surface Area and Particle Size of MSWIFA, Mae-Moh CFA, and Portland Cement

Sample	Specific Surface Area, cm ² /g		d _{10%} , microns	d _{50%} , microns	d _{90%} , microns
	Blaine Air Permeability Meter	Particle Size Distribution Analysis			
MSWIFA	ND	179	95.275	292.142	816.322
Washed MSWIFA	ND	1487	6.237	182.548	646.104
Portland Cement	3120	1672	5.910	22.880	72.227
NJIT MSWIFA¹	NR	NR	5.930	25.360	133.620
Mae-Moh CFA²	2370	NR	NR	28.500	NR

Note: from (1) Rachakornkij (2000); (2) Jaturapitakkul et al. (2001); “ND” means cannot be detected. “NR” means does not be reported.

4.1.3 Moisture Content and Loss on Ignition (LOI)

Moisture content presents the mass of free water evaporated when the sample was dried at 105 °C. It is important to various aspects. Maximum compaction density, very important parameter with respect to disposal of ash, is one of the aspects. Moreover, it is used together with absorption to correct content of mixing water for concrete production. Moisture content of incinerator’s residue greatly depends on the ash handling equipment. Unfortunately, air pollution control device that is currently installed at the Phuket incinerator injects water to recovered MSWIFA from the bag house filter to prevent a spreading of fugitive dust during the transportation of MSWIFA to dispose in a landfill site. Therefore, the moisture content of MSWIFA was the highest (14.81%) when compared to the other samples as shown in Table 4.1. Moreover, CaCl₂ and calcium chloride hydroxide hydrate, main products from dry scrubber process, are known as hygroscopic material. It may absorb extra moisture from the air after MSWIFA was moistened and disposed. In contrast, moisture content of washed MSWIFA is only 0.44% because it was dried in an oven at 105 °C after the washing process. Although the washed MSWIFA was not stored in a completely sealed container after drying, the low water content showed that little of moisture was

absorbed from atmosphere. This may be because CaCl_2 and calcium chloride hydroxide hydrate nearly completely dissolved after the washing process. As expected, moisture content of Portland cement was very low due to the absorbed water was chemically bonded. Therefore, it was not possible to be liberated at low temperature (105°C). CFA showed low moisture content because it was not moistened as MSWIFA. If MSWIFA is not moistened, its moisture content should be comparable to that of NJIT MSWIFA, 2.83%.

ASTM C618 limits the moisture content of the fly ash to a maximum 3 percent because high moisture content causes handling difficulty and self-cementing in high calcium content fly ash. From the result, moisture content of MSWIFA exceeded a limitation, while washed MSWIFA did not.

In case of Portland cement, loss on ignition (LOI) is mainly used to represent the hydrated amount of the Portland cement. Conversely, LOI is mainly used to determine the carbon content of fly ash. Because carbon content can adsorb the air entrainment additive in the concrete, concrete requires larger amount of water to achieve the same workability. Although ideally LOI is used to show the carbon content, re-volatilized of condensed compounds and loss of water bounded in the hydration products of excess lime ($\text{Ca}(\text{OH})_2 \rightarrow \text{H}_2\text{O} + \text{CaO}$) in MSWIFA are also included in LOI. Table 4.1 also shows the result of LOI ignited at 750°C overnight. All of the incinerator residues had very high LOI values (MSWIFA 12.44%, washed MSWIFA 17.33%). Therefore, all of the incinerator fly ashes failed the ASTM C618 LOI limit of 6 percent. Other methods such as particulate carbon, total organic carbon (TOC), and total inorganic carbon (TIC) should be considered instead of LOI to determine the content of carbon in MSWIFA.

Washed MSWIFA showed the highest LOI value because during the washing process the water reacted with MSWIFA and produced hydrated products. Drying process at low temperature (105°C) can only evaporate the absorbed water. However, the hydrated products were ignited at very high temperature in the furnace (750°C) and liberated the chemically combined water.

4.1.4 Absorption Capacity

The absorption test predicts the change in weight due to water absorbed in the pore space within the particles. It is mainly used for correcting the mixing water and aggregate proportions. Absorption can also be used to assess physical properties such as a weathering due to freeze-thaw. According to standard method ASTM C128, the absorption capacities of MSWIFA and washed MSWIFA were determined.

As shown in Table 4.1, absorption capacity of MSWIFA (21.01%) was higher than that of washed MSWIFA (10.32%). It was revealed that MSWIFA was not completely saturated by moisture in dust control process at the incinerator. Very high absorption capacity can be attributed to high content of non-combusted carbonaceous material (Alba et al., 2001) and highly porous structure. Therefore, the mixing water was added to compensate for the absorbed water by MSWIFA and washed MSWIFA. Nonetheless, the absorption capacity determined by this method was not suitable for MSWIFA as discussed in section 4.2.1.

4.1.5 Morphology

Microstructures of MSWIFA, washed MSWIFA, and Portland cement sample were viewed at high magnification using a scanning electron microscope (SEM). Micrograph of MSWIFA magnified at 150x is shown in Figure 4.2. As seen in this micrograph, the overall shape of MSWIFA was irregular and various in contrast to a particle of CFA which is mainly spherical as shown in Figure 4.4. Its observed size was in the range of 10 μm up to almost 200 μm . Higher magnification of MSWIFA at 2000x is shown in Figure 4.3. We can clearly see that particle of MSWIFA consisted of many porous structures. Particles of MSWIFA seem to be a combination of elongated small particles.

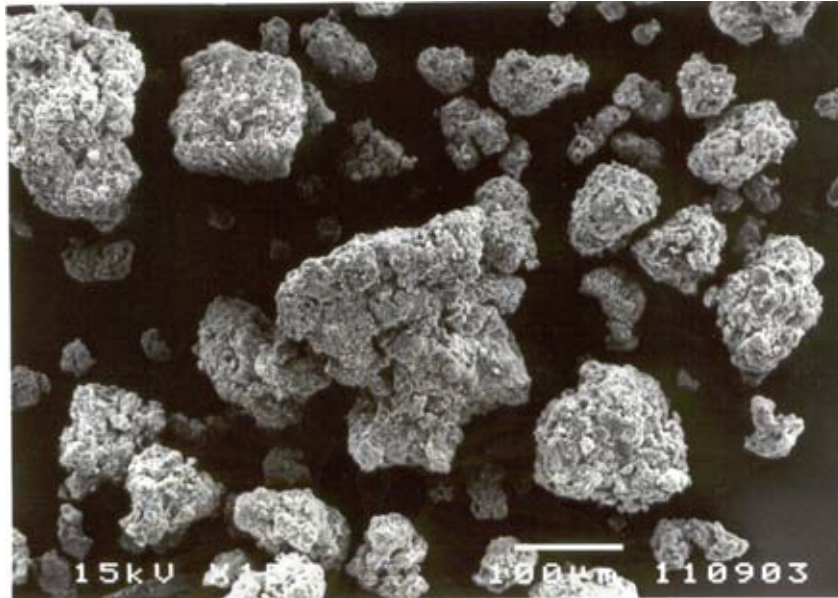


Figure 4.2 Micrograph of MSWIFA, 150x

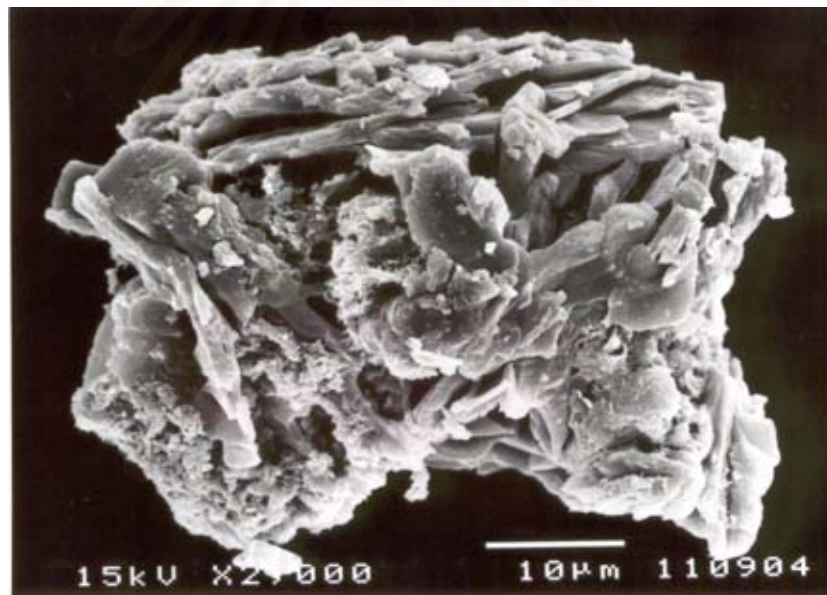


Figure 4.3 Micrograph of MSWIFA, 2000x

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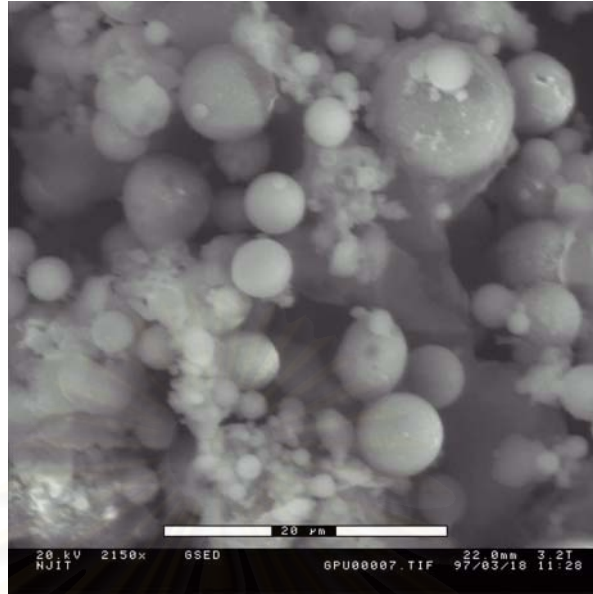


Figure 4.4 Micrograph of CFA, 2150x

Note: from (1) Rachakornkij (2000)

Micrograph at magnification 1500x of washed MSWIFA is shown in Figure 4.5. Particle of washed MSWIFA also appeared to consist of many elongated particles. However, it showed more porous particles than MSWIFA.

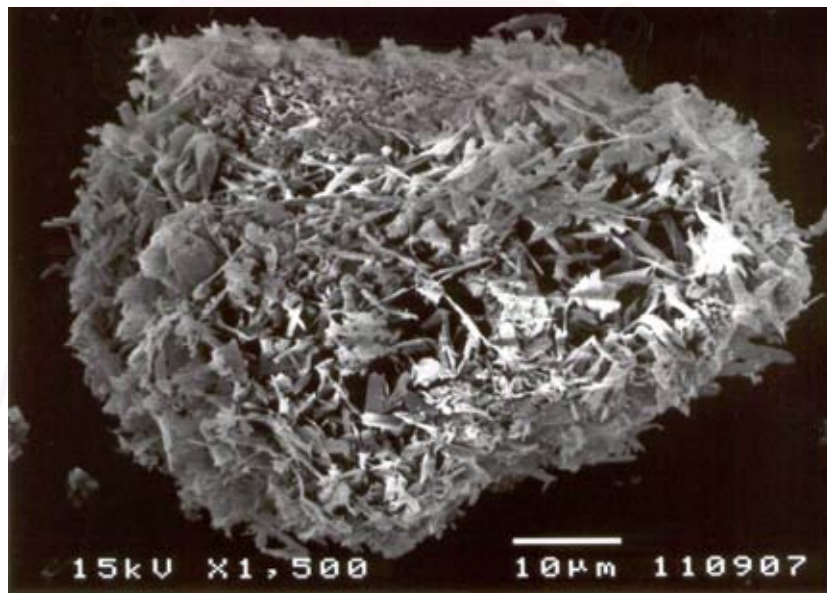


Figure 4.5 Micrograph of Washed MSWIFA, 1500x

As expected, micrograph shown in Figure 4.6 showed an angular and irregular shape of the cement particle at 3500x magnification. Porous structure cannot be observed like MSWIFA and washed MSWIFA.

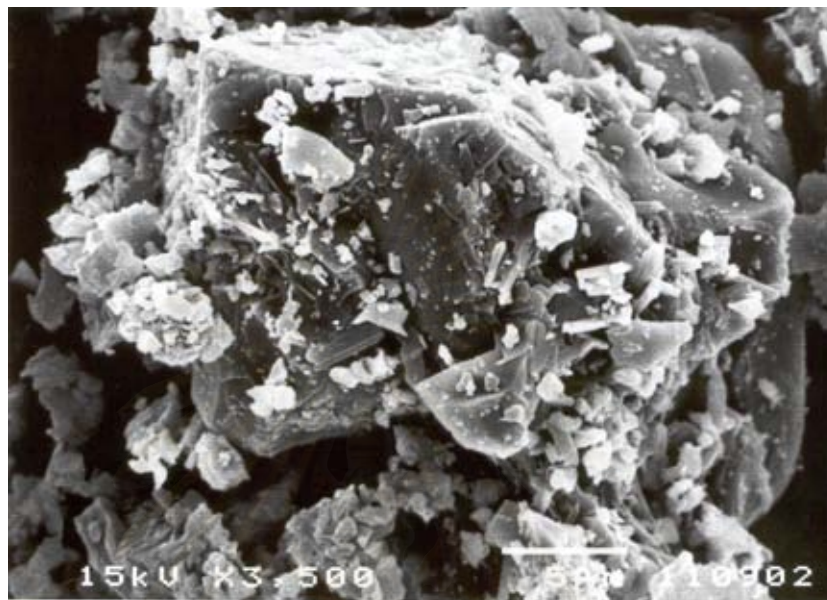


Figure 4.6 Micrograph of Portland Cement, 3500x

4.1.6 Bulk Chemical Compositions

Table 4.3 shows the results of the bulk chemical analysis of the samples from the X-ray fluorescent spectrometry. All of MSWIFA, washed MSWIFA, and Portland cement were analyzed. The literature of the chemical compositions of Mae-Moh CFA is also reported as a comparison. MSWIFA is formed under the oxidizing condition; therefore, the chemical compositions results are presented in terms of percent by weight of its oxide form. Moreover, oxide forms are normally used to report the chemical compositions of Portland cement.

Table 4.3 Bulk Chemical Compositions of MSWIFA, Portland Cement, and Mae-Moh CFA

Chemical Composition	MSWIFA	Washed MSWIFA	Portland Cement	Mae-Moh CFA¹
Al₂O₃	2.08	4.90	4.58	26.43
CaO	34.36	44.38	62.05	7.61
Cr₂O₃	0.00	0.03	0.00	NR
CuO	0.05	0.07	0.00	NR
Fe₂O₃	0.68	1.23	3.16	10.71
K₂O	5.27	0.65	0.39	3.07
MgO	1.30	4.12	1.50	2.21
MnO	0.03	0.08	0.05	NR
Na₂O	3.70	1.53	0.14	1.11
PbO	0.15	0.23	0.00	NR
P₂O₅	0.95	2.60	0.06	NR
SiO₂	5.88	8.55	21.33	46.25
SnO₂	0.13	0.27	0.00	NR
SO₃	4.15	7.93	4.07	1.85
SrO	0.04	0.05	0.04	NR
TiO₂	0.39	0.83	0.19	NR
ZnO	0.58	0.76	0.00	NR
Br	0.00	0.00	0.00	NR
Cl	27.80	4.48	0.00	NR
Rb	0.00	0.00	0.00	NR
LOI	12.44	17.33	2.44	0.23
Total	100.00	100.00	100.00	99.47

Note: from (1) Jaturapitakkul et al. (2001); “NR” means does not be reported.

The major elements measured in MSWIFA were CaO (34.36%) and Cl (27.80%). These two major elements are the main products of the dry scrubber system, a part of the air pollution control system. This system injects dry lime powder to the cooled flue gas. The dry lime powder (CaO) neutralizes the acid gases such as hydrochloric (HCl) and sulfur dioxide (SO₂) in the flue gas as shown in the equations in section 2.2.3. Their products are calcium chloride and calcium sulfate salt. Sources of chloride mainly are the combustion of plastics, newspapers, and solvents present in the waste stream. Moreover, to ensure that contaminated heavy metals in MSWIFA captured by the air pollution control system will not leach to the environment after disposal. The excess dry lime powder is normally injected to MSWIFA to provide an alkaline condition to the residue to transform easily solved heavy metal salts into insoluble salts such as silicates, hydroxides, and carbonates. Other major compositions were alkaline (K₂O and Na₂O), SiO₂, and sulphate. Various metals were

also detected in trace quantities. They were Cu, Fe, Mg, Pb, Sn, Sr, Ti, and Zn. Pb and Zn are concerned metals due to their prominent presence in MSWIFA as reported by many researchers. (Alba et al., 1997; Alba et al., 2001; Remond et al., 2002)

Unfortunately, chloride is known as depassivating agent of ferric oxide film around the reinforced steels and causes corrosion of reinforced steel. High chloride content in MSWIFA is associated with higher possibility of the steels to corrode. However, the result of water-soluble chloride content in MSWIFA concrete was in the acceptable range as discussed in section 4.2.5.

Range of bulk chemical compositions of MSWIFA from various sources as reported in previous literatures, is shown in Table 4.4. When compared the current results of Phuket's MSWIFA to the previous study (Inthasaro, 2002) of raw and sifted MSWIFA through sieve No. 200 (75 μm), the effect of particle size on the chemical compositions can be evaluated. However, it should be noted that difference in sample collection period also effects the chemical compositions. As shown, the difference in particle size slightly affect the chemical compositions of Phuket's MSWIFA contrast to the result of Mangialardi et al. (1998). Except for the alkaline (K_2O and Na_2O), their content were higher in fine particles (sifted MSWIFA) than coarse particles (raw MSWIFA and MSWIFA). Similar to washed NJIT MSWIFA, obvious decreasing of chloride and alkaline can be observed.

After MSWIFA was simply washed by tap water, the bulk chemical compositions of washed MSWIFA were analyzed. The result showed that simple washing process can effectively remove the soluble fractions especially chloride salts such as NaCl and KCl from the MSWIFA. Therefore, the K_2O , Na_2O , and chloride contents were reduced from 5.27%, 3.70%, and 27.80% in MSWIFA to 0.65%, 1.53%, and 4.48% in washed MSWIFA respectively. This explanation was confirmed by the x-ray diffraction results in the section 4.1.7. Reduction of those elements caused increase of the contents of other insoluble fractions during calculation stage of the XRF analyses; for example, Al_2O_3 (2.08% to 4.90%), Fe_2O_3 (0.68% to 1.23%), and SiO_2 (5.88% to 8.55%).

According to ASTM C618, the Standard Specifications for Fly Ash and Raw or Calcined Natural Pozzolan for Use as a Mineral Admixture in Portland

Cement Concrete, two types of fly ash, class C and class F, can be categorized depending on the summation of Al_2O_3 , Fe_2O_3 , and SiO_2 contents. The total content of the three oxides in MSWIFA is only 8.64%, which is lower than the requirement for both classes (at least 50% for class C, and 70% for class F). ASTM C618 also limits the LOI value and SO_3 content to 6% and 5% respectively. Because higher carbon content representing by LOI value reduces air entrainment and increases water demand of concrete. SO_3 affects the development of compressive strength and reduces durability of concrete due to ettringite's formation. The LOI value (12.44%) exceeded the maximum limit; however, SO_3 content (4.15%) of MSWIFA was a little bit lower than the maximum limit. Moreover, maximum available alkalis as equivalent as Na_2O is regulated to prevent the alkali-aggregate reaction during the service life. Alkalis content of MSWIFA (7.17%) also failed to meet the limit. Table 4.5 shows the comparison between the requirements of ASTM C618 and characteristics of MSWIFA and Mae-Moh CFA.

Although the insoluble fractions of MSWIFA were relatively increased after the washing process, the summation of Al_2O_3 , Fe_2O_3 , and SiO_2 contents of washed MSWIFA (14.68%) was still lower than the requirement of ASTM C618. While the LOI value (17.33%) was still higher than the limit. It should be noted that the LOI value does not exactly represent the carbon content of the sample as discussed in section 4.1.3. Because of washing process, the SO_3 content (7.93%) was increased and exceeded the maximum limit. Although equivalent alkaline of washed MSWIFA was lower than that of Mae-Moh CFA due to the washing process, its equivalent amount also slightly exceeded the limit.

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Table 4.4 Bulk Chemical Compositions of MSWIFA from Various Sources

Chemical Composition	Phuket		Phuket ¹		NJIT ²		MSWIFA ³		FA ⁴	MSWIFA ⁵			
	FA	Washed FA	Raw FA	Sifted FA	FA	Washed FA	Mass-Burn	RDF		Raw	> 500 microns	125-250 microns	< 63 microns
Al₂O₃	2.08	4.90	2.32	2.42	3.66	5.07	13.74	15.74	11.72	10.03	6.93	6.58	6.80
BaO	-	-	-	-	0.00	0.03	-	-	0.22	0.17	-	-	-
CaO	34.36	44.38	34.83	34.40	40.46	45.47	26.62	21.72	16.42	17.04	5.88	12.11	8.12
CdO	-	-	-	-	0.02	0.04	-	-	0.03	0.00	-	-	-
Cr₂O₃	0.00	0.03	-	-	0.03	0.05	-	-	0.05	0.10	-	-	-
CuO	0.05	0.07	0.05	0.05	0.09	0.17	-	-	0.07	0.03	-	-	-
Fe₂O₃	0.68	1.23	0.82	0.71	0.53	0.93	3.24	3.00	1.80	1.44	0.99	1.43	0.47
K₂O	5.27	0.65	6.90	9.12	2.27	0.98	1.97	0.67	5.80	3.30	2.49	1.98	3.89
MgO	1.30	4.12	1.77	1.43	0.68	1.11	2.44	2.03	2.52	1.41	0.88	1.01	1.03
MnO	0.03	0.08	0.05	0.04	0.01	0.03	0.13	0.13	0.05	0.09	-	-	-
Na₂O	3.70	1.53	6.59	7.81	5.50	0.65	2.59	2.24	5.86	2.83	2.31	2.15	3.04
NiO	-	-	-	-	0.01	0.01	-	-	0.01	0.04	-	-	-
PbO	0.15	0.23	0.12	0.14	0.32	0.55	-	-	0.40	0.43	-	-	-
Sb₂O₃	-	-	-	-	0.11	0.21	-	-	-	-	-	-	-
P₂O₅	0.95	2.60	1.63	1.26	0.37	0.60	1.39	1.12	0.34	-	-	-	-

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Table 4.4 Bulk Chemical Compositions of MSWIFA from Various Sources (Continued)

Chemical Composition	Phuket		Phuket ¹		NJIT ²		MSWIFA ³		FA ⁴	MSWIFA ⁵			
	FA	Washed FA	Raw FA	Sifted FA	FA	Washed FA	Mass-Burn	RDF		Raw	> 500 microns	125-250 microns	< 63 microns
SiO ₂	5.88	8.55	4.07	3.21	4.65	6.84	26.71	34.17	27.23	10.49	13.21	11.99	7.67
SnO ₂	0.13	0.27	0.08	0.10	-	-	-	-	0.02	0.03	-	-	-
SO ₃	4.15	7.93	6.23	5.20	8.01	8.26	10.73	2.93	3.00	5.10	3.49	6.57	3.72
SrO	0.04	0.05	0.04	0.03	0.04	0.03	0.03	0.04	0.01	-	-	-	-
TiO ₂	0.39	0.83	0.59	0.51	0.88	1.48	2.49	2.68	0.84	0.73	-	-	-
ZnO	0.58	0.76	0.18	0.54	1.05	2.20	-	-	1.10	0.81	-	-	-
Br	0.00	0.00	0.03	0.03	-	-	-	-	-	-	-	-	-
Cl	27.80	4.48	23.94	23.28	17.98	5.17	-	-	7.20	5.50	-	-	-
Rb	0.00	0.00	0.02	0.02	-	-	-	-	-	-	-	-	-
LOI	12.44	17.33	9.74	9.70	12.94	19.56	4.90	12.17	13.00	14.65	16.27	8.73	10.90
Total	100.00	100.00	100.00	100.00	99.61	99.44	96.98	98.63	97.67	74.22	52.45	52.55	45.64

Note: from (1) Inthasaro (2002); (2) Rachakornkij (2000); (3) Hamernik and Frantz (1991); (4) Remond et al. (2002); (5) Mangialardi et al. (1998)

Sifted MSWIFA: Pass through sieve No.200 (75 µm); RDF: refuse-derived fuel; “ - “ means not be reported.

Table 4.5 Comparison between Requirements of ASTM C618 and Characteristics of MSWIFA

Chemical Composition	ASTM C 618-96		MSWIFA	Washed MSWIFA	Mae-Moh CFA ¹
	Class C	Class F			
1. 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	83.39
2. Sulfur trioxide (SO ₃), max , %	5.00	5.00	4.15	7.93	1.85
3. Moisture Content (MC), max , %	3.00	3.00	14.81	0.44	0.09
4. Loss on Ignition (LOI), max , %	6.00	6.00	12.44	17.33	0.23
5. Available alkalis, as equivalent, as Na ₂ O, max , %	1.50	1.50	7.17	1.96	3.13

Note: from (1) Jaturapitakkul et al. (2001)

4.1.7 Mineralogical Compositions

All of MSWIFA, washed MSWIFA, and Portland cement were subjected to the XRD analysis to clearly identify their crystalline phases. This led to better understanding of the phenomena in the MSWIFA concrete.

XRD spectrum of MSWIFA is shown in Figure 4.7. The major crystalline phases detected were KCl (sylvite), and NaCl (halite). Moreover, CaCO₃ (calcite), CaCl₂.Ca(OH)₂.H₂O (calcium chloride hydroxide hydrate), CaSO₄ (anhydrite), and Ca₈Al(OH)₂₄(CO₃)Cl₂(H₂O)1.6(H₂O) (hydrocalumite) were also detected in lower intensities. This result confirmed the bulk chemical compositions from XRF analysis that showed high content of Ca, Na, K, Cl, and SO₃. It should be noted that because the great complexity of the patterns and numerous overlapping peaks, other present crystalline phases were difficult to detect (Fermo et al., 1999).

This XRD examination also confirmed the explanation of high chloride and sulphate contents as discussed in section 4.1.6. The chloride and sulphate were present in the MSWIFA as chloride and sulphate salts. High intensity CaCl₂ as the major product from the scrubber process was not detected. However, higher levels of NaCl and KCl were detected due to orientation of crystalline structures (Rachakornkij, 2000).

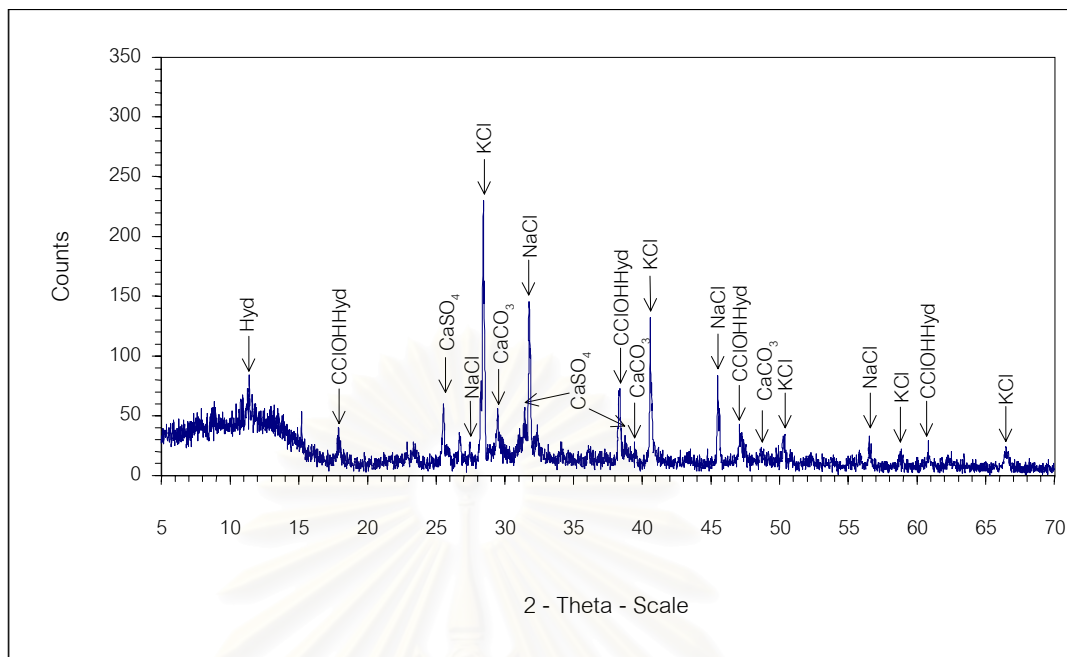


Figure 4.7 XRD Spectrum of MSWIFA

Note: Hyd: Hydrocalumite; CClOHHyd: Calcium Chloride Hydroxide Hydrate

Figure 4.8 shows the XRD spectrum of MSWIFA simply washed by tap water. The major crystalline phase detected was $\text{Ca}(\text{OH})_2$ (portlandite). Moreover, CaSO_4 , CaCO_3 , and hydrocalumite were still detected. However, KCl and NaCl, major compounds found in MSWIFA, cannot be detected in this sample. The new phases, SiO_2 (quartz) and $\text{Ca}_2\text{Al}_2\text{SiO}_7$ (gehlenite), were detected instead.

Washing process effectively solved chloride salts from the MSWIFA; therefore, they completely disappeared from the spectrum due to their solubility were very high. In contrast, sulphate salt, slightly solved, still present in the washed MSWIFA. Moreover, removing the soluble fractions, washing process produced the hydrated product $\text{Ca}(\text{OH})_2$. The washing process may help identification of some crystalline phases more reliable; therefore, the new phases can be detected after washing.

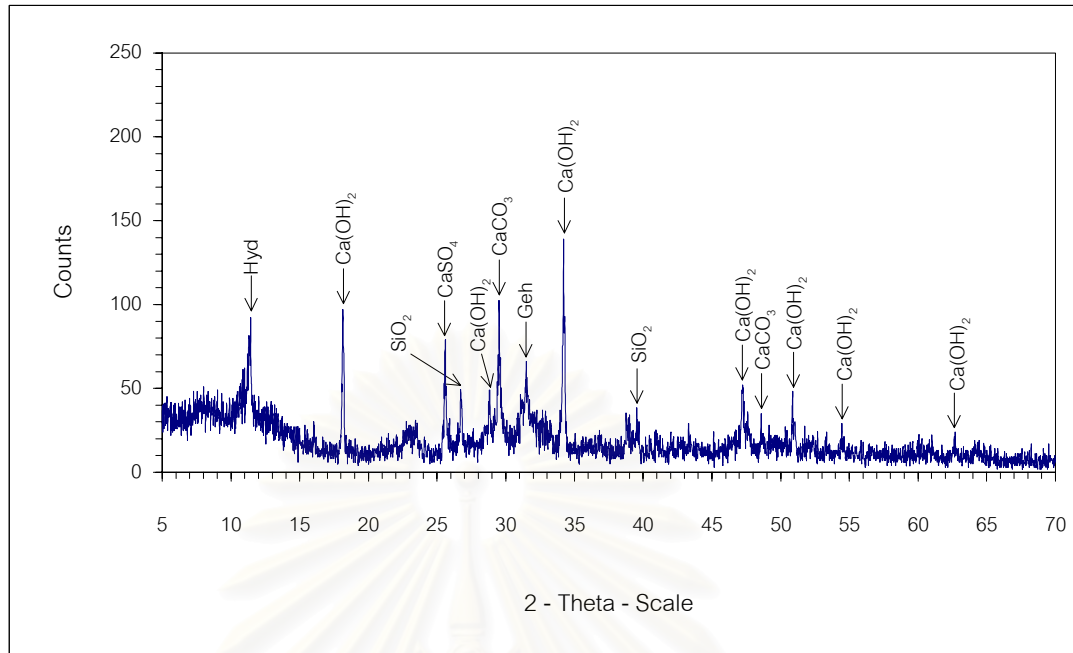


Figure 4.8 XRD Spectrum of Washed MSWIFA

Note: Hyd: Hydrocalumite; Geh: Gehlenite

Figure 4.9 compares the relative intensities of some crystalline phases before and after the washing process. Intensities of soluble fractions at some specific angle, such as sylvite (28.42), halite (31.76), and calcium chloride hydroxide hydrate (38.38) are shown. We can obviously perceive the decreasing of them. In contrast, after the washing process, the new phase, portlandite, was formed as evident by its obvious increase in intensity at 34.20 2-theta angle.

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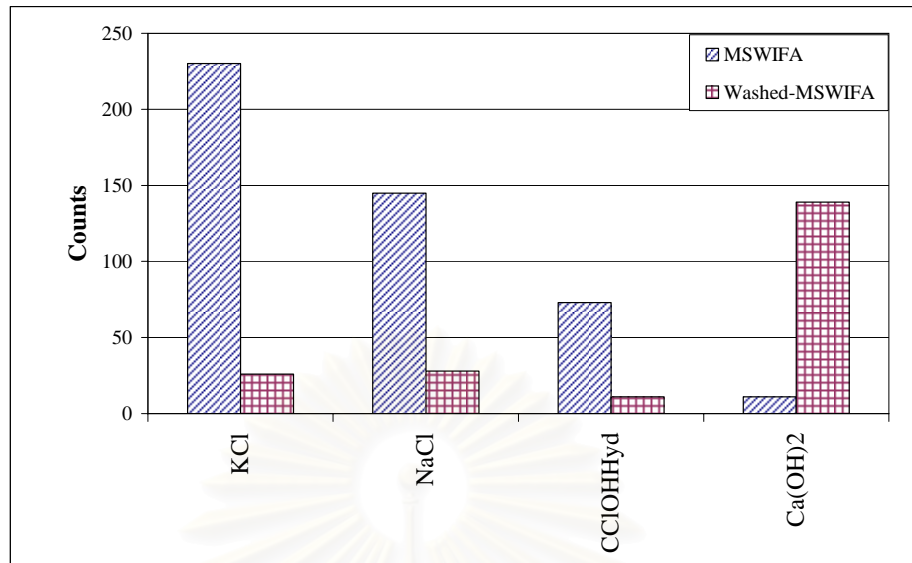


Figure 4.9 Comparison of Intensity of MSWIFA before and after Washing Process

Note: CCl(OH)Hyd: Calcium Chloride Hydroxide Hydrate

The XRD spectrum of Portland cement, used in this study, also shown in Figure 4.10. Very sharp peaks of only two major phases of cement; namely, tricalcium silicate (C_3S) and dicalcium silicate (C_2S), can be detected.

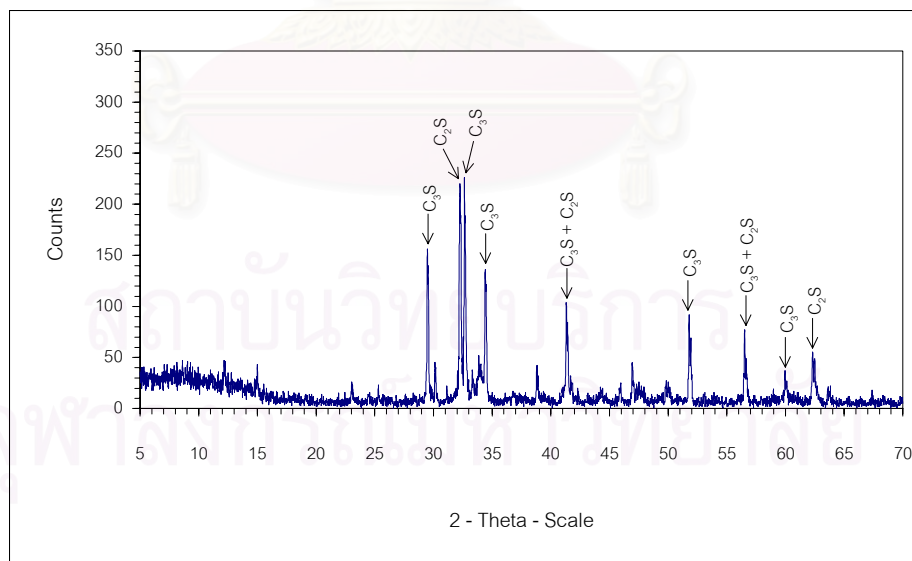


Figure 4.10 XRD Spectrum of Portland Cement

Note: C_3S : Tricalcium Silicate; C_2S : Dicalcium Silicate

4.2 Effect of MSWIFA on Properties of Concrete

4.2.1 Slump Test

One of the major property improvements of concrete incorporating CFA is a workability, because of sphericity of CFA particles. In contrast to CFA, shape of MSWIFA was irregular as shown by the SEM analysis. However, slump of the fresh concrete mixtures shown in Table 4.6 revealed a greater slump of MSWIFA concrete compared to control concrete. The higher percentage of cement replacement, the higher slump was observed. This result disagreed with all previous literatures (Hamernik and Frantz, 1991b; Remond et al., 2002). 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 shown in the beginning of this chapter was determined following the standard method to determine the absorption capacity of fine aggregate, ASTM C128 (The international ash working group, 1997). Unfortunately, this standard method is mainly appropriate for the inert materials like sand, while the MSWIFA is not. As shown in the XRD analysis result, the formed crystalline phases after the washing process such as Portlandite (Ca(OH)_2) were detected in the washed MSWIFA. 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. Therefore, the absorption capacity obtained was higher than the actual value. As a result, the corrected mixing water for MSWIFA concrete was overestimated. A different phenomenon was observed in case of washed MSWIFA, which the reactive compositions were completely reacted.

Table 4.6 Slump and Unit Weight of Fresh Concrete

Sample	Slump, cm	Unit Weight of Fresh Concrete, kg/m^3
F00	9.85	2440
F10	12.15	2414
F15	12.85	2379
F25	15.20	2379
WF15	10.44	2397

4.2.2 Unit Weight of Concrete

The unit weight of fresh concrete mixture was also shown in Table 4.6. As expected, the unit weight of MSWIFA concrete was lower than that of the control concrete. The unit weight of F10 and F15 were lower than F00 1.1% and 2.5% respectively. Larger decrease in the unit weight was observed as greater of the cement replaced level except for F25. This decrease in unit weight was due to the specific gravity value of MSWIFA that was approximately 39% lower than that of Portland cement.

4.2.3 Setting Time of Concrete

The initial and final setting times of concrete were measured by the penetration resistance according to ASTM C403. From the plotted curve, the time that penetration resistances equal to 500 and 4000 psi refers to initial and final setting time as shown in Figure 4.11.

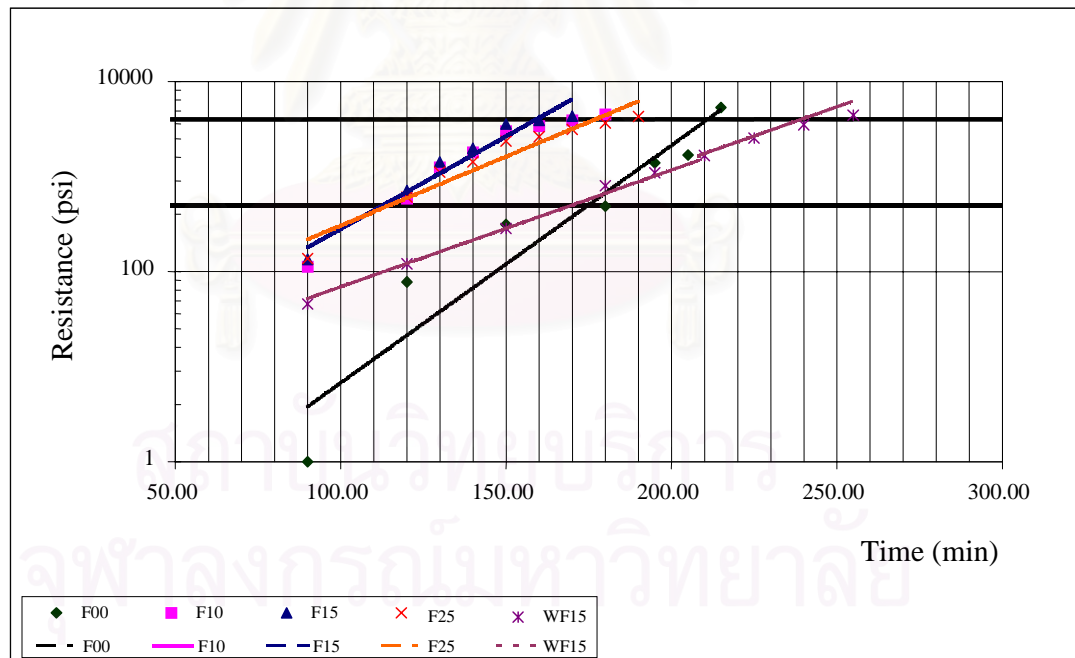


Figure 4.11 Penetration Resistances versus Time of Concrete Mixture

As determined from the plotted curve, the initial and final setting times are presented in Table 4.7. The results showed that the initial and final setting times of concrete were accelerated due to replacement of MSWIFA. The most accelerated

sample was at 15% replacement. The initial setting time was reduced from 175 min in control mixture to 113 min and the final setting time was reduced from 211 min to 159 min. However, with the maximum replacement level of 25%, the setting times were slightly slower than 15% replacement. This may be due to the lower amount of Portland cement in F25 than F15. Also lead and zinc present in the MSWIFA are known as retarding agent. With higher replacement level, the retarding effect of lead and zinc was more dominant than accelerating effect of chloride as discussed later. Therefore, the concrete was slightly retarded. These results are in contrast to the previous studies (Hamernik and Frantz, 1991b; Rachakornkij, 2000; Remond et al., 2002) who concluded that the MSWIFA retarded the setting time of cement. However, there was a research (Alba et al., 2001) which revealed that the residue from the air pollution control system accelerated the setting time of concrete.

Two major reasons contributing to the rapid setting of MSWIFA concrete. First is false set, rapid development of rigidity in a freshly mixed concrete without the evolution of much heat. Alba et al. (2001) revealed that calcium sulphate in the form of hemihydrates was dehydrated and produced gypsum then caused the false set. Because gypsum is known as an accelerator of the silicates (Neville, 1995). Second is the high chloride content in the MSWIFA. It is known that calcium chloride is one of the widely used as the accelerator in concrete. Although the result from XRD analysis revealed that the present chloride in MSWIFA was mainly in the forms of NaCl (halite), and KCl (sylvite). It also should be noted that XRD is difficult to detect compounds with mass percentage of lower than 5% (Remond et al., 2002). The result in section 4.3 also revealed that soluble fractions affected the setting time.

Table 4.7 Initial and Final Setting Time of Concrete Mixtures

Sample	Initial Setting Time, min	Final Setting Time, min
F00	175	211
F10	116	166
F15	113	159
F25	115	177
WF15	170	243

4.2.4 Compressive Strength Test

As shown in Table 3.1, four MSWIFA concrete mixtures with different MSWIFA replacement levels of 0%, 10%, 15%, and 25% by weight were prepared. The compressive strength tests were performed according to ASTM C39 at curing age of 3, 7, 14, 28, 56, 90 days. The development of compressive strengths is shown in Figure 4.12.

From Figure 4.12, it can be obviously seen that all compressive strengths of the MSWIFA concrete were lower than those of control concrete (F00) at all ages of specimens. The decrease in compressive strengths was larger as the replacement level was increased. At 28 days, control concrete (F00) achieved 360 ksc, while F10, F15, and F25 specimens achieved were 310, 280, 187 ksc, respectively. To clearly recognize the relative relation of compressive strengths compared with the controls at each test ages, Figure 4.13 is proposed.

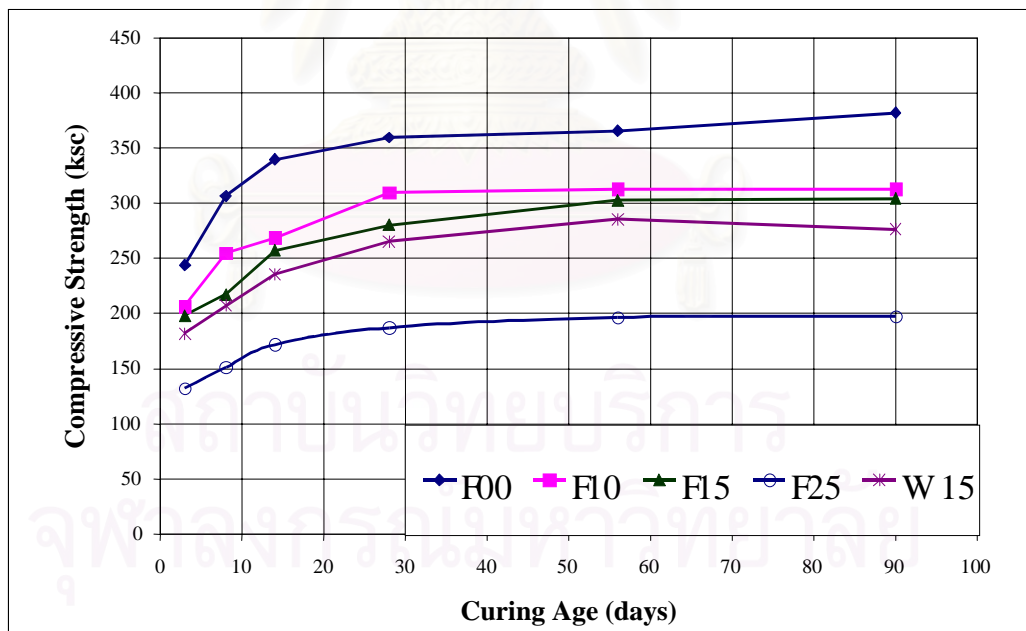


Figure 4.12 Compressive Strength Development of Concrete Sample

In Figure 4.13, compressive strength of control concrete (F00) was normalized to 100 % at all ages. The other samples were also normalized compared to control concrete at the same test ages. The relative expression of compressive

strengths can be obtained. From this figure, the 28-day compressive strengths of F10, F15, and F25 were 86.1%, 77.8%, and 52.1% compared to F00. At the longest period of curing in this study (90 days), all of MSWIFA concretes still showed lower compressive strength than F00 (F10, 81.9%; F15, 79.5%; F25, 51.7%). In contrast to CFA concrete, the compressive strength gradually increased due to pozzolanic reaction at later age. Resulting CFA concrete normally show the equivalent or higher compressive strength compared to control concrete.

Aside from, the compressive strength at specific age, the rate of compressive strength development is also an important aspect. It can be assessed from the slope of each curve in Figure 4.12 or easier identified by Figure 4.13. It can be seen that MSWIFA retarded the strength development during the first period of hydration (3-7 days) as the difference in compressive strengths between MSWIFA concrete and control concrete is larger. This result was contrast to the setting time result that revealed the setting time of concrete was accelerated by MSWIFA. However, the rate of strength development of MSWIFA concrete increase after seventh day.

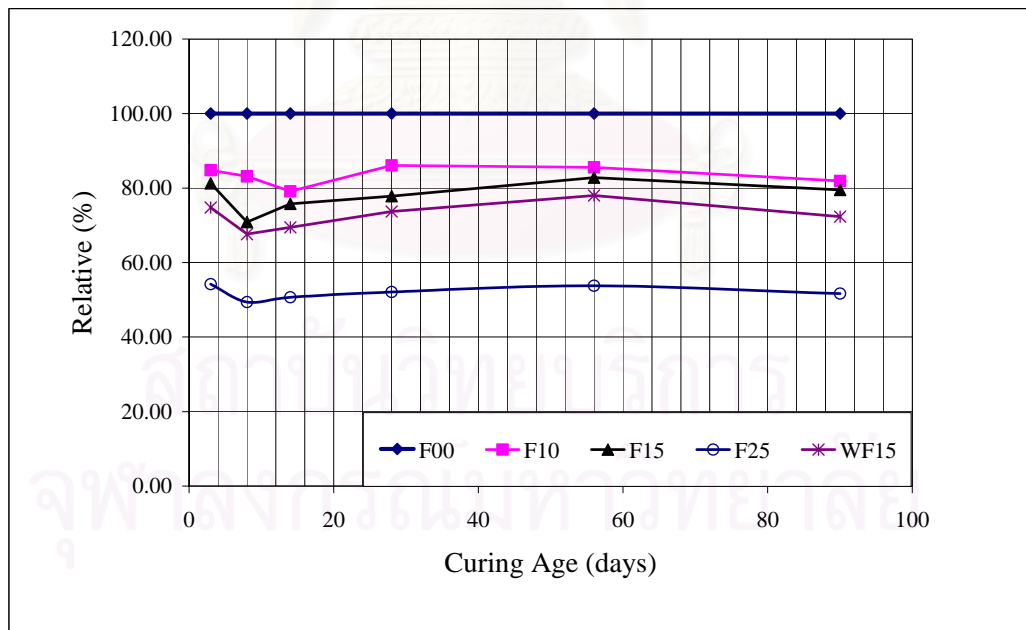


Figure 4.13 Relative Compressive Strength Development of Concrete Sample Compared to that of Control Concrete at the Same Age

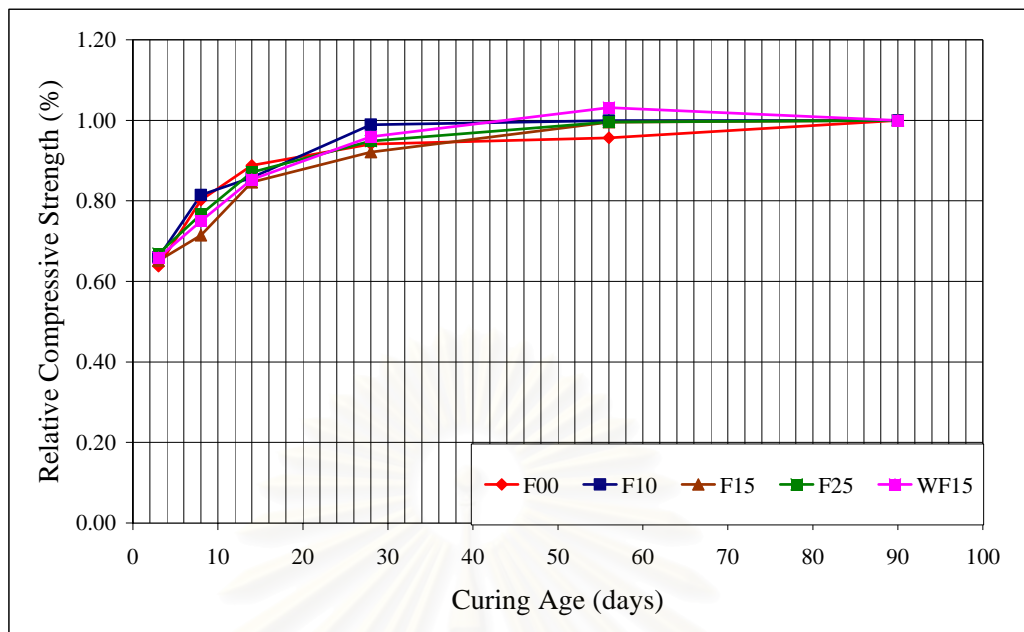


Figure 4.14 Relative Compressive Strength Development of Concrete Sample Compared to 90-days Compressive Strength of the Same Sample

Finally, Figure 4.14 shows the relative compressive strength of concrete compared to 90-days compressive strength of each specimen. Figure revealed that strength development of MSWIFA concretes were not significantly different from that of control concrete. In contrast, utilization of CFA concrete in construction project within limited timeframe is slightly a problem because of lower early strength development of CFA concrete. In contrast, results showed in this study revealed that MSWIFA did not retard the early strength development of MSWIFA concrete. This will not limit the opportunity to utilize MSWIFA in concrete structure.

4.2.5 Water-Soluble Chloride Content

As discussed earlier, the chemical composition analysis results revealed that MSWIFA contains very high content of chloride. To assess the possibility of the steel corrosion due to chloride the water soluble chloride contents in MSWIFA concrete specimens were determined according to ASTM C1218.

Figure 4.15 shows the water-soluble chloride concentrations in extracted water from samples. Similar to the XRF and XRD analysis results, the highest chloride content was found in MSWIFA. Therefore, as percent of Portland

cement replaced by MSWIFA increased, the water-soluble chloride content increased. It should be noted that the concentration of chloride in wastewater from washing process was 37,462 ppm. Thus, before wastewater is discharged, treatment to remove chloride must be performed. The recovery processes of NaCl or CaCl₂ from MSWI residues were reported elsewhere (The international ash working group, 1997).

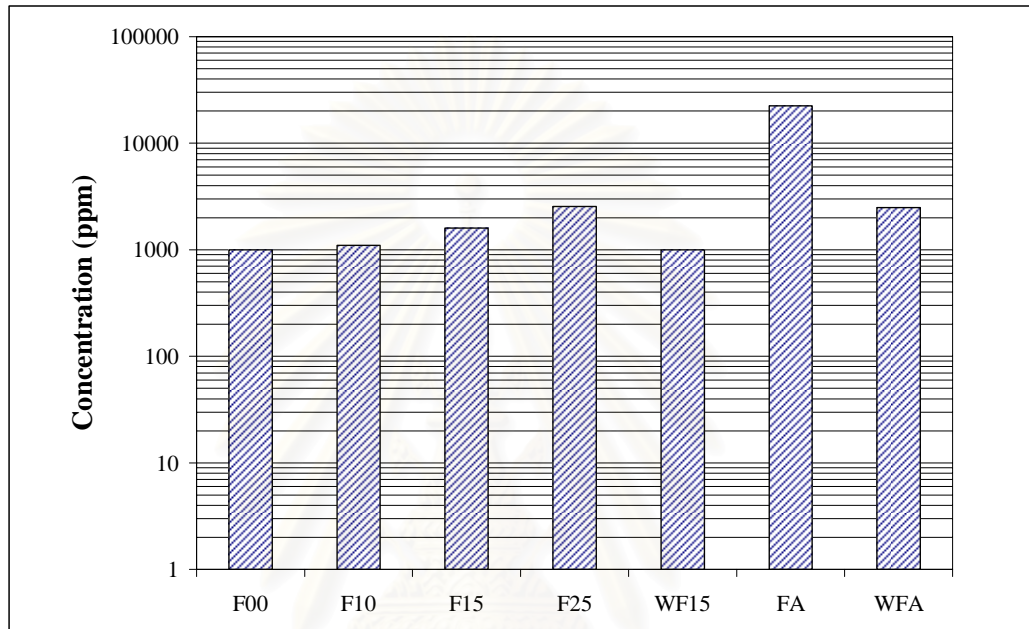


Figure 4.15 Concentrations of Water-Soluble Chloride

Figure 4.16 represents the percent of chloride content in extracted water by weight of cement. In this figure, chloride levels in all replacement levels were lower than the limit of 0.15% by weight of cement set by the Engineering Institute of Thailand (E.I.T.) for reinforced concrete that has no protection from moisture. However, the chloride level increased as the replacement percentage increased. This result contradicted that of Triano et al. (1992) who revealed that total chloride contents of MSWIFA concrete were 15 times higher than control concrete and could not be used in reinforced concrete. However, their test was based on total chloride test that used acid as a leachant. It means that both of fixed chloride and soluble chloride were extracted. This study showed that most of chloride was fixed in the hydrated forms such as Friedel's salt and was not dissolved in the extracted water. Therefore, Portland cement can be replaced by MSWIFA up to 25 % to produce steel reinforced concrete with low possibility of the steel reinforcement corrosion.

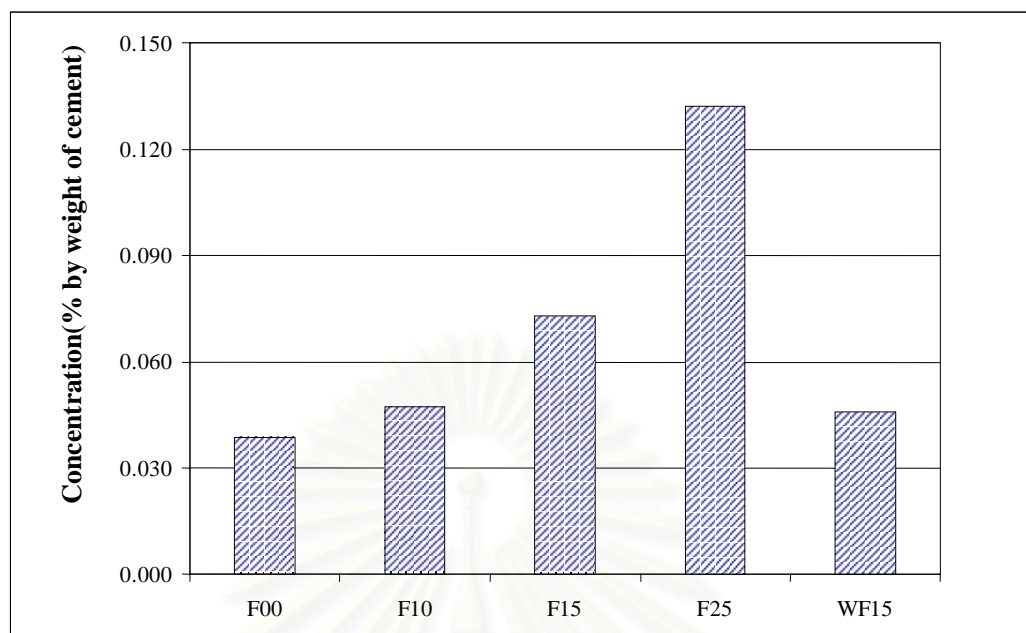


Figure 4.16 Percent Water-Soluble Chloride Content by Weight of Cement

4.3 Effect of Washed MSWIFA on Properties of Concrete

In this study, the MSWIFA was simply washed by tap water to study the effect of the soluble fractions consisted in MSWIFA. Simple washing process can remove the water-soluble fractions such as chloride salts from MSWIFA before being used as a Portland cement replacement. The comparison between properties of MSWIFA concrete and washed MSWIFA concrete at the same Portland cement replacement level (15%) was shown in Table 4.8.

Table 4.8 Comparison between Properties of Control, MSWIFA and Washed MSWIFA Concrete

Result	F00	F15	WF15
1. Slump, cm.	9.85	12.85	10.44
2. Unit Weight, kg/m ³	2440	2379	2397
3. Initial Setting Time, min	175	113	170
4. Final Setting Time, min	211	159	243
5. Compressive Strength, 28 days, ksc	359.83	280.07	265.29
6. Compressive Strength, 90 days, ksc	382.31	304.09	276.59
7. Water-soluble Chloride, % by wt. of cement	0.039	0.073	0.046

In contrast to MSWIFA concrete, slump of washed MSWIFA concrete was slightly higher than control concrete. The main reason may be because the chemical reaction of MSWIFA completely finished after the washing process. Therefore, the absorption capacity obtained after the washing presents the actual physical absorbed water of the MSWIFA.

Same as MSWIFA concrete that the unit weight decreased as cement was replaced by MSWIFA, the unit weight of WF15 was approximately 1.8% lower than that of F00. However, this decrement was lower than the same percentage replaced by MSWIFA (F15), due to the fact that the specific gravity of washed MSWIFA was higher than that of MSWIFA by about 17.7%.

Setting time was significantly affected by the washing process as shown in Figure 4.11 and Table 4.7. At the same replacement level (15%), the initial setting time of MSWIFA concrete (F15) increased from 113 min to 170 min in washed MSWIFA concrete (WF15), while the final setting time increased from 159 min to 243 min. The initial setting time of WF15 was comparable to that of the control concrete (F00); however, the delay in final setting time was observed in WF15. As discussed in section 4.2.3, calcium chloride can accelerate the setting of concrete. Simple washing process can effectively dissolve the chlorides from MSWIFA in the water, as shown in the XRF and XRD results. Therefore, the accelerating effect from chloride was diminished. The retarding of final setting time observed in washed MSWIFA concrete compared to control concrete was due to lower content of Portland cement in washed MSWIFA concrete.

The washed MSWIFA concrete was mixed using 15% replacement to evaluate the effect of the washing process. As seen in Figures 4.12 and 4.13, the compressive strength of washed MSWIFA concrete (WF15) was lower than MSWIFA concrete at the same replacement level (F15). This was also found by a study done by Remond et al. (2002). They also found that the compressive strength of concrete that used MSWIFA-washing water as mixing water significantly increased. The soluble fractions in MSWIFA showed positive effect on the compressive strength of concrete. CaCl_2 and excess lime (CaO) present in MSWIFA were believed to be the cause. One of the explanation is that $\text{CaCl}_2 \cdot 4\text{H}_2\text{O}$ was formed after dry residue is exposed to moisture. Excess lime (CaO) reacted with water then the heat of hydration

was generated. Due to low melting point of $\text{CaCl}_2 \cdot 4\text{H}_2\text{O}$ (29.9°C), it melted during the hydration of CaO . When temperature decreased, melted $\text{CaCl}_2 \cdot 4\text{H}_2\text{O}$ will solidified and filled the pores of concrete, making it denser (The international ash working group, 1997). Rachakornkij (2000) concluded that newly formed phase, hydrocalumite ($\text{C}_3\text{A} \cdot \text{CaCl}_2 \cdot 10\text{H}_2\text{O}$), response for greater compressive strength of MSWIFA concrete.

In Figure 4.15, the concentration of chloride in the extracted water from washed MSWIFA (WFA) was quite lower than that of MSWIFA. It means that the chloride presented in the MSWIFA was easily dissolved in the water during the washing process. Therefore, the concrete mixture incorporating 15% washed MSWIFA (WF15) almost had the same concentration of water-soluble chloride as the control concrete. In Figure 4.16, the percent of chloride content by weight of cement of the WF15 was slightly higher than that of the control concrete because WF15 had lower cement content than the control concrete. As evidenced by the water-soluble chloride analysis result in this study, washing process was not required if the replacement ratio was less than 25% by weight of Portland cement. Prior to real application of the washing process, further researches on the parameters affecting the washing efficiency should be conducted such as optimum liquid to solid ratio, pH, temperature, chemical addition, percolation rate, etc. One of other concrete durability aspects that should be concerned is high sulphate in presented in MSWIFA. Due to sulphate causes a formation of ettringite. Moreover, it cannot be simply removed from the MSWIFA to the acceptable level by the washing process because its solubility is low.

The analysis of concentration of heavy metals in the wastewater from the washing process revealed that the concentration of lead exceeded the limit set by the wastewater standard regulated under the Notification of Ministry of Industry No.2, B.E. 2539 (1996). Table 4.9 shows the concentration of heavy metals in wastewater from the washing process. Therefore, wastewater from the washing process should be analyzed for heavy metal concentrations and properly treated before discharge to the environment. The recovery of metals and other soluble fractions is possible.

Table 4.9 Concentrations of Heavy Metals in Wastewater from the Washing Process

Metal	Condition	Concentration, ppm	
		Discharge Limit ¹	Wastewater
Silver (Ag)	Normal	NR	0.030
	Concentrated		0.0265
Arsenic (As)	Normal	0.25	< 0.10
	Concentrated		< 0.10
Barium (Ba)	Normal	1	1.644
	Concentrated		1.96
Cadmium (Cd)	Normal	0.03	< 0.005
	Concentrated		< 0.005
Chromium (Cr)	Normal	0.25	0.046
	Concentrated		0.045
Lead (Pb)	Normal	0.2	5.3
	Concentrated		7.25
Mercury (Hg)	Normal	0.005	ND
Selenium (Se)	Normal	0.02	< 0.10
	Concentrated		< 0.10

Note: from (1) Ministry of Industry, 2003a; “NR” means does not be reported.

4.4 Leachate Characteristics

Air pollution control devices installed at the incinerator cause highly volatile metals to condense on the surface of the MSWIFA particles. The suitable management strategy for MSWIFA really depends on the potential of contaminants to contaminate the environment and cause negative effect to human health. This, to some extent, can be evaluated by leaching tests. Leaching tests provide information about the constituent leached from a waste under reference conditions that simulate conditions in a landfill or in the environment. Table 4.10 shows the concentrations of eight metals in the leachate according to the leaching procedure described in the Notification of Ministry of Industry No. 6, B.E. 2540 (1997).

From this table, all of concentrations of heavy metals leached from the MSWIFA and WFA samples were within the limits in the Notification. This may be due to many reasons. First is availability, original content of those metals in the municipal solid waste stream fed to the incinerator is low. Second is the boiling point of those metals. Some of the metals have higher boiling points than the combustion temperature so they are not volatilized and mainly present in bottom ash such as copper. Some metals such as mercury have very low boiling point compared to temperature in the combustion chamber. Although mercury easily vaporizes during combustion, it may not condense from the flue gases in the subsequent air pollution control devices. However, the current air pollution control technology can remove the contaminants from the flue gas more effectively before emission through the stack. There are some researches showing that metals contents in the MSWIFA from advanced air pollution control technology were higher than those from older technology (Alba et al., 1997). Finally, the solubility of the metals highly depends on many factors. For example, pH of the solution is one of the most important factors. Solubility of some metals such as chromium, and lead depend on pH, while barium does not.

Although the leachates were concentrated before analysis, the concentrations of silver, arsenic, cadmium, mercury, and selenium were still lower than the detection limit of the equipment. Due to fact that only barium, chromium, and lead could be measured in significant levels, only these three metals were further discussed.

Figure 4.17 to 4.19 show the concentrations of three metals in the leachates from each sample and also the comparison between normal and concentrated (leachants were concentrated prior the analysis) concentrations. Concentrations of barium are shown in Figure 4.17. It revealed that MSWIFA was responsible for the increasing of barium content in the MSWIFA concrete mixtures. As the percent replacement increased, the barium concentration also increased. In case of washed MSWIFA (WFA), the barium concentration was quite less than MSWIFA. However, the barium concentration of washed MSWIFA concrete (WF15) was higher than of that of the MSWIFA concrete at the same replacement level (F15).

This might be due to the carry over effect from the former batch during the casting stage.

Table 4.10 Heavy Metals Concentrations in Extracted

Metal	Condition	Concentration, ppm							
		Limit ¹	F00	F10	F15	F25	WF15	FA	WFA
Silver (Ag)	Normal	5	< 0.007	< 0.007	< 0.007	< 0.007	< 0.007	< 0.007	< 0.007
	Concentrated		< 0.007	< 0.007	< 0.007	< 0.007	< 0.007	< 0.007	< 0.007
Arsenic (As)	Normal	5	< 0.10	< 0.10	< 0.10	< 0.10	< 0.10	< 0.10	< 0.10
	Concentrated		< 0.10	< 0.10	< 0.10	< 0.10	< 0.10	< 0.10	< 0.10
Barium (Ba)	Normal	100	0.267	0.233	0.244	0.367	0.3	0.956	0.322
	Concentrated		0.222	0.184	0.204	0.301	0.261	1.13	0.3
Cadmium (Cd)	Normal	1	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005
	Concentrated		0.0003	< 0.005	< 0.005	< 0.005	< 0.005	0.002	< 0.005
Cromium (Cr)	Normal	5	0.069	0.064	0.052	0.034	0.053	0.062	0.043
	Concentrated		0.063	0.057	0.047	0.034	0.049	0.066	0.047
Lead (Pb)	Normal	5	< 0.05	0.078	< 0.05	0.067	< 0.05	3.344	2.033
	Concentrated		< 0.05	0.009	0.009	0.026	0.017	4.044	1.752
Mercury (Hg)	Normal	0.2	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005
Selenium (Se)	Normal	1	< 0.10	< 0.10	< 0.10	< 0.10	< 0.10	< 0.10	< 0.10
	Concentrated		< 0.10	< 0.10	< 0.10	< 0.10	< 0.10	0.026	< 0.10

Note: (1) Ministry of Industry, 2003b

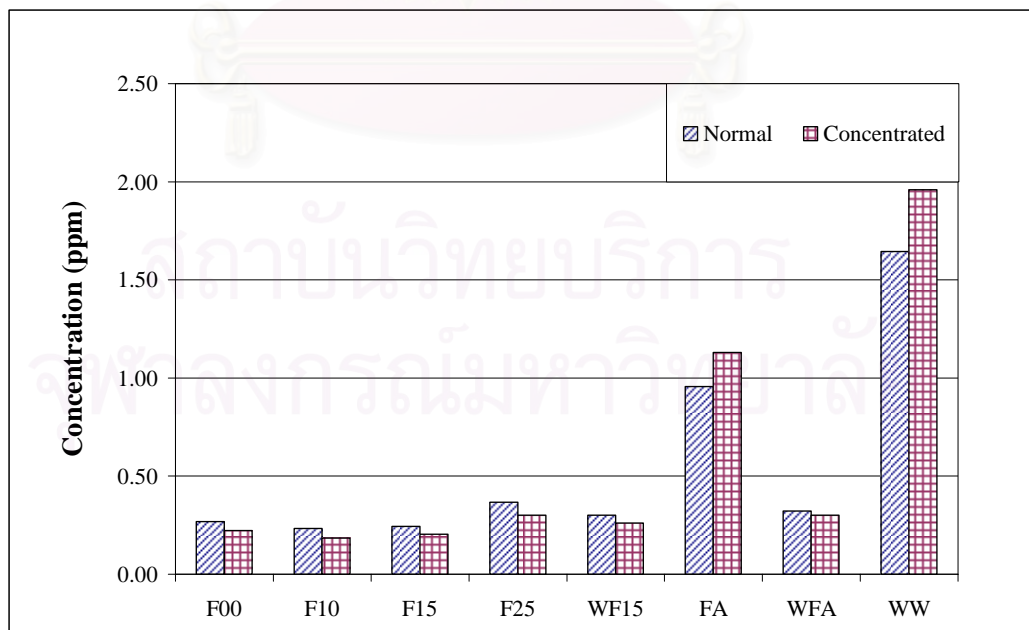


Figure 4.17 Concentrations of Barium in Extracted Water

Figure 4.18 shows the concentration of chromium. In contrast to barium, the graph revealed that the major source of chromium was Portland cement not the MSWIFA. Because chromium concentrations decreased as Portland cement content was reduced. However, the result of chemical compositions of Portland cement did not indicate the significant amount of chromium. In contrast, chromium can be detected as a trace element in the washed MSWIFA. This may be explained by Alba et al. (1997) who reported different results in the determination of chromium contents in MSWIFA using different methods, total acid digestion and extractable digestion. This was because chromium is usually associated with non-reactive silicate matrices that have lower potential of being leached.

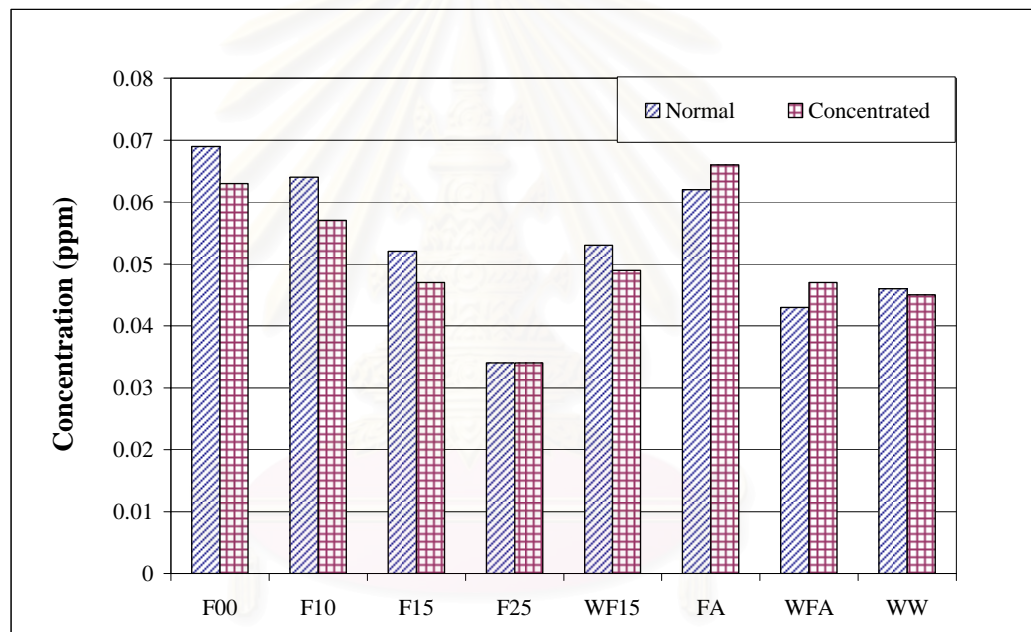


Figure 4.18 Concentrations of Chromium in Extracted Water

Figure 4.19 shows the concentrations of lead. This figure revealed that lead was efficiently stabilized in the concrete matrix by high alkalinity of cement. Therefore, the concentrations of leached lead from the concrete mixtures were significantly lower than the original leached concentration of MSWIFA.

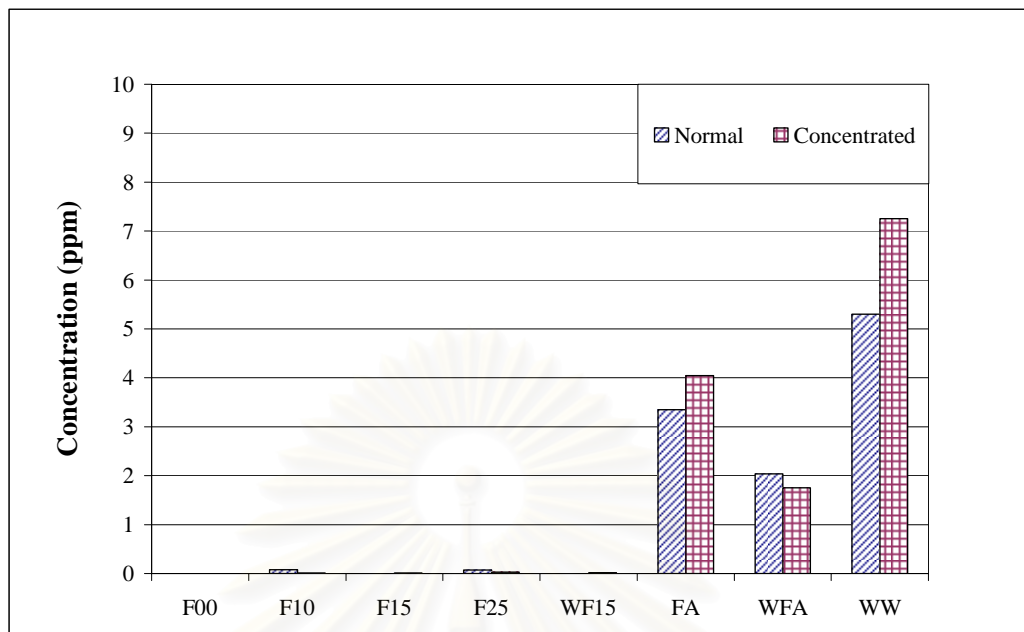


Figure 4.19 Concentrations of Lead in Extracted Water

It should be noted that the leaching test conducted in this study followed the method described in the notification. Prior to leaching test, the solidified sample had to be crushed. Therefore, aspect of decreasing the surface area of waste was diminished. The new method to evaluate the leaching behavior of MSWIFA concrete product should be performed like a monolithic test.

4.5 Economic Considerations

To evaluate the possibility of using MSWIFA as an alternative resource, economic considerations such as cost-to-benefit ratio should be considered rather than the physical properties of the final products. In this study, MSWIFA was utilized as a Portland cement replacement in concrete. Therefore, the related economic considerations of ready-mixed concrete plant were performed as well as the benefit of incinerator's operator.

MSW incinerator involves high investment cost as well as operation and maintenance (O&M) costs. O&M costs comprise fixed operating costs like administrative cost, and salaries; variable operating costs like cost of chemicals for the flue gas cleaning system, and cost of residue disposal; and maintenance costs (Rand et al., 2000). The most important cost of the variable costs is the residue

disposal cost. Normally, generated MSWIFA from Phuket incinerator is transported and disposed of at a nearby sanitary landfill. There are costs associated with this operation; namely, land cost, construction cost of landfill, transportation cost, and cost of daily cover up. Based on Rand et al. (2000), the disposal cost of MSWIFA is approximately US\$ 100 per ton or 4,300 baht (1US\$ = 43.00bht). While disposal costs of bottom ash is only US\$ 5 per ton or 215 baht per metric ton. Due to MSWIFA was focused in this study, only the disposal cost of MSWIFA is considered.

For potential MSWIFA users, two different cases may be considered; as-received and pre-treated MSWIFA. Cost of as-received MSWIFA is certainly lower than that of Portland cement because it is a byproduct or, to be precise, a waste. Its cost was assumed to be similar to that of Mae-Moh CFA that is 1000 baht per metric ton. Therefore, cost of concrete is reduced as cement is replaced by MSWIFA as shown in Table 4.11. Transportation, storage, and mixing methods can be adapted from the methods used for CFA. Similar types of transportation truck and storage unit used for Portland cement can be used for MSWIFA. However, lower bulk unit weight of MSWIFA should be concerned. In the mixing process, conveyor of MSWIFA from silos to a weighing machine should be specially designed to prevent fugitive dust of MSWIFA.

Table 4.11 Cost and Benefit of MSWIFA Utilization: Case of Concrete
Producer

Ingredient	Material Price, baht/kg	Mix Proportion, kg/m ³			
		F00	F10	F15	F25
Cement	2.436*	282	253.8	239.7	211.5
MSWIFA	1	0	28.2	42.3	70.5
Sand	0.14*	816	816	816	816
Gravel	0.17*	1098	1098	1098	1098
Water	0.016**	178	178	178	178
Total Cost, baht/m³		990.70	950.20	929.96	889.46
Benefit, baht/m³		0.00	40.50	60.74	101.24
Percent Reduction, %		0.00	4.09	6.13	10.22

Note: from (*) Bureau of Trade and Economic Indices (2003); (**)

Metropolitan Waterworks Authority (2003)

Due to high concentration of chloride and sulphate, pretreatment of MSWIFA may be required for some applications prior to utilization. Mulder et al. (1997) recommended the pretreatment process for easily leached compounds. By their method, cadmium and chloride could be reduced by as much as 90%, while zinc and sulphate were removed by more than 50%. Costs associated with pretreatment process are mainly costs of water used, chemical used, and wastewater treatment cost. Approximate total cost is 5,000 baht or 250 Guilder per ton of MSWIFA (1Guilder =20.00bht). To enhance utilization, treatment process should be performed by incinerator's organization because of extremely high treatment cost. Although treatment cost is currently higher than the disposal cost, the disposal cost should increase drastically in the future due to closure of existing landfill and dramatically high costs associated with construction, operation, and maintenance of new landfills. It should be noted that method of Mulder et al. (1997) used nitric acid to maintain pH at 4 to increase the solubility of metals. However, heavy metals present in MSWIFA have already been stabilized by alkalinity of cement hydration product, chemical treatment is not necessary. Therefore, treatment cost is lower. Table 4.12 shows cost, benefit, and net benefit in case of incinerator's operator.

Table 4.12 Cost and Benefit of MSWIFA Utilization: Case of Incinerator

	As-received MSWIFA	Pre-treated MSWIFA
Cost		
Treatment Cost, baht/ton*	0.00	5,000.00
Benefit		
Disposal Cost Saved, baht/ton**	4,300.00	4,300.00
Revenue, baht/ton***	<u>1,000.00</u>	<u>1,000.00</u>
Net Benefit, baht/ton	<u>5,300.00</u>	<u>300.00</u>

Note: from (*) Mulder et al. (1997); (**) Rand et al. (2000); (***)

Torcharenkij (2003)

If as-received MSWIFA finds its niche in the market as a Portland cement replacement in concrete similar to CFA, their disposal cost will be completely diminished. However, similar to the first stage of utilizing Mae-Moh CFA,

unfavorable variation of chemical compositions of MSWIFA is expected due to fluctuations in composition of the feed waste, burning condition, and type and operation of air pollution control units. These factors should be further investigated to control the quality of MSWIFA. Therefore, capital investment required for modification of incineration system should be further concerned. Moreover, storage units and distribution units of MSWIFA are required to facilitate the future trading.

4.6 Social and Environmental Considerations

As shown in previous section, both of incinerator and concrete distributors obtain the economic benefit by utilization of MSWIFA in concrete. There are other benefits, which are difficult to be quantified; namely, social and environmental aspects.

We realized that Phuket incinerator would reach its capacity in the near future. Therefore, the second incinerator should be constructed to deal with the expected higher amount of MSW. However, public concern related to contamination of the surrounding environment, air, water, and soil, leads to difficulty in proposing a new MSW incinerator. While advanced air pollution control devices can prevent distribution of contaminants to the atmosphere, many contaminants are trapped in the residues from these devices. Therefore, there is anxiety that water and soil will be contaminated by leachate from the landfill of residue. Results shown in this study suggested that the concentrations of leached heavy metals from MSWIFA satisfied the limits described in the Notification of Ministry of Industry No. 6, B.E. 2540 (1997). As a result, public acceptance of an incinerator may be enhanced. Not only economical benefit stemming from utilization of MSWIFA, but also environmental benefit can also be realized. Stabilization and solidification process can greater reduces the leached concentrations of heavy metals from MSWIFA. This means public acceptance will be further enhanced. However, seasonal variation of leached heavy metals concentrations and dissolved chloride should be further studied to ensure the overall safety.

Similar to the beginning period of utilizing CFA in concrete, there are many researches that have to be further conducted to clearly understand positive and negative effects of MSWIFA to the properties of concrete products. It is expected that

the further researches related to utilization of MSWIFA in concrete concerning both of civil and environmental engineering aspects will lead to the most valuable and safest final destination for MSWIFA, instead of landfill disposal. Suggestions for further researches are recommended in the chapter 5.



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CHAPTER 5

CONCLUSIONS AND SUGGESTIONS FOR FUTURE WORKS

5.1 Conclusions

Based on the results obtained from this investigation, the following conclusion can be made:

5.1.1 Characteristics of MSWIFA

1. Specific gravity of MSWIFA was 39 % lower than that of Portland cement, while that of washed MSWIFA was 28 % lower.
2. Particle size distribution of MSWIFA was the coarsest compared to washed MSWIFA and Portland cement.
3. Determination of specific surface area by Blaine air permeability method was not applicable for MSWIFA and washed MSWIFA, because accurate and precise measurement of time was impossible.
4. Physical and chemical characteristics of MSWIFA and washed MSWIFA did not meet the requirements of ASTM C618. Only SO_3 content of MSWIFA and moisture content of washed MSWIFA met those requirements. However, it should be noted that ASTM C618 is mainly applicable for coal fly ash. It was used as a guideline to evaluate MSWIFA because there is no particular standard for evaluating MSWIFA.
5. Microstructure of MSWIFA and washed MSWIFA determined by SEM showed irregular and porous structures.
6. Major chemical compositions of MSWIFA were CaO and Cl as determined by XRF spectroscopy, while those of washed MSWIFA mainly consisted of CaO and other insoluble compounds.
7. The results of MSWIFA obtained from XRD spectrometer showed high peak intensities of KCl, NaCl, CaCO_3 , $\text{CaCl}_2 \cdot \text{Ca}(\text{OH})_2 \cdot \text{H}_2\text{O}$, and CaSO_4 agreed with the results of chemical compositions obtained from XRF

analysis. New crystalline phase, $\text{Ca}(\text{OH})_2$, was formed after the washing process, while soluble fractions such as KCl and NaCl dissolved from the sample.

5.1.2 Effect of MSWIFA on Properties of Concrete

1. When cement replacement percentage had been increased, MSWIFA concrete showed higher slump value compared with control concrete. Slump value of washed MSWIFA concrete was lower than MSWIFA concrete at the same cement replacement level (15%).
2. Unit weights of all MSWIFA and washed MSWIFA concrete were lower than that of control concrete, because of lower specific gravity of MSWIFA and washed MSWIFA.
3. MSWIFA accelerated the setting time of concrete because of high chloride content. The most accelerated sample was at 15% replacement of which initial setting time and final setting time were accelerated 35% and 25%, respectively.
4. In contrast to CFA concrete, MSWIFA concrete did not showed lower early compressive strength compared to that of control concrete.
5. All of MSWIFA concrete and washed MSWIFA concrete showed lower compressive strength than control concrete. The maximum relative compressive strength, 86.06%, was at 10% replacement (F10) at the age of 28 days. However, greater reduction of compressive strength was observed as percent cement replacement increased.
6. Fortunately, abundance of chloride in MSWIFA was chemically fixed in the hydration products. Therefore, water-soluble chloride contents of all samples, including 25% replacement, were within the E.I.T. limits to prevent corrosion of reinforced steel.

5.1.3 Leachate Characteristics

1. All of concentrations of leached heavy metals from MSWIFA and MSWIFA concrete products were within the limits in the Notification. Although extracts were concentrated prior to measure concentration of heavy metals, only concentrations of barium, chromium, and lead were detected at significant levels.

2. MSWIFA was a source of barium contamination in MSWIFA concrete, while Portland cement was a source of chromium contamination in concrete. Although lead was present in MSWIFA in a significant level, its concentrations were extremely low in extracts of MSWIFA concrete product because of stabilization mechanism.
3. It should be noted that wastewater from washing process of MSWIFA is contaminated with both heavy metals, especially barium and lead, and chlorides. Therefore, proper treatment process should be done prior to discharge to environment.

5.1.4 Economic, Social, and Environmental Considerations

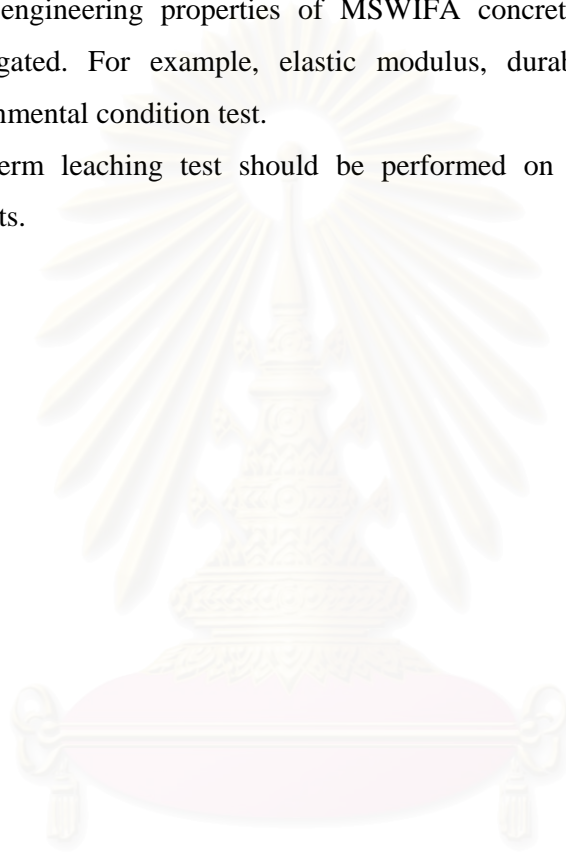
1. Both vendor (incinerator) and buyer (concrete mixer) of MSWIFA gain the economical benefits from utilizing MSWIFA. Incinerator can reduce disposal cost, while concrete produce can reduce cost of cement used.
2. Environmental benefit is also realized. Stabilization and solidification process can greater reduces the leached concentrations of heavy metals from MSWIFA. This means public concern related to contamination of the surrounding environment will reduce.
3. Seasonal variation of leached heavy metals concentrations and dissolved chloride should be further studied to ensure the overall environmental safety.

Similar to the beginning period of CFA utilization in concrete, there are more researches that have to be further conducted to clearly understand positive and negative effects of MSWIFA to the properties of concrete products. It is expected that the further researches related to utilization of MSWIFA in concrete concerning both of civil and environmental engineering aspects will lead to the most valuable and safest final destination for MSWIFA, instead of landfill disposal. Suggestions for further researches are recommended in next section.

5.2 Suggestions for Future Works

1. MSWIFA collected prior to dust control should be used to study its effect on concrete product.

2. Utilization of MSWI bottom ash should be simultaneously explored to achieve overall residue management from the MSWI.
3. Variation in chemical compositions of MSWIFA due to fluctuations in composition of the feed waste, burning condition, and type and operation of air pollution control units should be studied. They should be optimized for satisfactory quality of MSWIFA.
4. Other engineering properties of MSWIFA concrete should be further investigated. For example, elastic modulus, durability test, and real environmental condition test.
5. Long-term leaching test should be performed on solidified MSWIFA products.



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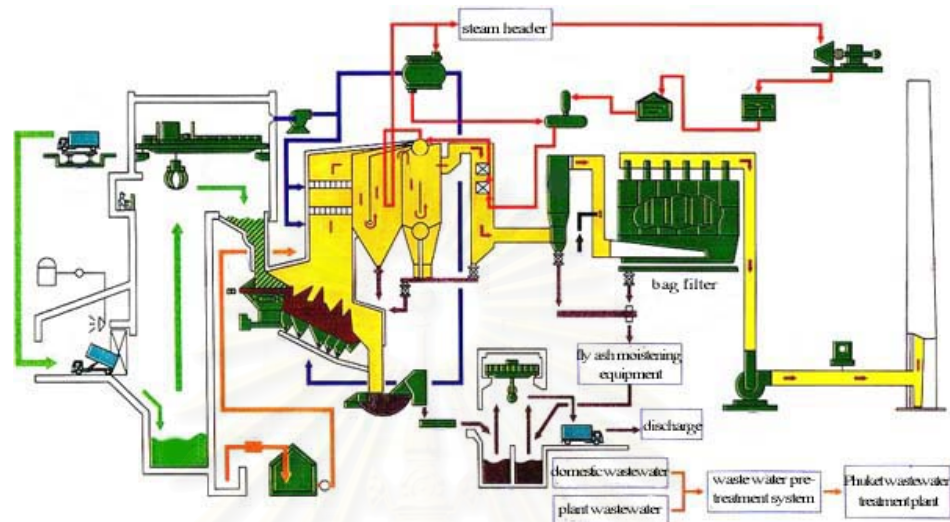
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APPENDICES

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APPENDIX A



Source: Adapted from <http://www.phuketcity.go.th>

Figure A-1 Phuket Municipal Solid Waste Incineration Plant Diagram

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APPENDIX B**Figure B-1** The Rotary Agitator**Figure B-2** Bruker Powder X-ray Diffraction Spectrometer Model D8 Advance



(a)



(b)



(c)



(d)

Figure B-3 Preparation and Testing of MSWI Fly Ash-Cement Mortar Specimens; a) Mixing Machine, b) Setting Time Testing, c) Cylindrical Mold Casting, and d) Curing Specimens in Moisture Room



Figure B-4 Compressive Strength Testing Machine



Figure B-5 The Microwave Digestion and Extraction Apparatus Model ETHOS SEL



Figure B-6 The Ashing Furnace Model AAF 1100



Figure B-7 The Particle Size Analyzer Model Mastersizer 2000 and Scirocco 2000

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APPENDIX C

Table C-1 XRD Spectrum Intensity of Mineralogical Compounds of MSWIFA and Washed MSWIFA

Mineralogical Compound	Intensity, counts	
	MSWIFA	Washed MSWIFA
KCl	230	26
NaCl	145	28
CClOHHyd	73	11
Ca(OH)₂	11	139

Table C-2 Compressive Strengths of MSWIFA and Washed MSWIFA Concrete

Sample	Compressive Strength, ksc					
	3-day	8-day	14-day	28-day	56-day	90-day
F00	243.78	306.62	339.56	359.83	365.72	382.31
F10	206.72	254.97	268.65	309.67	312.91	313.09
F15	198.07	217.28	257.30	280.07	302.82	304.09
F25	132.10	151.40	172.08	187.41	196.74	197.51
WF15	182.26	207.43	235.94	265.29	285.29	276.59

Note: Each reported value is an average of 3 mortar cubes.

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Table C-3 Relative Compressive Strengths of MSWIFA and Washed MSWIFA Concrete Compared to that of Control Concrete at the Same Ages

Sample	Relative Compressive Strength, %					
	3-day	8-day	14-day	28-day	56-day	90-day
F00	100.00	100.00	100.00	100.00	100.00	100.00
F10	84.80	83.16	79.12	86.06	85.56	81.89
F15	81.25	70.86	75.77	77.83	82.80	79.54
F25	54.19	49.38	50.68	52.08	53.80	51.66
WF15	74.76	67.65	69.48	73.73	78.01	72.35

Table C-4 Relative Compressive Strength Development of Concrete Sample Compared to 90-days Compressive Strength of the Same Sample

Sample	Relative Compressive Strength, %					
	3-day	8-day	14-day	28-day	56-day	90-day
F00	0.64	0.80	0.89	0.94	0.96	1.00
F10	0.66	0.81	0.86	0.99	1.00	1.00
F15	0.65	0.71	0.85	0.92	1.00	1.00
F25	0.67	0.77	0.87	0.95	1.00	1.00
WF15	0.66	0.75	0.85	0.96	1.03	1.00

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Table C-5 Concentrations of Water-Soluble Chloride of MSWIFA, Washed MSWIFA, MSWIFA Concrete, and Washed MSWIFA Concrete

Sample	Water-Soluble Chloride	
	Concentration, ppm	Concentration, % by weight of cement
F00	999	0.039
F10	1098	0.047
F15	1598	0.073
F25	2547	0.132
WF15	999	0.046
FA	22477	-
WFA	2497	-
Wastewater (WW)	37462	-

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BIOGRAPHY

Mr. Pakawat Sanchaoren was born on September 10, 1979 in Bangkok, Thailand. He graduated primary and secondary school in 1997 from Saint Gabriel's College, Bangkok. He received his Bachelor's Degree in Civil Engineering from Faculty of Engineering, Chulalongkorn University in 2001. He pursued his Master Degree studies in the International Postgraduate Programs in Environmental Management, Inter-Department of Environmental Management, Chulalongkorn University in May 2001. He was awarded Master Degree of Science in Environmental Management in September 2003.



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