Municipal solid waste fly ash washing for cement application

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การชะล้างเถ้าลอยจากการเผาขยะชุมชนเพื่อประยุกต์ใช้ร่วมกับปูนซีเมนต์

น.ส.สุทัตตา ดนตรีรส

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เถ้าลอยจากการเผาขยะชุมชนได้ส่งผลกระทบต่อสิ่งแวดล้อมเนื่องจากเถ้าลอยจากการเผาขยะชุมชนนั้นมีปริมาณโลหะหนักสูง ดังนั้นจึงได้นำวิธีการปรับเสถียรและตรึงโลหะหนักด้วยวิธี solidification-stabilizationมาประยุกต์ใช้ เพื่อลดการชะละลายของโลหะหนักสู่สิ่งแวดล้อม นอกจากนั้นในเถ้าลอยขยะยังมีปริมาณคลอไรด์และซัลเฟตสูง ทำให้ก้อนซีเมนต์ที่มีเถ้าลอยขยะผสมมีความแข็งแรงต่ำ ดังนั้นจึงได้มีการนำวิธีการบำบัดหรือปรับสภาพเถ้าลอยขยะเพื่อลดปริมาณเกลือคลอไรด์และซัลเฟต

ในงานวิจัยนี้ได้ศึกษาการบำบัดเถ้าลอยขยะด้วยวิธีการชะล้างโดยใช้สารละลายดังนี้ น้ำกลั่น, 0.01Mและ 0.1M กรดไนตริก และ0.1M และ0.25M โซเดียมคาร์บอเนต เพื่อกำจัดคลอไรด์และซัลเฟต นอกจากนี้ยังได้ศึกษาคุณสมบัติทางกายภาพและเคมีของเถ้าลอยขยะที่ถูกชะล้างรวมทั้งกลไกการชะล้างคลอไรด์และซัลเฟต เถ้าลอยที่ผ่านการชะล้างจะถูกนำมาผสมกับปูนซีเมนต์เพื่อศึกษากำลังอัดของมอร์ตาร์ จากผลการศึกษาพบว่าการชะล้างไม่สามารถเปลี่ยนรูปร่างและขนาดอนุภาคของเถ้าลอยขยะได้ สารชะล้างทุกชนิดสามารถกำจัดคลอไรด์ได้ในปริมาณเท่าๆกันประมาณ แต่โซเดียมคาร์บอเนตสามารถกำจัดซัลเฟตได้มากที่สุด เนื่องจากโซเดียมคาร์บอเนตสามารถเปลี่ยนแคลเซียมซัลเฟตเป็นโซเดียมซัลเฟตที่สามารถละลายน้ำได้ดีกว่า ในส่วนของมอร์ตาร์นั้นเถ้าลอยที่ผ่านการชะล้างด้วยน้ำกลั่นให้กำลังอัดสูงสุดที่ 24.25 MPa ที่การแทนที่ปูนซีเมนต์ 5%และผลการศึกษาการชะล้างโลหะหนักจากมอร์ตาร์ด้วยวิธี TCLP พบว่ามอร์ตาร์ทุกสูตรผ่านมาตรฐาน

สาขาวิชา	วิศวกรรมสิ่งแวดล้อม	ลายมือชื่อนิสิต ....
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Waste incineration is general solution to manage of municipal solid waste. However, large amount of municipal solid waste incineration fly ash (MSWI FA) accumulating heavy metals poses problem to the environment. One of the fundamental treatments is called solidification-stabilization of MSWI FA with cement to cap hazardous elements. Elements such as chloride and sulfate are captured in MSWI FA when it is collected in an air pollution control device causing low compressive strength of concrete. Thus, a further treatment of MSWI FA to remove these salts are required.

Therefore, this study investigated MSWI FA treatment by deionized water, 0.01M and 0.1M HNO_3, and 0.1M and 0.25M Na_2CO_3 to remove chloride and sulfate. Physical and chemical structures of treated and untreated MSWI FA was studied to understand the chloride and sulfate removal mechanisms. Treated MSWI FA was further used as cement replacement in mortar, and the compressive strength was tested. Results suggested that all of the treated solutions can equally remove chloride, but Na_2CO_3 can remove sulfate in highest level. In addition, mortar with DI-water-treated MSWI FA gave the highest compressive strength. Moreover, heavy metals in the mortar leached by Toxicity Characterization Leaching Procedure (TCLP) method pass the standard.

Field of Study:	Environmental Engineering	Student's Signature ....
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Suthatta Dontriros

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ABBREVIATION

°C	- Degree Celsius
% by wt.	- Percent by weight
%R LC	- Percent removal in leachate
%R MW	- Percent removal calculated from microwave digestion
ASTM	- American Society for Testing and Materials
ICP-OES	- Inductive Couple Plasma-Optical Emission Spectrometer
FA-APC	- Municipal solid waste fly ash from air pollution control device
FA-BT	- Bituminous fly ash
FA-LF	- Municipal solid waste fly ash from landfill
FA-LN	- Lignite fly ash
g	- Gram
hr	- hour
L/S	- Liquid/solid
M	- Molar
mg/kg	- Milligram/kilogram
mg/L	- Milligram/liter
min	- Minute
MSWI FA	- Municipal solid waste fly ash
MΩ	- Meg-ohm
µm	- Micron

CHAPTER 1

INTRODUCTION

1.1 Background and rationale

An increasing of municipal waste production is a worldwide environmental problem, and incineration is a generally method used to reduce volume of waste where recycling or reuse is not possible (Wang et al., 2010). After incineration two main residues are released and considered as municipal waste incineration ashes (Weibel et al., 2017). These ashes can be separated in 2 parts; bottom ash (around 80% by wt.), and fly ash (20% by wt.) (Gines et al., 2009 and Yang, Liao and Wu, 2012). Fly ash is collected by air pollution control device with lime addition to remove acid gas. After that, fly ash is disposed of to landfill. However, the area for landfill is limited, and fly ash has special characterization upon composition of waste that usually makes fly ash hazardous (Bie et al., 2016 and Funari et al., 2017).

Various researches have been investigated so as to reduce the hazardous composition and reuse municipal solid waste fly ash (MSWI FA). Solidification and stabilization are the most commonly employed treatments (Wang et al., 2015), and these methods also give a benefit in construction material (Gines et al., 2009). Results from many research used fly ash as a binder in concrete around 10%-15% by wt. (Siddique, 2010) because compressive strength decreased with increasing fly ash amount. One of the reasons of low compressive strength arose from chemical composition of fly ash especially chloride (Cl^-) and sulfate (SO_4^{2-}). High chloride (29.3% by wt.) and sulfate content (4.03% by wt.) in fly ash resulted in concrete corrosion. Chloride also decreases formation of calcium silicate hydrate gel (C-S-H) and hydration reaction (Joseph et al., 2018). The ettringite structures acting like needle and formed from sulfate decreased compressive strength and density of mortar (Garcia-Lodeiro et al., 2016).

As a utilization of municipal solid waste fly ash, there is an increasing interest in chloride and sulfate removal by various solutions. The most popular solution is water because it can wash almost chloride except insoluble chloride (Joseph et al., 2018). In addition, there are related studies about acid treatment. These studies identified that acid solution could better dissolve insoluble chloride and sulfate including heavy metal than water (Ito et al., 2006 and Aguiar del Toro et al., 2009). Other researches studied about sodium carbonate (Na_2CO_3) which could decrease chloride and sulfate from municipal solid waste fly ash, and the treated calcium could react with carbonate to form a useful structure of calcium carbonate ($CaCO_3$) to replace a mortar void. Treated MSWI FA could replace around 25% by wt. of cement (Aubert et al., 2007 and Saikia et al., 2015) because the treatment increased specific surface area which affected chemical reaction efficiency. Moreover, smaller size of particle also increased fly ash replacement in the concrete void. Besides, when sulfate was washed, the formation of spiky ettringite decreased resulting in higher compressive strength of mortar (Saikia et al., 2015).

This aim of this study was to consider the efficiency of chloride and sulfate treatment from MSWI FA from air pollution control device and landfill by deionized water, 0.01M nitric acid, 0.1M nitric acid, 0.1M sodium carbonate and 0.25M sodium carbonate. This study investigated the effect of acid-base condition, and concentration of chemical solution to physical and chemical composition of MSWI FA. After the treatment, fly ash was used to replace cement in mortar. Compressive strength of mortar following the TIS 1776-2542 were studied. To our knowledge, this is the first study to investigate the effect of chemical and physical properties of treated MSWI FA on mortar property. Environmental concern related to the product is also investigated.

1.2 Objectives

1.2.1 To investigate physical and chemical characteristics of municipal solid waste fly ash

1.2.2 To investigate physical and chemical characteristics of municipal solid waste fly ash after washing by nitric acid solution, sodium carbonate solution and deionized water

1.2.3 To investigate the effect of treated municipal solid waste fly ash on properties of mortar including density, compressive strength, dimension and wryness

1.3 Research gap

1.3.1 Limited researches compared chloride and sulfate removal using nitric solution and sodium carbonate solution

1.3.2 Limited researches study comparison between municipal solid waste fly ash from air pollution control device and landfill

1.3.3 Limited researches study concentration of elements in leachate and municipal solid waste fly ash after treatment

1.4 Scope of study

Municipal solid waste fly ash was collected from air pollution control device (spray dryer absorber) at Phuket municipal solid waste incineration plant on 22 May 2018 and cured at 105 ± 5°C before being sieved though 75 µm-sieve.

Lignite and Bituminous fly ashes were donated from Taurus Pozzolans Co., LTD. Fly ash samples were stored in airtight plastic container.

Chemical solutions of this study are prepared in laboratory at ambient temperature. There are 3 types of solution:

1. deionized water
2. 0.01M and 0.1M nitric acid solution
3. 0.1M and 0.25M sodium carbonate solution

These solutions were determined in order to study the effect of concentration and type to chloride and sulfate dissolving. Then, treated and untreated municipal solid waste fly ashes were utilized with cement to form mortar. Physical tests such as compressive strength compared with TIS 1776-2542 Standard.

CHAPTER 2

THEORY AND LITERATURE REVIEW

2.1 Municipal solid waste incinerator fly ash

Municipal solid waste management in Thailand has focused on open dumping around 65% because this method has low cost and can manage easily. However, this method has negative effect on environmental and local people in surrounding area in form of pungent aroma (Kaosol, 2009). Next time a government had built incinerator to support a large amount of waste which method can save operating area and can decrease volume of waste in short time. Nowadays the municipal solid waste management in small areas such as Japan and Phuket island have usually used incineration as main method.

Although the incineration method uses lesser area than open dumping and landfill and reduce cost and volume of waste, it has by product that cannot be burned called ash. Ash can be separated in two types the first type is bottom ash that compose with non-combustion material like glass and the second type is fly ash which is air pollutant with 80% and 20% of whole ash respectively (Sancharoen, 2003).

2.1.1 Characterization of municipal solid waste fly ash (MSWI FA)

The physical characterization of MSWI FA usually has gray and black colour which depend on source and has a lot of type of pollutant such as Pb, Se and dioxin. The quality of MSWI FA depends on composition of waste, type of combustion and type of air pollution control device (Siddique, 2010).

The research about influence of air pollution control device in four types (Song et al., 2004) which composed of (1) water spray tower (2) spray dryer absorber (3) bag filter and (4) selective catalytic reactor. Result from X-ray fluorescence showed chemical composition of bottom ash had more SiO_2 than MSWI FA in bag filter system while Cl^- content in MSWI FA from bag filter and spray dryer absorber was higher MSWI FA from water spray tower and bottom ash. It showed that air pollution control device could remove some heavy metals and Cl^- from MSWI ash. CaO content in MSWI FA from water spray tower and bottom ash stay at same level but CaO was usually found in MSWI FA from spray dryer absorber more than other types because this system used lime for acid gas removing that affected to base condition of MSWI FA.

The physical characterization of MSWI FA from research of Bie et al., 2016 which studied about MSWI FA in China and they found density of MSWI FA was 2,580 kg/m^3. The specific surface area was 5.28 m^2/g, pore volume was 0.022 cm^3/g and moisture content was 0.6-2.0%. From study of Sancharoen, 2003 which studied about MSWI FA from Phuket province, Thailand and he found that MSWI FA had moisture content equaled 14.81%, specific gravity was 1.92 and loss of ignition was 12.44.

The age of MSWI FA has effect to particle structure of MSWI FA. In Fig 2.1 shows particle shape and microstructure of MSWI FA in two type with Fig 2.1A-B was Fresh MSWI FA which was collected from air pollution control device and Fig 2.1C-D was Aged MSWI FA which was obtained from place that fly ash was already for several months. Following Fig 2.1A-B, Fresh MSWI FA had amorphous shape and single particles were generally smaller than result of laser diffraction measurements but held together to present as aggregates with small porous structure (Fedje et al., 2010). In Fig 2.1C-D, the Aged MSWI FA had plate-like particles with large void spaces and had amorphous phase. Plate-like particles can be broken and create void spaces after treatment process (Zhang et al., 2016).

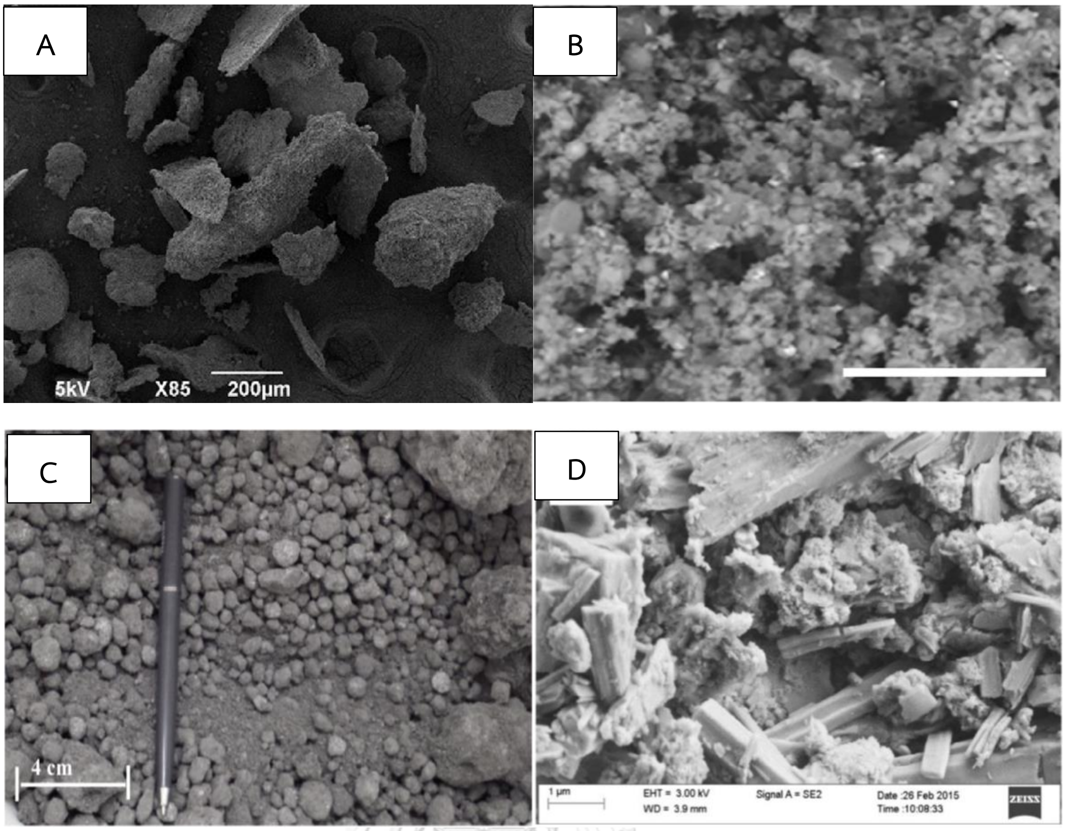

Fig 2.1 SEM images of MSWI FA: A) Fresh MSWI FA (Fujii et al., 2018), B) Fresh MSWI FA (Fedje et al., 2010), D) Aged MSWI FA (Zhang et al., 2016) and photography of C) Aged MSWI FA (Zhang et al., 2016)

The study of structure of MSWI FA by backscattered electron in research of Remond et al., 2002. MSWI FA from two waste incineration plant named FA1 and FA2 as shown in Fig 2.2 which had various shape and some sphere shape had void in structure including some large particle was glass.

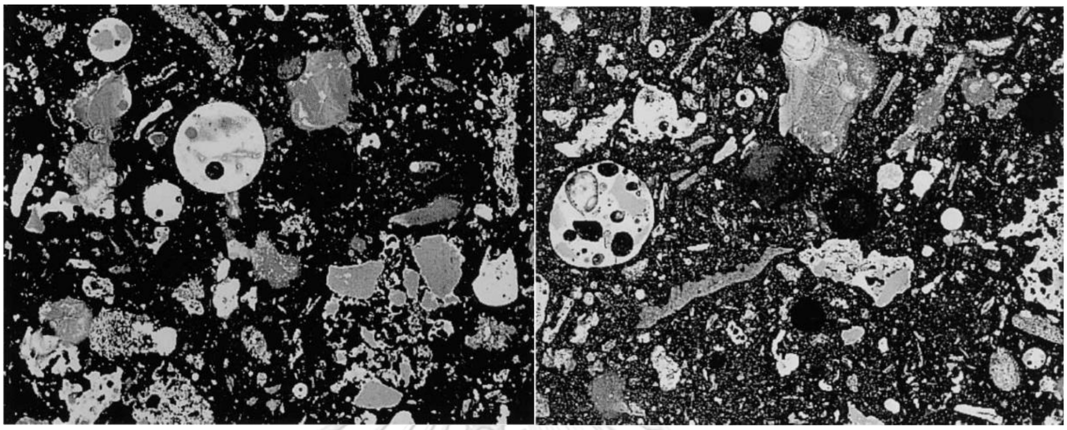

Fig 2.2 Backscattered electron images of MSWI FA: A) FA1 and B) FA2 (Remond et al., 2002)

MSWI FA has high Cl^- and SO_4^{2-} contents which are soluble element (Chen et al., 2012) therefore Cl^- and SO_4^{2-} can be leached to environment easily. These elements are produced from air pollution control device in acid gas removal process. MSWI FA which is cooled down by transferring heat to boiler. The cool air will mix with vapor of lime to remove acid gas such as HCl and SO_2 and transform to $CaCl_2$ and $CaSO_4$. After that, this air will be collected by bag filter and fly ash from air pollution control device has chloride and sulfate. Following Table 2.1, the chemical composition of municipal solid waste incineration fly ash has high amount of chloride and sulfate at 29.10 and 5.76% wt. respectively which is higher than lignite and bituminous fly ash.

Heavy metal in MSWI FA such as Pb, Cu and Zn are higher than lignite and bituminous around 0.1% wt. while lignite and bituminous do not have these heavy metals therefore MSWI FA is recognized about hazardous to environment by leaching of heavy metal.

The particle size of MSWI FA had impact to concentration of heavy on surface (Song et al., 2004) because heavy metals usually accumulate on surface of small particle than large particle and MSWI FA has heavy metal concentration more than in bottom ash because vapor of heavy metals condense and catch on surface of MSWI FA when temperature of system cool down. MSWI FA from bag filter system has most heavy metals concentration compared with MSWI FA from other systems because this system collected MSWI FA which has high surface area.

Yang et al, 2012 used TCLP method according to US EPA 1992 to studied concentration of Pb, Cd and Cu in leachate which result showed MSWI FA had Cd and Cu in lower concentration of standard but Pb concentration had over standard concentration around 20 mg/L.

Chang, Chen and Chang, 1998 studied toxicity of bottom ash and MSWI FA by using TCLP method which result showed Pb, Cd, Cu, Zn, Cr, Hg and As concentration in bottom ash were lower than standard concentration while concentration of these elements in MSWI FA were higher standard concentration.

From research of Remond et al., 2002 studied about utilization of MSWI FA with cement that they found MSWI FA had large amount of Cl^-, Na and K and had Pb and Zn as main of heavy metals. The mineral morphology was quartz (SiO_2), sylvite (KCl), halite (NaCl), anhydrite ($CaSO_4$), calcite ($CaCO_3$) and lime (CaO).

Table 2.1 Chemical composition of MSWI FA, lignite and bituminous

Chemical composition (%)	MSWI FA		Lignite	Bituminous
	Chiewchan, 2003	Jiao et al., 2016	Chiewchan, 2003	Siddique, 2004
SiO_2	3.56	3.80	42.48	55.3
Al_2O_3	2.68	2.54	23.10	25.7
Fe_2O_3	0.79	1.12	14.14	5.3
K_2O	10.10	3.31	2.21	0.6
CaO	34.79	53.7	11.30	5.6
Na_2O	8.65	5.42	0.83	0.4
TiO_2	0.56	0.72	NA	1.3
MnO	0.04	NA	NA	NA
MgO	1.58	1.09	2.40	2.1
SO_3	5.76	4.18	3.48	1.4
P_2O_5	1.39	0.67	NA	NA
CuO	0.05	NA	NA	NA
PbO	0.15	NA	NA	NA
SnO_2	0.11	NA	NA	NA
SrO	0.03	NA	NA	NA
ZnO	0.60	NA	NA	NA
Cl	29.10	22.0	NA	NA
Rb	0.02	NA	NA	NA
Br	0.03	NA	NA	NA

* : mg/kg

2.2 Municipal solid waste incineration fly ash treatment

According to previous paragraph, MSWI FA had non-stable characterization which depends on type of waste therefore MSWI FA was usually tested about heavy metals to prevent environmental problem from leaching process. General heavy metals in MSWI FA are Pb, Zn, Cd and Cu that cause of cancer and other diseases. Cl^- and SO_4^{2-} salts are easily soluble in water therefore they are easily to be leached out from landfill and contaminate to the environment.

2.2.1 Solidification and stabilization

Solidification and stabilization are the method for stabilize the heavy metals in MSWI FA which use alkalinity of cement or lime make base condition and increases precipitation of heavy metals. Due to air pollution control device, vapors of heavy metals are condensed on MSWI FA particles that causes of hazardous condition of MSWI FA. There are many researches study about solidification and stabilization process to cap hazardous elements from MSWI FA.

Solidification is a process by which sufficient quantities of solidifying material, including solids, are added to the hazardous materials to result in a solidification mass of material. In contrast, stabilization is 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. Generally, these methods are used together to get high efficiency of waste treatment. Chiewchan, 2003 studied solidification of heavy metals in MSWI FA by using cement-based treatment which result showed when increased MSWI FA ratio to cement, heavy metals concentration in leachate increased but cement decreased heavy metals leaching in MSWI FA around 82.57%, 65.73% and 69.32% for Cu, Zn and Pb concentration.

Product from solidification and stabilization is concrete or mortar therefore this can be increased value by using as construction materials. However, MSWI FA has large amount of Cl^- and SO_4^{2-} which cause of crack and low compressive strength of product from solidification and stabilization or mortar.

Cl^- is a cause of corrosion which destroy ferric film around iron and increase corrosion rate. Generally, hydration reaction in cement can cap some Cl^- but free-Cl^- in void of structure can destroy film because Cl^- reacts with $CaCO_3$ and releases out $CaCl_2$ (Joseph et al., 2018). Garcia-Lodeiro et al., 2016 studied effect of Cl^- to hydration reaction in cement and result showed Cl^- was a cause of chloroaluminates formation such as Friedel's or Kuzel's salt and chloroaluminates can attach on surface of calcium silicate hydrate (C-S-H) crystal which reduced strength of mortar. Moreover, free-Cl^- can reacted with $Ca(OH)_2$ and released out $CaCl_2$ and $Mg(OH)_2$ which can increase corrosion rate (Joseph et al., 2018) following Eqn (2.1).

$$2Cl^- + Ca(OH)_2 \longrightarrow CaCl_2 + 2OH^- \qquad \text{Eqn (2.1)}$$

Effect of SO_4^{2-} is studied by Garcia-Lodeiro et al., 2016 which showed Al complex reacted with OH^- in base condition and released gas H_2 following Eqn (2.2) and Al can form to be $Al(OH)_3$ and can release gas H_2 following Eqn (2.3).

$$2Al + 2OH^- + 6H_2O \longrightarrow 2[Al(OH)_4]^-_{(aq)} + 3H_{2(gas)} \qquad \text{Eqn (2.2)}$$

$$Al(OH)_3 + OH^- \longrightarrow [Al(OH)_4]^-_{(aq)} \qquad \text{Eqn (2.3)}$$

$[Al(OH)_4]^-$ can react with SO_4^{2-} and Ca^{2+} to form ettringite structure which is likes needle structure and decrease strength and density of mortar moreover SO_4^{2-} can form ettringite structure even if specimen set to solid called mortar.

Remond et al., 2002 studied MSWI FA replacement as cement in 5%, 10%, 15% and 20% which showed adding MSWI FA increased flow time and setting time of mortar and more difference between 10% and 15% replacement. Mortar with MSWI FA shrinked more than mortar without MSWI FA in initial time because Cl^- and SO_4^{2-}

increased ettringite and chloroaluminates formation that caused of crack and low strength of mortar.

2.2.2 Treatment procedure

Treatment procedure is the process by which contaminants are transferred from a stabilize matrix to a liquid medium such as water. For MSWI FA is usually treated out heavy metals for transforming to non-hazardous waste and heavy metals in leachate can be reused in industry. In this study focuses on Cl^- and SO_4^{2-} removal and some heavy metals leaching from MSWI FA. The quality of treatment procedure depends on pH, liquid/solid (L/S), temperature, treatment time and type of treated solution. In following paragraphs explain three categories of treated solution including water treatment and acid and basic solution treatment.

2.2.2.1 Water treatment

The water treatment procedure give a good result of MSWI FA treatment for utilization with cement because water can remove soluble Cl^- such as NaCl, KCl and $CaCl_2$, then the using of treated MSWI FA by water in cement can reduce the emissions hydrogen chloride and volatile metallic chlorides which cause of corrosion (Yang et al., 2017). Joseph et al., 2018 studied water treatment to remove Cl^- SO_4^{2-} and heavy metals which water was the best treated solution because water can treat all of soluble Cl^- and leaved non-soluble Cl^- around 0.5%.

Wang et al., 2010 studied about effect of L/S and treatment time and result shown in Fig 2.3. Water could remove more Cl^- and SO_4^{2-} when increased L/S for example percent of Cl^- removal that increased from 62.1% to 94.8% for L/S equaled 3/1 and 50/1 respectively. However, percent of SO_4^{2-} removal was usually lower than percent of Cl^- removal equaled 50%, increasing L/S is not factor for that.

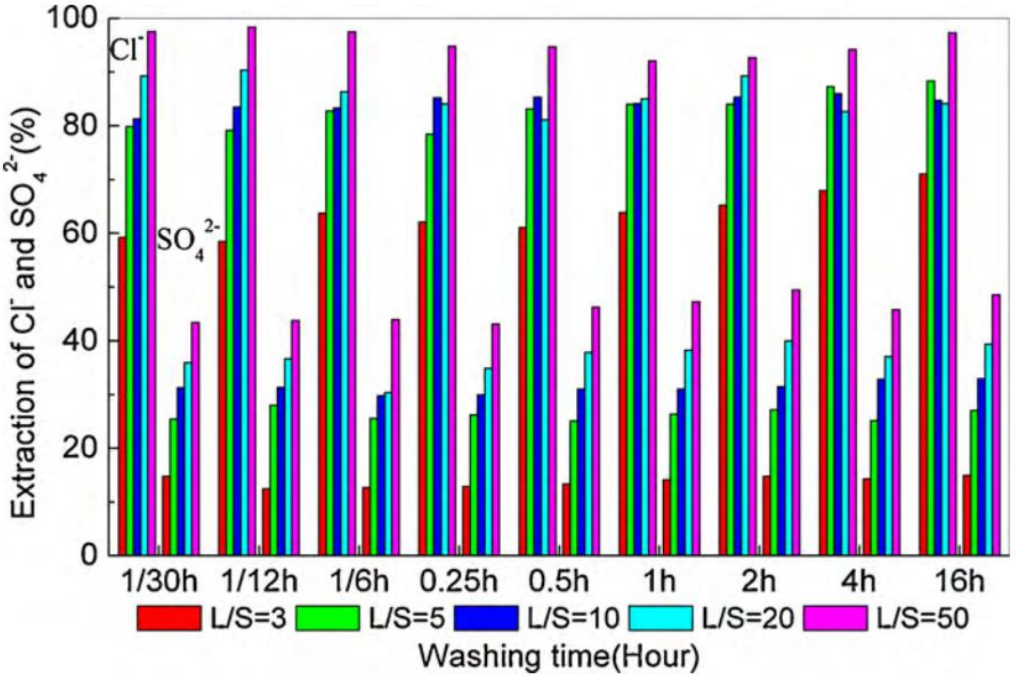

Fig 2.3 Result of Cl^- and SO_4^{2-} removal in different of L/S and time (Wang et al., 2010)

Yang et al., 2017 found that treatment time had lesser impact than L/S according to Fig 2.4. Researcher controlled L/S at 3:1 and vary treatment time which showed efficiency of treatment did not increase during treatment time because Cl^- and SO_4^{2-} had dissolution-precipitation equilibrium in short time within 2 minutes and structure of untreated and treated MSWI FA were similar. Cl^- dissolved from MSWI FA follow Eqn (2.4), (2.5) and (2.6).

$NaCl_{(s)} \longrightarrow Na^+ + Cl^-$ Eqn (2.4)

$KCl_{(s)} \longrightarrow K^+ + Cl^-$ Eqn (2.5)

$CaSO_{4(s)} \longrightarrow Ca^{2+} + SO_4^{2-}$ Eqn (2.6)

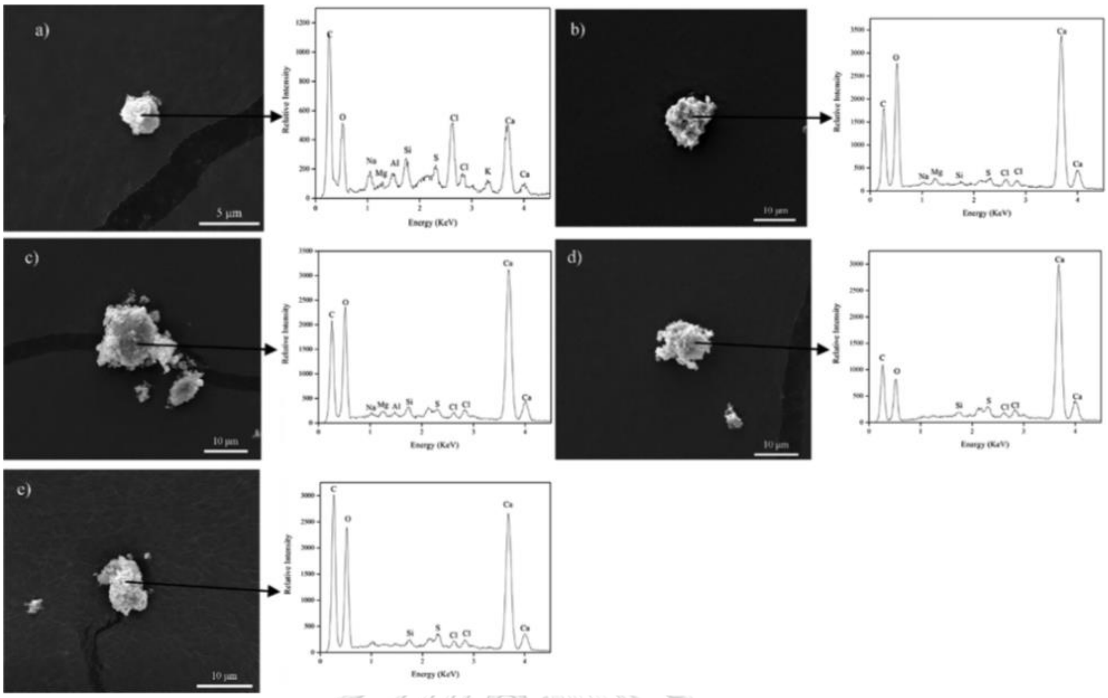

Fig 2.4 SEM images and EDS analysis: A) untreated MSWI FA and treated MSWI FA with L/S 3:1 after B) 2 mins, C) 30 mins, D) 1 hr and E) 16 hr (Yang et al., 2017)

From XRD result of untreated and water treated MSWI FA following Fig 2.5 shows untreated MSWI FA had phase of calcite and CaClOH from using lime in acid gas removal following Eqn (2.7) while phase of anhydrite, sylvite and soluble salt such as CaClOH disappeared in water treated MSWI FA and peak of $Ca(OH)_2$ showed in water treated MSWI FA following Eqn (2.8).

$$CaO_{(s)} + HCl \longrightarrow CaClOH_{(s)} \qquad \text{Eqn (2.7)}$$

$$2CaClOH \longrightarrow Ca(OH)_{2(s)} + CaCl_2 \qquad \text{Eqn (2.8)}$$

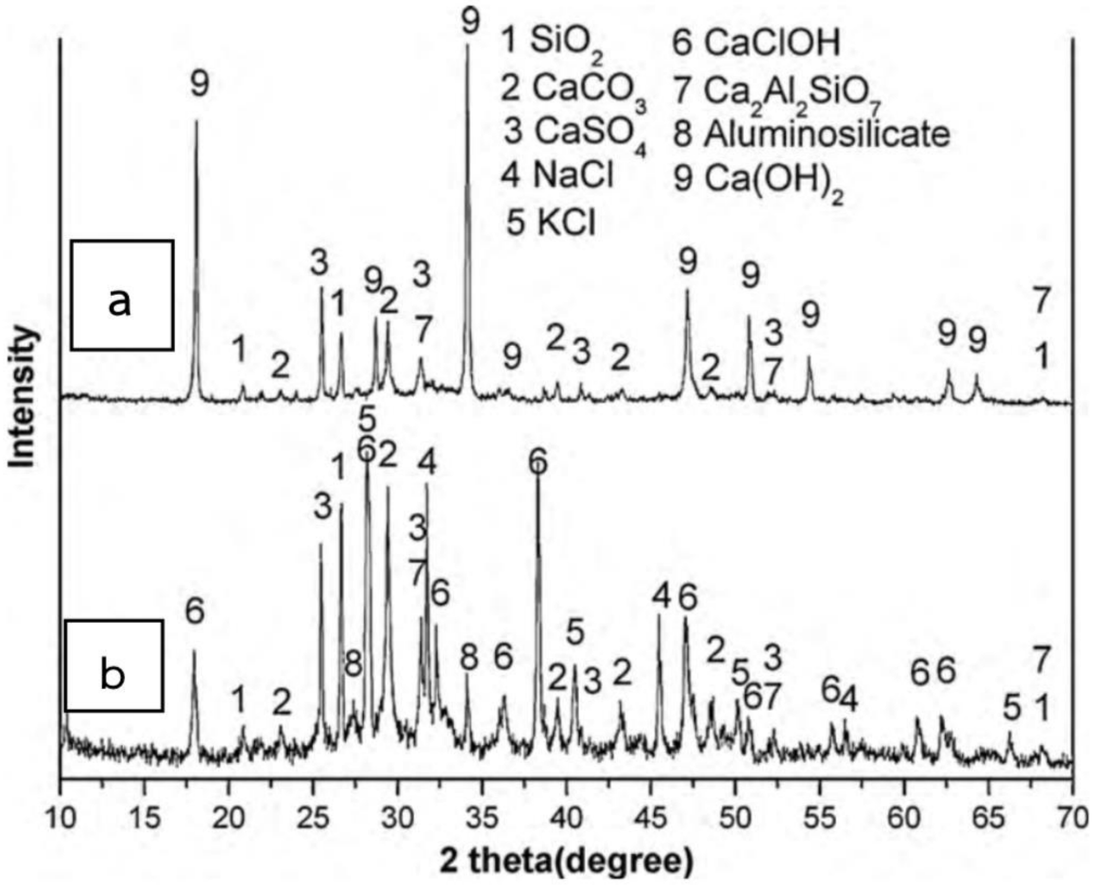

Fig 2.5 XRD result: A) water treated MSWI FA and B) untreated MSWI FA

From research of Bie et al., 2016 explained the result of Cl^- and SO_4^{2-} removal by water treatment with L/S equaled 5:1 and treatment time was 30 minutes at ambient temperature that Cl^- in treated MSWI FA decreased from 12.80% to 1.71% and SO_4^{2-} decreased from 13.61% to 2.77%.

2.2.2.2 Acid and base solution treatment

Ito et al., 2006 studied the efficiency of Cl^- from bottom ash by three acid solution named HCl, HNO_3 and H_2SO_4 with L/S equaled 10:1 in 10 minutes which showed bottom ash size 0.4 µm had Cl^- content more than in larger size (1.0 mm) because small particle had more surface area for catching with Cl^- vapor. The treatment procedure gave high efficiency when it used with small particle size with high surface area and grinding ash before treatment can increase efficiency of treatment. The concentration of treated solution was one of factors for treatment. Ito et al., 2006 used 0.1N and 2N HNO_3 treat Cl^- and 2N HNO_3 can remove Cl^- 85% while 0.1N HNO_3 and water can treat Cl^- 43% and 17% respectively.

Aguiar del Toro, Calmano and Ecke, 2009 studied L/S had effect to Cl^- and heavy metal especially Cu by using H_2SO_4. At pH equaled 3 with L/S was 18:1 and treatment time was 120 minutes, percentage of Cl^- removal was 90%, Cd 60%, Pb 4%, Cu 44% and Zn 70% because H_2SO_4 can remove Cl^- which cannot soluble in water.

Fedje et al., 2010 studied MSWI FA treatment with L/S was 5:1 in 24 hr that showed the particle size and specific surface area of treated MSWI FA changed that depended on pH. Untreated MSWI FA had size 20-40 µm but after treatment by water and ethanol MSWI FA size decreased to 10-20 µm because particles were separated. Structure of treated MSWI FA had lesser of pore and specific surface area is 5.1±0.2 m^2/g. From SEM analysis showed precipitation of crystal and amorphous Ca structure on surface of treated MSWI FA but treated MSWI FA from 3M HCl did not have Ca structure of surface because large content of Ca was removed by 3M HCl. It can say that MSWI FA from acid treatment had more pore volume and specific surface area. For Zn removal which can be removed by 3M HCl and 3M HNO_3 around 40-100% because Zn transferred to soluble form in pH<1 and be non-soluble form in pH between 11.5-12.5. Zn was treated in form of oxide solution such as ZnO and Zn_2SO_4 in acid condition. Pb can remove by water around 14% and 20-40% when used formic acid and lactic acid which Pb transferred to soluble form like $Pb(OH)_2$ in acid condition while in base condition Pb transferred to non-soluble form like $Pb(OH)_3^-$ and $Pb(OH)_4^{2-}$. Water and diluted acid solution cannot treat Cu in 100%.

Aubert et al., 2006 used DI water to treat soluble salt especially Cl^- and water can be reused in caustic soda production industry because water had large amount of Na^+. During water treatment, researcher added Na_2CO_3 to increase base condition and SO_4^{2-} treatment because Na_2CO_3 can transfer $CaSO_4$ to be Na_2SO_4 which was more soluble more than $CaSO_4$ following Eqn (2.9). Another reaction product, $CaCO_3$ was known as filler material can improve the mortar properties. The XRD result from Saikia et al., 2015 shows Na_2CO_3 solution can decrease peak of Al and $CaSO_4$ because $CaSO_4$ transferred to Na_2SO_4 and $CaCO_3$. For study of concentration of Na_2CO_3 found that 0.1M Na_2CO_3 can improve properties of MSWI FA by removing metallic aluminum and SO_4^{2-} for replacement as sand in mortar but 0.25M Na_2CO_3 gave more efficiency.

$$Na_2CO_3 + CaSO_4 \longrightarrow Na_2SO_4 + CaCO_3 \qquad \text{Eqn (2.9)}$$

2.3 Utilization of treated MSWI FA with cement

From many previous researches showed the percent of untreated MSWI FA replacement in mortar is only 10-15% (Siddique, 2010) that caused of treatment MSWI FA by treatment procedure to remove Cl^- and SO_4^{2-} before utilization with cement.

Bertolini et al., 2004 studied utilization of treated MSWI FA which was treated by water until MSWI FA had Cl^- content lower than 0.4% with cement. 30% wt. replacement of treated MSWI FA and water to powder at 1:2 were used to make concrete. The result showed compressive strength of concrete without MSWI FA was 63.5 MPa while concrete with treated MSWI FA was 51.7 MPa at 28 days which was different from concrete with 30% coal fly ash only 1.7 MPa. The water treatment increased efficiency of MSWI FA when it was utilized with cement 30%.

Aubert, Husson and Sarramone, 2006 studied Na_2CO_3 treatment for Cl^- and SO_4^{2-} from MSWI FA which showed 75% of treated MSWI FA with 25% $CaCO_3$ in paste had more $Ca(OH)_2$ and lesser of $CaSO_4$ and ettringite. $Ca(OH)_2$ was used to build structure of calcium aluminate hydrate crystal which increased strength and density of paste.

Aubert et al., 2007 studied treated MSWI FA by Na_2CO_3 replace in mortar as cement 30% with sand/binder ratio was 3:1 and water/binder equaled 1:2 in cement type I and cement type III. The result showed treated MSWI FA increased flow table more than 30 seconds because treated MSWI FA had more pore volume than untreated MSWI FA and mortar wanted more water to set the structure. Pozzolanic reaction in mortar made from MSWI FA was different from coal fly ash because coal fly ash had sphere particle shape and high of SiO_2 and Al_2O_3 content which reacted with lime to build amorphous structure of calcium silicate hydrate (C-S-H), gehlenite hydrate (C_2ASH_8), calcium aluminate hydrate (C-A-H) and sometime SO_4^{2-} in coal fly ash build calcium carboaluminate and ettringite. For pozzolanic reaction of MSWI FA was built from calcium alumino silicate in MSWI FA. In MSWI FA which had low SO_4^{2-} content had calcium carboaluminate while in MSWI FA with high SO_4^{2-} content had gehlenite and ettringite. For leaching test of hazardous element showed mortar with MSWI FA can cap hazardous element in ettringite because ettringite can cap Cr, As and Se but ettringite decreased compressive strength of mortar.

Keppert et al., 2013 used DI water to treat MSWI and increased percent of Si, Al, Fe and Ca. The compressive strength of mortar with MSWI FA replacement as cement 10%, 20% and 30% showed mortar with 30% MSWI FA had strength at 37 MPa while 10% MSWI FA had 42 MPa that was a slightly difference.

Bie et al., 2016 brought DI water to treat MSWI FA and used treated MSWI FA replace as cement in mortar with binder:sand:water was 1:0.5:3 and cured 28 days at 20°C. The leaching test of Pb, Cu, Zn, Cd, Cr and Ni showed these elements were leached when stay in acid condition and at 50% MSWI FA replacement gave the reasonable ratio.

Saikia et al., 2015 used bottom ash and MSWI FA which had size range 0.1-2 mm replace as sand in mortar 25%. The result showed mortar with untreated MSWI FA had more viscosity because small particle size of MSWI FA absorb more water. Moreover, compressive strength decreased when it is compared to mortar with treated MSWI FA by DI water and mortar without MSWI FA. For mortar with treated MSWI FA by 0.1M Na_2CO_3 and 0.25M Na_2CO_3, compressive strength of mortar with treated MSWI FA by 0.1M Na_2CO_3 increased slightly while for mortar treated MSWI FA by 0.25M Na_2CO_3 increased moderately (47.2 MPa at 28 days) that lower than only 2% of mortar without MSWI FA because 0.25M Na_2CO_3 can remove metallic aluminum and SO_4^{2-} which decreased ettringite formation.

Hartmann et al., 2015 studied water treatment for MSWI FA three times and used to replace as cement 50% which showed treated MSWI FA at 50% replacement gave strength enough to be concrete floor and strength decreased only 0.33% from 25 MPa to 24.89 MPa for mortar with untreated MSWI FA and treated MSWI FA. The comparation of percent replacement of MSWI FA with cement shown in Table 2.2.

Table 2.2 Summary of research used treated MSWI FA with cement

Type of ash	Type of replacement material	% replacement of ash	Treated solution	Source
Bottom ash	Sand	25%	0.25M Na_2CO_3	Saikia et al., 2015
Fly ash	Cement	30%	DI water	Bertolini et al., 2004
Fly ash	Cement	12%	DI water + H_3PO_4 + Heat treatment	Aubert, Husson and Vaquier, 2004
Fly ash	Cement	25%	DI water 3 times	Nartmann et al., 2015
Fly ash	Cement	30%	DI water + Na_2CO_3 + H_3PO_4 + Heat treatment	Aubert et al., 2007
Fly ash	Binder in geopolymer mortar	50%	DI water	Ferone et al., 2013
Fly ash	Cement	30%	DI water	Keppert et al., 2013

CHAPTER 3

MATERIALS AND METHODS

3.1 Materials

There are 4 types of fly ashes used in this study. The first two ashes are lignite coal fly ash (FA-LN) and bituminous coal fly ash (FA-BT), respectively. FA-LN and FA-BT are used as a common and well-characterized sample which were donated from Taurus Pozzolans CO., LTD. After that, 5 kg of fly ash samples were cured at 105 ± 5°C around 24 hr and stored in airtight plastic container that is shown in Fig 3.1C-D at Department of Mining and Petroleum Engineering, Faculty of Engineering, Chulalongkorn University. FA-LN is brown while FA-BT is gray, and both of coal fly ash are dry. Both municipal solid waste incineration fly ashes (MSWI FA) from air pollution device (FA-APC) and MSWI FA from landfill (FA-LF) were collected from air pollution control of spray dryer absorber, and from a landfill at Phuket municipal solid waste incineration plant on 22 May 2018. Around 5 kg of both ashes were cured at 105 ± 5°C for 24 hr before being sieving with 75-μm sieve that is shown in Fig 3.1A-B at Department of Mining and Petroleum Engineering, Faculty of Engineering, Chulalongkorn University. These oven-dried ashes were kept in desiccators until use. FA-APC is dark grey while FA-LF is light gray, and particles of FA-APC can accumulate and form bigger size in short time. After treatment process by DI water, 0.01M HNO_3, 0.1M HNO_3, 0.1M Na_2CO_3 and 0.25M Na_2CO_3, the treated FA-APC and FA-LF were collected for chemical and physical analysis.

The treated solutions were prepared at Hazardous waste laboratory, Department of environmental engineering, Chulalongkorn University using lab grade chemical product. 18 MΩ DI water was used to prepare chemical solution and element analysis by Inductive Couple Plasma- Optical Emission Spectrometer (ICP-OES). The nitric solution was prepared from concentrated nitric acid and diluted with 18 MΩ DI water in different volume for 0.01M HNO_3 and 0.1M HNO_3 solution. The sodium carbonate solution was prepared from anhydrous Na_2CO_3 and dissolved by 18 MΩ DI water with different weight for 0.1M Na_2CO_3 and 0.25M Na_2CO_3.

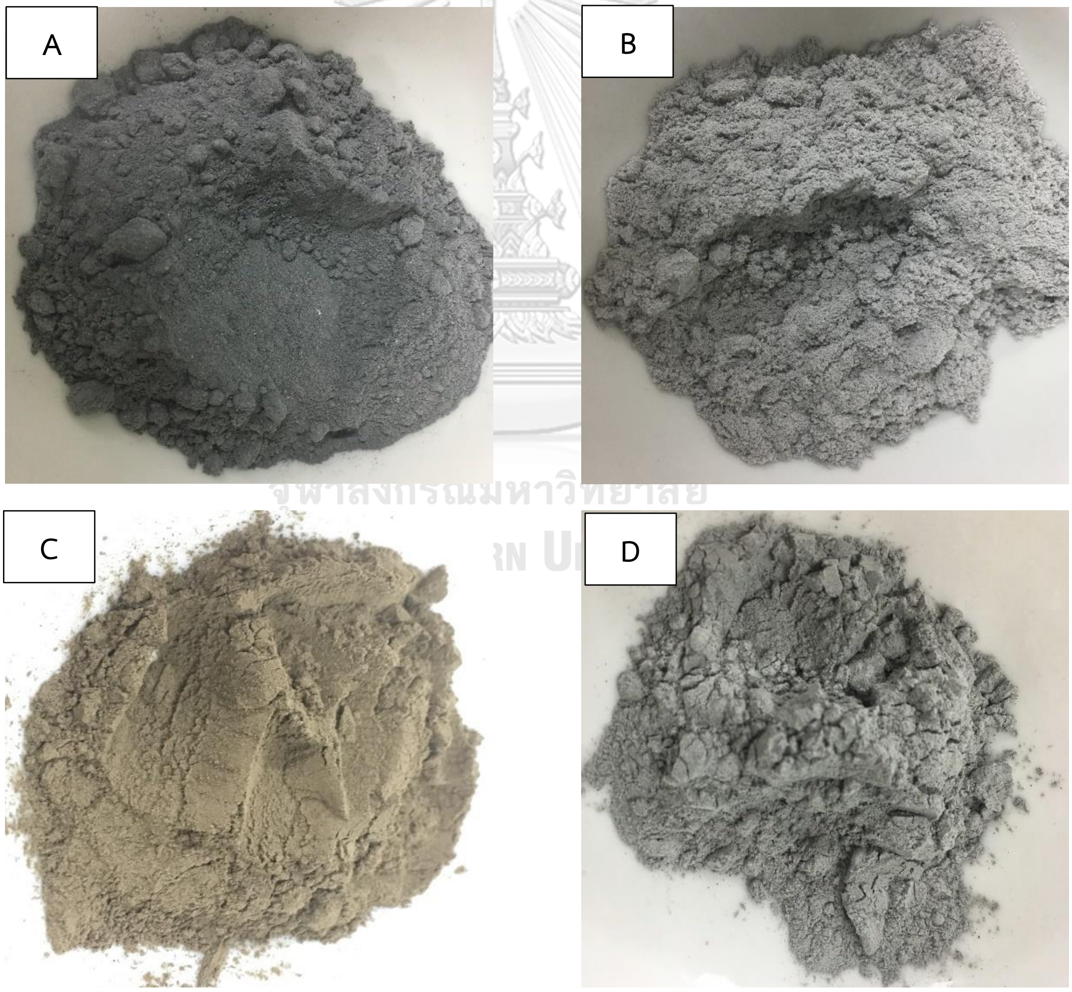

Fig 3.1 Fly ash samples: A) FA-APC, B) FA-LF, C) FA-LN, D) FA-BT

3.2 Characterization of fly ash

Chemical composition of fly ashes was analyzed by using X-ray Fluorescence (XRF) spectrometer (Bruker model S8 Tiger). The particle size distribution of samples was analyzed by using laser diffraction spectroscopy (Malvern Mastersizer 3000). For studying microstructure of samples, scanning electron microscope (JEOL, JSM-IT300) was employed. The mineralogical phases identification of fly ash was tested by using X-ray diffraction (D8-Discover). XRF, XRD and particle size distribution were analyzed at Scientific and Technological Research Equipment Centre, Chulalongkorn University. In addition, surface area and pore volume of fly ash were measured by BET specific surface area (BELSORP, mini-II nitrogen adsorptometer) at Department of chemistry, Faculty of Science, Chulalongkorn University.

The following was analyzed at Hazardous waste laboratory, Department of Environmental Engineering, Chulalongkorn University. Fly ash pH was measured by pH meter according to US EPA method 9045 Part D. To prepare solution, 20 g of fly ash was added to 20 mL of DI water and mixed for 5 min.The mixture was stored at room temperature for 1 hr to allow precipitation of fly ash before filtered through a 45-μm membrane filter. Aliquot was used for pH measurement. Density of fly ashes was measured according to ASTM C-188. This method involved adding fly ash in kerosene to measure the displaced volume in Le Chatelier flask. The density can be calculated by using mass of fly ash added in the flask and the difference of level of kerosene in flask. Moisture content was measured according to ASTM D2216. Crucibles were dried in an oven at 110 ± 5°C for 24 hr and weighed to get a constant mass. Then, fly ash was added in dried crucible and placed in the oven at 110 ± 5°C for 24 hr. After 24 hr, dried fly ash was stored in desiccator to cool down before being weighed. Several replications were done until getting a constant mass. The loss of mass due to drying is considered to be water. The moisture content was calculated using the mass of water and the mass of the dry fly ash.

3.3 Extraction of chloride and sulfate

FA-APC and FA-LF were brought to treatment with 5 types of treated solutions: 18 MΩ deionized water (DI water), 0.01M HNO_3, 0.1M HNO_3, 0.1M Na_2CO_3 and 0.25M Na_2CO_3 with liquid/solid ratio (L/S) equal to 5:1 (mL/g) (Sancharoen, 2003). For chloride and sulfate extraction following Fig 3.4, 7g of FA-APC or FA-LF were mixed with 35 mL individual treated solution in 50 mL centrifuge tube following the ratio in Table 3.1 at 30 ± 2 rpm for 60 min by a rotary agitation device. After 60 min, each sample was filtered through glass fiber filter, and leachate was collected and fixed with nitric acid in pH<2. Leachate was stored at 4°C for further chemical analysis (US EPA 1992). Treated FA-APC and FA-LF were dried at 105 ± 5°C for 24 hr, and kept in a plastic bag.

The untreated fly ashes (FA-APC, FA-LF, FA-LN and FA-BT) and treated FA-APC and FA-LF were digested using microwave digestion method (ETHOS PLUS, June 2000) at Hazardous waste laboratory, Department of Environmental Engineering, Chulalongkorn University to analyze the elements in fly ash. For this test, 0.25 g of fly ash was mixed with 7 mL of HNO_3 65% and 1 mL of HCl 37% in vessel, and was digested at 140°C for 3.5 min. Then, the temperature was increased to 240°C for 20 min. After that, the vessel was cooled down in microwave machine to 50°C before acid solution in vessel was filtered through filter paper. Solution collected from digestion was stored at 4°C for further chemical analysis. The liquids from leaching and digestion process were determined the concentration of Ca, Na, K, Fe, Mg, Al and 5 heavy metals including Pb, Zn, Cu, Cd and Cr in leachate. This elemental analysis was conducted using Inductive Couple Plasma- Optical Emission Spectrometer (ICP-OES) at Hazardous waste laboratory, Department of Environmental Engineering, Chulalongkorn University. For ICP-OES analysis, the calibration curve was created by standard solution (ICP multi-element standard solution IV Plasma Emission Standard (ICP)) with various concentrations. The calibration curve for high concentration was created with 5 point of concentration (1, 25, 50, 75, 100 mg/L) as seen in Fig 3.2 and the calibration curve for low concentration was created with 5 point of concentration (0.05, 0.1, 0.5, 1, 5 mg/L) as seen in Fig 3.3, and correlation (R^2) of calibration curve was shown in Table 3.2. Chloride and sulfate concentrations were identified by Potentiometric Method 4500-Cl^- (HACH, HQ440d multi) and Turbidimetric Method 4500-SO_4^{2-} (HACH, 2100P turbidimeter), respectively at Environmental Research Institute Chulalongkorn University.

Table 3.1 The ratio of leaching test at 1-hr extraction

Type of fly ash	Type of treated solution	Fly ash (g)	Treated solution (mL)	Replicate (tubes)
FA-APC	DI water	7.0	35.0	3
	0.01M HNO_3	7.0	35.0	3
	0.1M HNO_3	7.0	35.0	3
	0.1M Na_2CO_3	7.0	35.0	3
	0.25M Na_2CO_3	7.0	35.0	3
FA-LF	DI water	7.0	35.0	3
	0.01M HNO_3	7.0	35.0	3
	0.1M HNO_3	7.0	35.0	3
	0.1M Na_2CO_3	7.0	35.0	3
	0.25M Na_2CO_3	7.0	35.0	3

Table 3.2 Correlation (R^2) of calibration curve for ICP-OES

Element	Wave length	High concentration (1, 25, 50, 75, 100 mg/L)	Low concentration (0.05, 0.1, 0.5, 1, 5 mg/L)
Ca	393.366	0.9941576	-
Na	588.995	0.9997622	-
K	766.490	0.9992097	-
Al	309.271	0.9990169	0.9997994
Fe	259.940	0.9997656	0.9998756
Mg	279.553	0.9987344	0.999768
Zn	213.856	0.9997714	0.9999591
Pb	220.353	0.9994618	0.9998757
Cu	324.754	0.9998236	0.999872
Cd	228.802	0.9998576	0.9999106
Cr	283.563	0.9993367	0.9998869

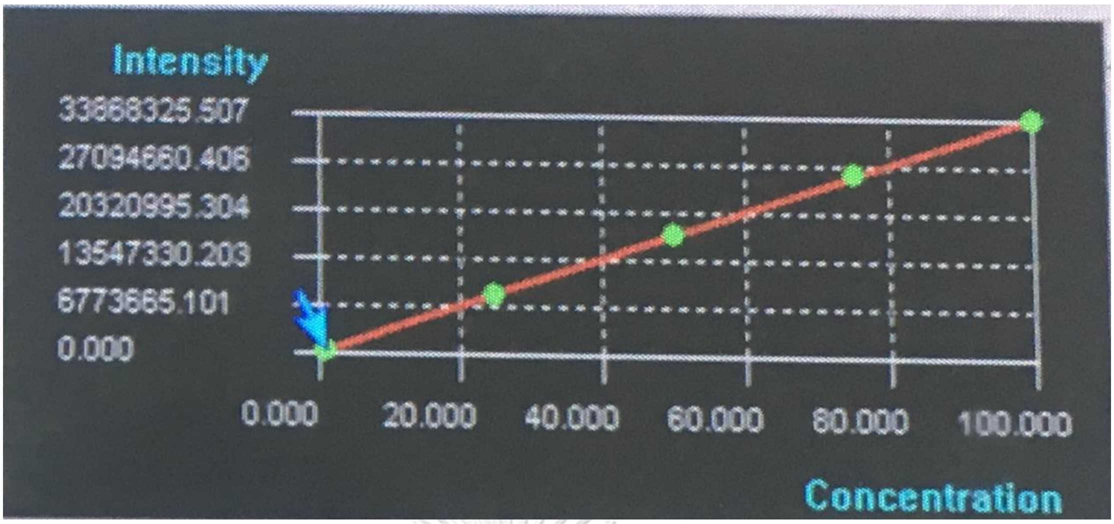

Fig 3.2 Calibration curve for high concentration (1, 25, 50, 75, 100 mg/L) from ICP-OES of Zn

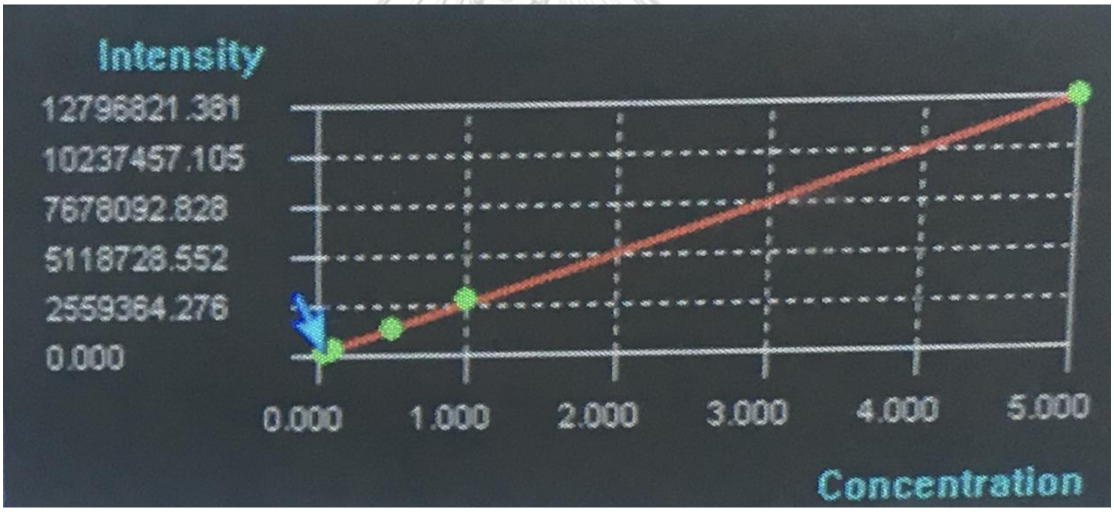

Fig 3.3 Calibration curve for low concentration (0.05, 0.1, 0.5, 1, 5 mg/L) from ICP-OES of Mg

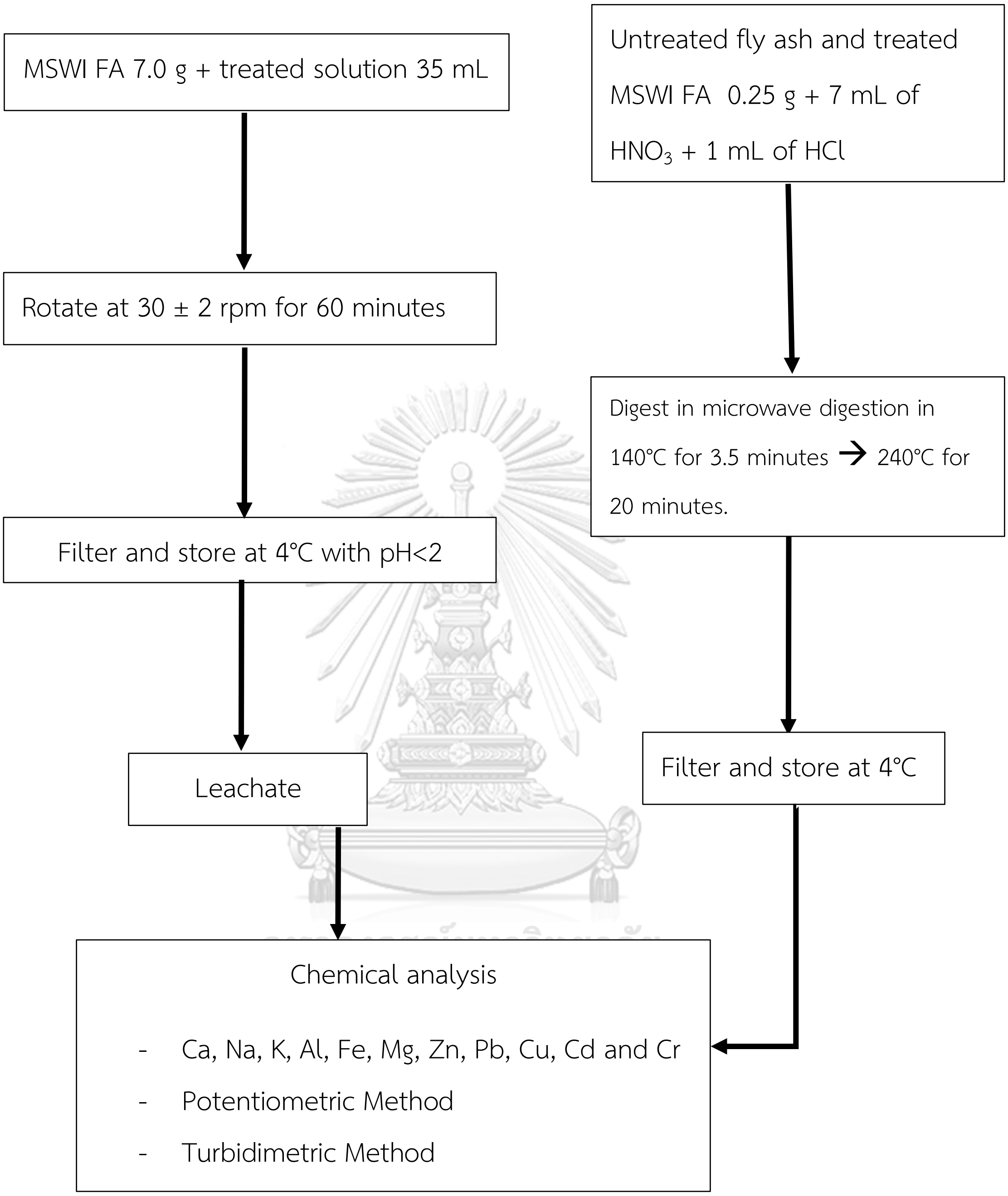

Fig 3.4 Extraction and digestion procedure of Cl^-, SO_4^{2-} and metals by treated solution (DI water, 0.01M HNO_3, 0.1M HNO_3, 0.1M Na_2CO_3 and 0.25M Na_2CO_3)

3.4 Preparation of mortars

Fly ash, cement and sand were mixed to form homogeneous powder in following ratio as shown in Table 3.3 before adding water to blend the specimens by the ratio of 0.5 liquid/solid by weight. The specimens were poured into the 5x5x5 cm^3 acrylic molds in two layers, wrapped by plastic film to prevent moisture loss, and cured at ambient temperature for 24 hr. After de-molding, the specimens were stored at ambient temperature for 28 days. The product of mortar from untreated FA-APC, FA-LF, FA-LN and FA-BT and treated FA-APC and FA-LF was measured the dimension of tolerance by using ruler, density by calculation from mass divided by volume, deviation from right angel by machinist square and compressive strength of mortar by using compression machine (Amsler 20 ton) at Department of Civil Engineering, Faculty of Engineering, Chulalongkorn University.

.

Table 3.3 The ratio of materials for preparing of mortars

Type of fly ash	% replacement of fly ash	Fly ash (g)	Cement (g)	Sand (g)	Water (g)	Replicate (samples)
Control						
-	0	-	198	554.5	99	3
Untreated fly ash						
FA-APC	5	9.9	188.1	544.5	99	3
	10	19.8	178.2	544.5	99	3
	15	29.7	168.3	544.5	99	3
	20	39.6	158.4	544.5	99	3
FA-LF	5	9.9	188.1	544.5	99	3
	10	19.8	178.2	544.5	99	3
	15	29.7	168.3	544.5	99	3
	20	39.6	158.4	544.5	99	3
Lignite	5	9.9	188.1	544.5	99	3
	10	19.8	178.2	544.5	99	3
	15	29.7	168.3	544.5	99	3
	20	39.6	158.4	544.5	99	3
Bituminous	5	9.9	188.1	544.5	99	3
	10	19.8	178.2	544.5	99	3
	15	29.7	168.3	544.5	99	3
	20	39.6	158.4	544.5	99	3

Table 3.3 The ratio of materials for preparing of mortars (continue)

Type of fly ash	% replacement of fly ash	Fly ash (g)	Cement (g)	Sand (g)	Water (g)	Replicate (samples)
Treated FA-APC by						
DI water	5	9.9	188.1	544.5	99	3
	10	19.8	178.2	544.5	99	3
	15	29.7	168.3	544.5	99	3
	20	39.6	158.4	544.5	99	3
0.01M HNO_3	5	9.9	188.1	544.5	99	3
	10	19.8	178.2	544.5	99	3
	15	29.7	168.3	544.5	99	3
	20	39.6	158.4	544.5	99	3
0.1M HNO_3	5	9.9	188.1	544.5	99	3
	10	19.8	178.2	544.5	99	3
	15	29.7	168.3	544.5	99	3
	20	39.6	158.4	544.5	99	3
0.1M Na_2CO_3	5	9.9	188.1	544.5	99	3
	10	19.8	178.2	544.5	99	3
	15	29.7	168.3	544.5	99	3
	20	39.6	158.4	544.5	99	3
0.25M Na_2CO_3	5	9.9	188.1	544.5	99	3
	10	19.8	178.2	544.5	99	3
	15	29.7	168.3	544.5	99	3
	20	39.6	158.4	544.5	99	3

Table 3.3 The ratio of materials for preparing of mortars (continue)

Type of fly ash	% replacement of fly ash	Fly ash (g)	Cement (g)	Sand (g)	Water (g)	Replicate (samples)
Treated FA-LF by						
DI water	5	9.9	188.1	544.5	99	3
	10	19.8	178.2	544.5	99	3
	15	29.7	168.3	544.5	99	3
	20	39.6	158.4	544.5	99	3
0.01M HNO_3	5	9.9	188.1	544.5	99	3
	10	19.8	178.2	544.5	99	3
	15	29.7	168.3	544.5	99	3
	20	39.6	158.4	544.5	99	3
0.1M HNO_3	5	9.9	188.1	544.5	99	3
	10	19.8	178.2	544.5	99	3
	15	29.7	168.3	544.5	99	3
	20	39.6	158.4	544.5	99	3
0.1M Na_2CO_3	5	9.9	188.1	544.5	99	3
	10	19.8	178.2	544.5	99	3
	15	29.7	168.3	544.5	99	3
	20	39.6	158.4	544.5	99	3
0.25M Na_2CO_3	5	9.9	188.1	544.5	99	3
	10	19.8	178.2	544.5	99	3
	15	29.7	168.3	544.5	99	3
	20	39.6	158.4	544.5	99	3

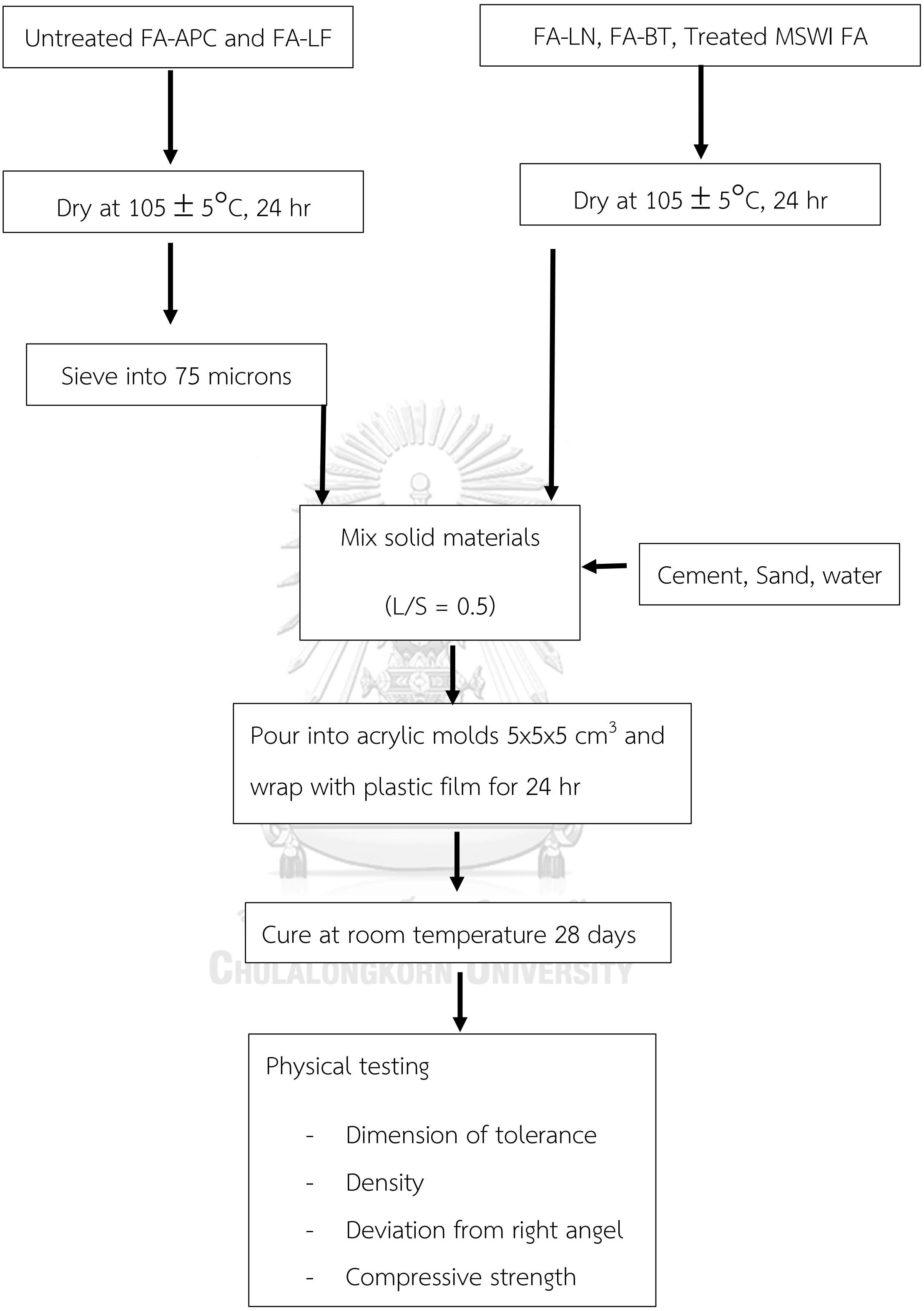

Fig 3.5 Production of mortars from untreated and treated FA-APC and FA-LF, untreated FA-LN and FA-BT, cement, sand and water

3.5 Leaching test

After physical testing of mortar, the chemical analysis on heavy metal according TCLP testing (US EPA 1992) was tested. For this test in Fig 3.6, around 1 g of mortar and untreated FA-APC and FA-LF with size smaller than 9.5 mm was used to mix with 20 mL acetic solution with pH 2.88 prepared by mixing acetic acid with DI water in 50 mL centrifuge tube and rotated at 30 ± 2 rpm for 18 hr by a rotary agitation device. After 18 hr, each sample was filtered through glass fiber filter. Leachate was collected and fixed with acid solution (pH<2). All samples were stored at 4°C for further chemical analysis at Hazardous waste laboratory, Department of Environmental Engineering, Chulalongkorn University. Heavy metals in the leachate including Pb, Cu, Cr and As were analyzed using ICP-OES at Environmental Research Institute Chulalongkorn University.

Table 3.4 The leaching test from mortar by TCLP method

Type of mortar	**Type of treated FA**	**Replicate (tubes)**
FA-APC replacement 5%	DI water	3
	0.01M HNO_3	3
	0.1M HNO_3	3
	0.1M Na_2CO_3	3
	0.25M Na_2CO_3	3
FA-LF replacement 5%	DI water	3
	0.01M HNO_3	3
	0.1M HNO_3	3
	0.1M Na_2CO_3	3
	0.25M Na_2CO_3	3
FA-LN replacement 5%	Untreated FA	3
FA-BT replacement 5%	Untreated FA	3

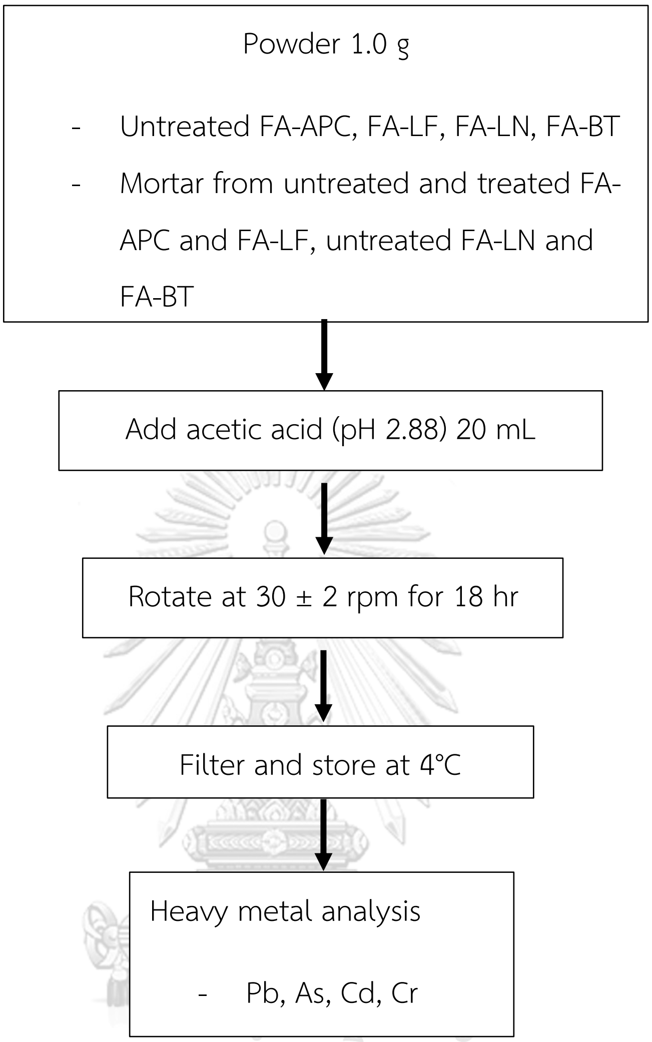

Fig 3.6 Toxicity Characteristic Leaching Procedure (TCLP) of 1) mortar with untreated and treated FA-APC and untreated FA-LN and FA-BT and 2) untreated FA-APC, FA-LF, FA-LN and FA-BT

3.6. Statistical analysis

ANOVA function was used to calculate the mean score. Standard deviation analysis of data was applied to compare concentration of element in leachate and characterization of mortar.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Characterization of MSWI FA

4.1.1 Microstructure

SEM micrograph shows that microstructure of untreated FA-APC from air pollution control device (Fig 4.1A) and untreated FA-LF from landfill (Fig 4.1B) have amorphous shape with rough surface, and particles of FA-APC and FA-LF in SEM images are formed by small particles. According to BET analysis, FA-LF has higher total pore volume of 0.1142 cm^3/g than FA-APC of 0.0203 cm^3/g. This result agrees with Zhang et al., 2016 that plate-like particles as seen in Fig 4.1B which form by reaction in landfill and can increase void space depending on compaction. For coal fly ash, Lignite (FA-LN) and Bituminous (FA-BT) have spherical shape with smooth surface of single particle, and these particles have a lower surface area and pore volume than FA-APC and FA-LF.

The EDS results shown in Fig 4.1 suggest that FA-APC particles have higher level of Ca, Cl^-, SO_4^{2-}, while Cl^- and SO_4^{2-} level decreases in FA-LF. This may be because Cl^- is soluble salt that can be dissolved from wet condition in the landfill (Kjeldsen et al., 2002, Lundtorp et al., 2003 and Brannvall and Kumpiene, 2016). For FA-LN and FA-BT, these samples have high amount of Si, Al and Fe (Thomas, 2007) which is main property of pozzolanic material of coal fly ash.

Fig 4.2 shows the microstructure of treated FA-APC and treated FA-LF. Particle shapes of treated FA-APC do not change after treatment process but pore size reduces slightly from 6.3049 nm to 5.4556 nm for untreated and treated FA-APC shown in Table 4.1. The treatment process can increase surface area from 12.886 m^2/g to 90.024 m^2/g and total pore volume from 0.0203 cm^3/g to 0.1381 cm^3/g.

For FA-LF, it can be seen that surface area decreases after treatment because the treated solutions dissolve the crystal around particle (Zhang et al., 2016) that is clear to see in EDS analysis in Fig 4.3. This analysis shows the removing of soluble salt because the content of Cl^-, Na and K on the surface of all treated samples is extremely low (Gines et al., 2009 and Weibel et al., 2017). From SEM images in Fig 4.3, microstructure of treated FA-LF is more tight than untreated FA-LF. However, pore size of untreated and treated FA-LF by 0.1M HNO_3 slightly increased from 14.517 to 17.799 nm, while pore volume does not change significantly. Specifically, pore volume before and after treatment with 0.1M HNO_3 is 0.1142 and 0.1195 cm^3/g, respectively.

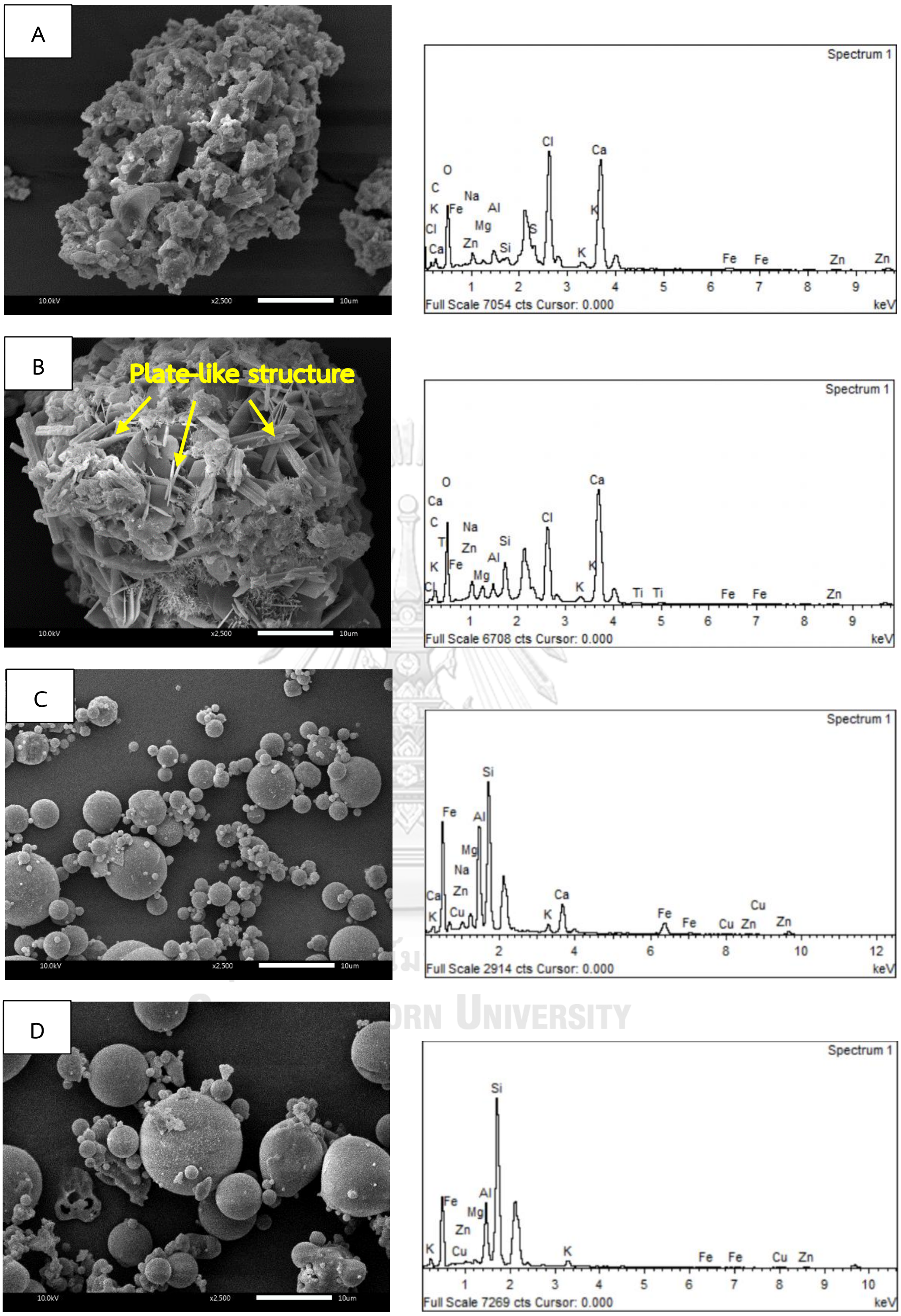

Fig 4.1 Scanning electron microscope (SEM) and Energy dispersive X-ray spectrometer (EDS) images illustrating morphology and elements of untreated fly ashes at 2500x: A) FA-APC, B) FA-LF C) FA-LN, D) FA-BT

Table 4.1 BET analysis of fly ash samples

FA-APC						
Characterization	Untreated FA	DI water	0.01M HNO_3	0.1M HNO_3	0.1M Na_2CO_3	0.25M Na_2CO_3
Surface area (m^2/g)	12.886	78.517	71.241	90.024	82.872	69.848
Total pore volume (cm^3/g)	0.0203	0.1381	0.101	0.1228	0.1214	0.098559
Mean pore diameter (nm)	6.3049	6.6729	5.6735	5.4556	5.8589	5.6442

FA-LF						
Characterization	Untreated FA	DI water	0.01M HNO_3	0.1M HNO_3	0.1M Na_2CO_3	0.25M Na_2CO_3
Surface area (m^2/g)	31.46	28.354	29.315	26.849	33.352	23.309
Total pore volume (cm^3/g)	0.1142	0.1176	0.1224	0.1195	0.1378	0.094038
Mean pore diameter (nm)	14.52	16.59	16.70	17.80	16.53	16.14

Coal fly ash		
Characterization	FA-LN	FA-BT
Surface area (m^2/g)	0.97067	2.5951
Total pore volume (cm^3/g)	0.0013324	0.0027528
Mean pore diameter (nm)	5.50	4.24

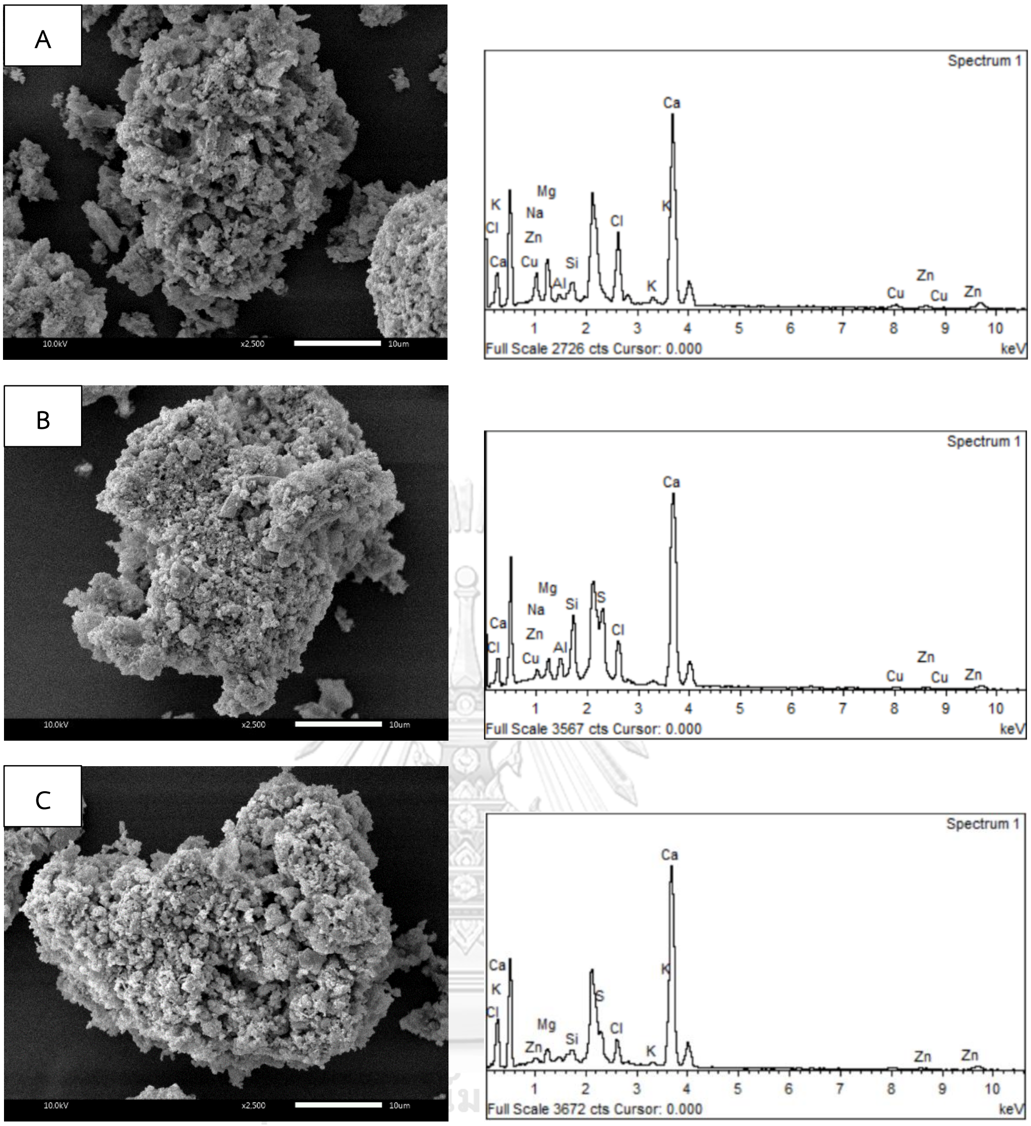

Fig 4.2 Scanning electron microscope (SEM) and Energy dispersive X-ray spectrometer (EDS) images illustrating morphology and elements of treated FA-APC at 2500x by: A) DI water, B) 0.01M HNO_3, C) 0.1M HNO_3, D) 0.1M Na_2CO_3, E) 0.25M Na_2CO_3 at 1-hr extraction

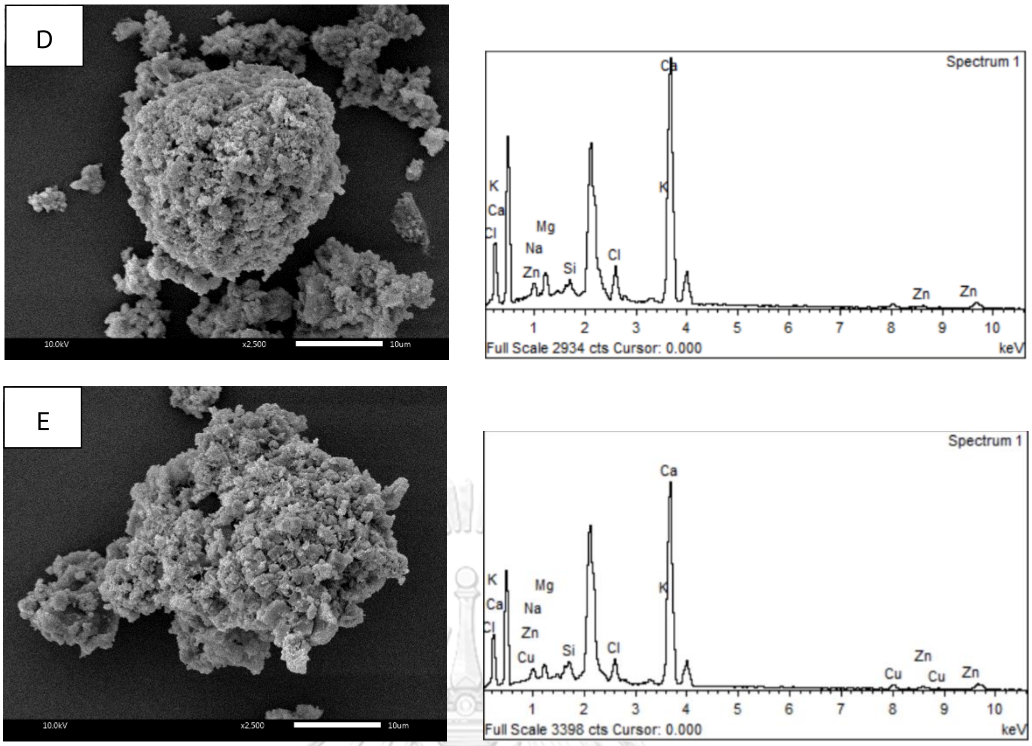

Fig 4.2 (cont.) Scanning electron microscope (SEM) and Energy dispersive X-ray spectrometer (EDS) images illustrating morphology and elements of treated FA-APC at 2500x by: A) DI water, B) 0.01M HNO_3, C) 0.1M HNO_3, D) 0.1M Na_2CO_3 E) 0.25M Na_2CO_3 at 1-hr extraction

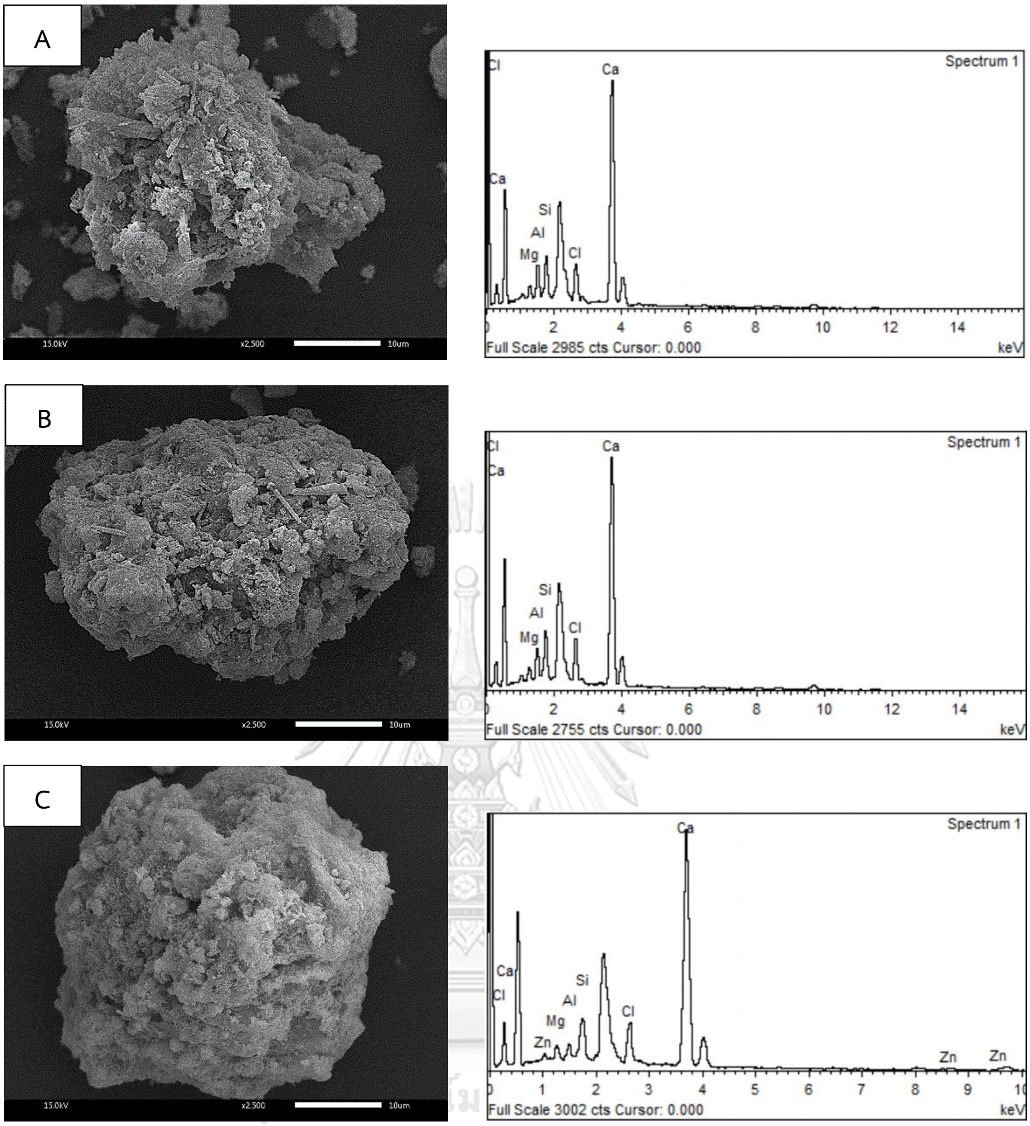

Fig 4.3 Scanning electron microscope (SEM) and Energy dispersive X-ray spectrometer (EDS) images illustrating morphology and elements of treated FA-LF at 2500x by: A) DI water, B) 0.01M HNO_3, C) 0.1M HNO_3, D) 0.1M Na_2CO_3, E) 0.25M Na_2CO_3 at 1-hr extraction

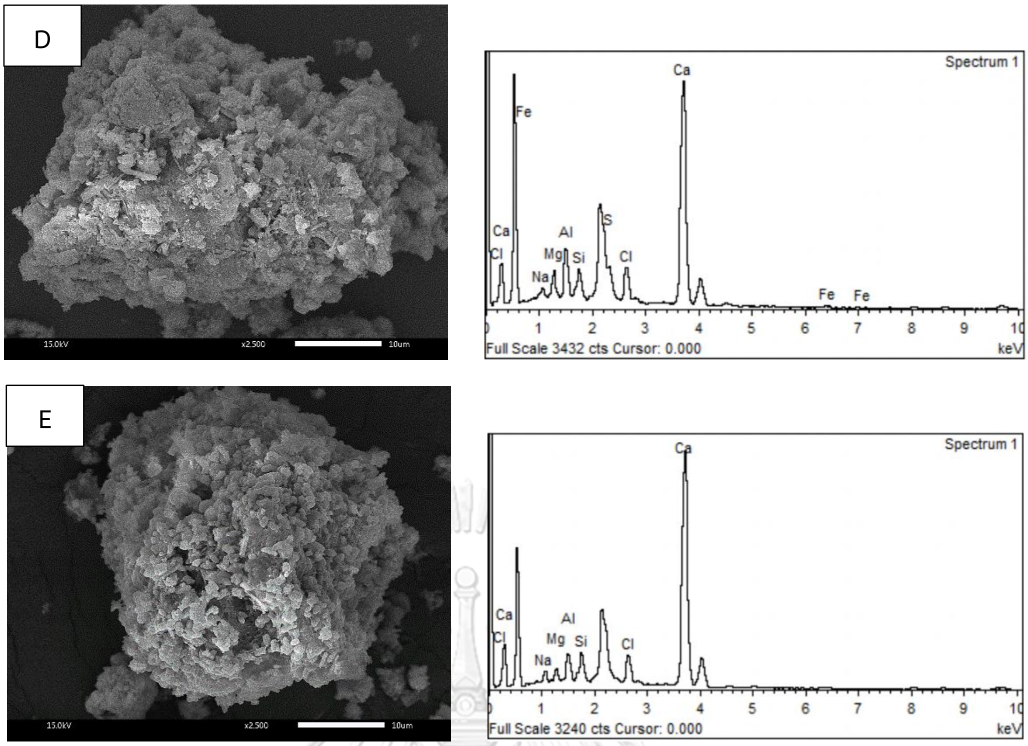

Fig 4.3(cont.) Scanning electron microscope (SEM) and Energy dispersive X-ray spectrometer (EDS) images illustrating morphology and elements of treated FA-LF at 2500x by: A) DI water, B) 0.01M HNO_3, C) 0.1M HNO_3, D) 0.1M Na_2CO_3 E) 0.25M Na_2CO_3 at 1-hr extraction

4.1.2 Particle characterization

The particle size distribution of untreated fly ashes is shown in Table 4.2. The particle size of FA-APC with D_{10}, D_{50} and D_{90} is 2.35, 8.71, and 69.70 µm, respectively. The particle size of FA-LF with D_{10}, D_{50} and D_{90} is 6.24, 28.53, and 123.00 µm, respectively. The results show that FA- APC is smaller than FA-LF. This may be because of higher moisture content in FA-LF (12.99%) which contributes to agglomeration of particles. Conversely, apart from bigger size FA-LF has lower density of 1,914 kg/m^3 than FA-APC of 2,207 kg/m^3 due to its higher pore volume as shown in Table 4.1. For coal fly ash, FA-LN has particle size distribution with D_{10}, D_{50} and D_{90} of 2.35, 29.37, and 156.67 µm, respectively. The particle size of another coal fly ash, FA-BT, with D_{10}, D_{50} and D_{90} is 2.01, 14.80, and 62.13 µm, respectively. Mucsi, Molnar and Kumar, 2014 and Hardjito and Rangan, 2005 also found that the size of FA-LN and FA-BT are around 10-20 µm, respectively.

According to Table 4.3, the results show particle size distribution of treated FA-APC and FA-LF. The treatment process increases D_{50} of FA-APC slightly, while FA-LF particle size decreases after treatment because the treated solutions dissolve the plate-like structure on the surface of particle.

Table 4.2 Particle characterization of untreated fly ash

Name	Particle size distribution (µm)			Density^A (kg/m^3)	Moisture^B (%)
	D_{10}	D_{50}	D_{90}		
FA-APC	2.35	8.71	69.70	2,207	3.72
FA-LF	6.24	28.53	123.00	1,914	12.99
FA-LN	2.35	29.37	156.67	2,288	0.13
FA-BT	2.01	14.80	62.13	2,166	0.28

^{A} : Result from appendix C Table C1

^{B} : Result from appendix B Table B1-B4

Table 4.3 Particle size distribution of treated FA-APC and FA-LF

Name		Particle size distribution (μm)		
		D_{10}	D_{50}	D_{90}
FA-APC	DI water	2.48	10.27	41.80
	0.01M HNO_3	2.88	11.13	46.93
	0.1M HNO_3	1.89	9.43	46.17
	0.1M Na_2CO_3	2.88	11.63	39.07
	0.25M Na_2CO_3	3.00	13.07	43.37
FA-LF	DI water	2.56	16.73	112.67
	0.01M HNO_3	3.97	20.23	127.00
	0.1M HNO_3	3.78	21.73	169.67
	0.1M Na_2CO_3	2.57	13.23	75.10
	0.25M Na_2CO_3	6.33	19.47	99.00

4.1.3 Chemical composition

Following Table 4.4, it can be seen that the proportion of chemical composition of FA-APC contains significant amounts of chloride, originating from plastic waste such as PVC (polyvinyl chloride) (Hartmann et al., 2015, Brannvall and Kumpiene, 2016 and Weibel et al., 2017). FA-APC has chloride salt more than FA-LF. This also includes Na and K, which may come from food scrap found in waste composition (Zhang et al., 2016). Treatment processes dissolve NaCl and KCl, which are the main chloride salt, from FA-APC and FA-LF resulting in a decrease in Cl, Na, and K in treated fly ashes. Specifically, percentage of Cl decreases from 29.3 to 2.17% by wt. in untreated and DI water-treated FA-APC. Interestingly, from XRF result in Table 4.4 heavy metals such as Cd and Pb are found in FA-APC and FA-LF, while they are not present in coal fly ash (FA-LN or FA-BT). Song et al., 2004 also found similar result. Pb and Cd are more likely to volatile in high temperature during waste incineration. Thus, these elements may accumulate on the surface of FA-APC and FA-LF (Song et al., 2004) such as FA-APC and FA-LF has 300 ppm for Cd while FA-LN and FA-BT do not have Cd in XRF result which are more likely to be volatile element in high temperature during incineration therefore these elements accumulate on surface of FA-APC and FA-LF.

For FA-LN, the highest proportion is silica (33.3%) and the aggregate of silica, alumina and iron is 64.3% which is classified as pozzolanic material class C (ASTM C618). On the other hand, FA-BT is considered pozzolanic material in Class F with combination of silica, alumina and iron of 86.76% according to ASTM C618. The concentration of As is detected in FA-LN because of property of As. As is a volatile element and can condense on the surface of particles such as FA-LN (Ram et al., 2015). Arsenic is a toxic element found in both natural and anthropogenic sources (Mar et al., 2013). Specifically, FA-LN from Mae Moh, Thailand has As concentration between 14.3 and 888.8 mg/kg (Wongyai, Garivait and Donald, 2010) which is close to As concentration of FA-LN in Table 4.4.

Table 4.4 Chemical composition of untreated fly ash

Chemical composition (%)	FA-APC	FA-LF	FA-LN	FA-BT
CaO	32.1	44.4	16.2	0.869
Cl	29.3	9.30	N/A	N/A
Na_2O	13.9	2.69	1.81	0.380
K_2O	6.52	1.71	2.29	0.854
SO_3	4.03	4.35	4.16	0.228
SiO_2	2.70	4.74	33.3	62.2
MgO	1.41	1.80	2.17	0.475
Al_2O_3	0.850	2.28	18.7	21.0
P_2O_5	0.724	1.07	0.203	0.198
ZnO	0.600	0.588	213*	212*
Fe_2O_3	0.578	0.729	12.3	3.56
TiO_2	0.369	0.469	0.368	1.06
PbO	0.130	0.103	N/A	N/A
CuO	687*	716*	97.1*	116*
CdO	304*	223*	N/A	N/A
Cr_2O_3	91.9*	96.3*	89.5*	73.5*
As_2O_3	0*	0*	252*	0*

*: ppm

After treatment, proportion of CaO of treated FA-APC samples is higher than untreated FA-APC around 10% by wt. because dissoluble element such as NaCl and KCl dissolves from FA-APC. During treatment process, the treated solutions can remove sulfate; therefore, the percentage of SO_3 reduce around 2% from 4.03 to 2.94% by wt. especially for 0.25M Na_2CO_3 treated FA-APC. Result from Table 4.5 suggests that treated solutions remove soluble chloride salt in a form of NaCl, KCl and CaClOH; thus, the percentage of Na_2O, K_2O and Cl decreases from 13.9 to 0.470 % by wt. for Na_2O, from 6.52 to 0.190% by wt. for K_2O and from 29.3 to 0.632 % by wt. for Cl. Conversely, the percentage of CaO increases from 32.1 to 44.3% by wt.

Table 4.5 Chemical composition of treated FA-APC

Chemical composition (%)	DI water	0.01M HNO_3	0.1M HNO_3	0.1M Na_2CO_3	0.25M Na_2CO_3
CaO	41.4	39.1	37.3	40.0	44.3
Cl	2.17	2.92	1.05	0.606	0.632
Na_2O	0.977	1.05	0.623	0.477	0.470
K_2O	0.522	0.72	0.227	0.190	0.208
SO_3	4.24	3.85	4.46	3.23	2.94
SiO_2	4.68	4.32	4.73	4.01	3.48
MgO	3.65	3.46	4.03	3.27	2.66
Al_2O_3	1.33	1.13	1.35	1.07	0.938
P_2O_5	1.13	1.05	1.29	0.961	0.888
ZnO	1.41	1.35	1.37	1.20	1.05
Fe_2O_3	0.775	0.761	0.894	0.675	0.612
TiO_2	0.406	0.378	0.533	0.301	0.361
PbO	0.243	0.241	0.222	0.221	0.224
CuO	0.149	0.149	0.145	0.127	0.109
CdO	594*	596*	491*	420*	616*
Cr_2O_3	N/A	N/A	N/A	N/A	364*
As_2O_3	0*	0*	0*	0*	0*

*: ppm

Table 4.6 Chemical composition of treated FA-LF

Chemical composition (%)	**DI water**	**0.01M HNO_3**	**0.1M HNO_3**	**0.1M Na_2CO_3**	**0.25M Na_2CO_3**
CaO	41.2	41.2	42.4	43.1	41.2
Cl	3.45	3.34	3.46	3.05	2.51
Na_2O	0.569	0.553	0.545	0.911	1.55
K_2O	0.297	0.269	0.267	0.273	0.281
SO_3	4.21	4.22	4.60	3.43	2.25
SiO_2	5.91	5.89	5.97	5.63	5.28
MgO	1.80	1.85	1.96	1.74	1.62
Al_2O_3	2.68	2.73	2.86	2.64	2.44
P_2O_5	1.20	1.22	1.27	1.15	1.07
ZnO	0.599	0.601	0.646	0.598	0.556
Fe_2O_3	0.962	0.986	1.01	0.948	0.886
TiO_2	0.499	0.517	0.550	0.508	0.461
PbO	0.100	981*	0.105	988*	898*
CuO	748*	787*	837*	759*	695*
CdO	183*	178*	190*	195*	161*
Cr_2O_3	150*	154*	153*	144*	137*
As_2O_3	0*	0*	0*	0*	0*

*: ppm

4.1.4 Mineralogical phase

The XRD pattern of FA- APC is shown in Table 4.7 with some dominant phases of halite (NaCl), sylvine (KCl), calcium chloride hydroxide (CaClOH) and anhydrite ($CaSO_4$) phase. Chen et al., 2012 also found that municiple solid waste fly ash used in their study contained these chloride-salted peaks. These results are relate to chemical composition in Table 4.4 that FA-APC has high amount of chloride and sulfate. In FA-LF, XRD pattern in Table 4.7 gives information about the dominant phases of calcite ($CaCO_3$), halite (NaCl) and sylvine (KCl) that link to the high proportion of chloride in FA-LF in Table 4.4. On the other hand, treated FA-LF has lower soluable salt such as Cl^- and SO_4^{2-} as these salts are removed from the outer surface of the partciles.

For XRD pattern of coal fly ash in Table 4.7, FA-LN has the same dominant phase of quartz as FA-BT. However, FA-LN has anhydrite ($CaSO_4$) and lime (CaO) phases, while another coal fly ash has mullite ($Al_6Si_2O_{13}$). Celik, Damci and Piskin, 2008 also found that FA-LN has quartz and mullite phase.

Following Table 4.7, the mineral structures of treated FA-APC and FA-LF show the treated solutions can dissolve soluble salt such as NaCl, KCl and CaClOH in FA-APC and FA-LF. For sulfate removal, it can be seen that Na_2CO_3 can dissolve $CaSO_4$ in FA-APC, and reduce sulfate accumulation in particle (see in appendix H Fig H1-H6).

Table 4.7 Minerals in all of untreated and treated fly ash analyzed by XRD

Minerals		Untreated	Treated FA				
			DI	0.01M HNO_3	0.1M HNO_3	0.1M Na_2CO_3	0.25M Na_2CO_3
Halite	$NaCl$	A L	A	A	A	A	A
Calcium chloride hydroxide	$CaClOH$	A	-	-	-	-	-
Sylvine	KCl	A L	-	-	-	-	-
Calcite	$CaCO_3$	A L	A L	A L	A L	A L	A L
Anhydrite	$CaSO_4$	A G	A L	A	A	A	A
Portlandite	$Ca(OH)_2$	L	A L	A L	A L	A L	A L
Quartz	SiO_2	L G B	-	-	-	-	L
Thaumasite	$Ca_3Si(OH)_6(H_2O)_{12}(SO_4)(CO_3)$	L	-	-	-	-	-
Sjogrenite	$Mg_6Fe_2(OH)_{16}(CO_3)(H_2O)_4$	L	L	L	L	L	L
Calcium sulfate hydrate	$CaSO_4(H_2O)_{0.583}$	-	A L	A	A	A	A
Potassic-ferrisadanagaite	$(K,Na)Ca_2(Fe,Mg)_3(Fe,Al)_2(Si_5Al_3O_{22})(OH)_2$	-	A	A	A	A	A
Defernite	$Ca_6(CO_{2.65})_2(OH_{0.657})_7(H_2O)_2$	-	L	L	L	L	L
Calcium silicate	$Ca_2(SiO)_4$	G	-	-	-	L	-
Sodium aluminum hydroxide hydrate	$Na_9(Al(OH)_6)_2(OH)_3(H_2O)_6$	-	-	L	L	L	L
Mullite	$Al_6Si_2O_{13}$	G B	-	-	-	-	-
Lime	CaO	G	-	-	-	-	-

A: FA-APC, L: FA-LF, G: FA-LN, B: FA-BT

* : Result from appendix H Fig H1-H14

4.2 Extraction of chloride and sulfate

4.2.1 Concentration of chloride and sulfate in leachate

The extraction factor (%) is calculated by using the concentration of element in leachate from DI water treatment as a baseline according Eqn (4.1).

$$\% \text{ extraction} = \frac{\left[\left(\frac{mg}{kg}\right)\text{in treated solution}\right]\times 100}{\left[\left(\frac{mg}{kg}\right)\text{ in deionized water}\right]} \qquad \text{Eqn (4.1)}$$

The extraction factors of Ca by DI water or acid solutions are higher than those treated by Na_2CO_3 as seen in Fig 4.4-4.5 and Table 4.8-4.9. Calcium in the form of CaClOH is found to be washed by DI water or HNO_3, and transformed to $CaCl_2$, which can further dissolve in treated solution as described in Eqn (4.2). Conversely, Ca concentration is lower in leachate treated by Na_2CO_3 because dissolved Ca^{2+} ion further reacts with CO_3^{2-} in Na_2CO_3 forming a precipitation of $CaCO_3$ as in Eqn (4.3).

$$2CaClOH_{(s)} \rightarrow Ca(OH)_{2(s)} + CaCl_{2(aq)} \qquad \text{Eqn (4.2)}$$

$$Ca^{2+} + CO_3^{2-} \rightarrow CaCO_{3(s)} \qquad \text{Eqn (4.3)}$$

Concentration of Na in DI water and acid leachates remains the same except for Na concentration in Na_2CO_3 leachate. This is because Na is added from Na_2CO_3 dissociation. For concentration of K in all of leachates, it is clear to see that all treated solutions remove Cl^- through dissolving KCl according to Eqn (4.4)-(4.5). The concentration of K in all leachate samples does not change significantly ($p<0.05$) as seen in Table G1 in appendix G. All of the treated solutions can dissolve soluble salt in a form of CaClOH, NaCl or KCl. For example, Cl^- concentration treated by DI water and 0.25M Na_2CO_3 is 251,136.6 mg/kg and 274,799.6 mg/kg, respectively. The Cl^- concentrations in all leachates stay constant.

$NaCl_{(s)}$ → $NaCl_{(aq)}$ Eqn (4.4)

$KCl_{(s)}$ → $KCl_{(aq)}$ Eqn (4.5)

For SO_4^{2-} removal, it is found that DI water and acid solutions can equally dissolve SO_4^{2-}, while Na_2CO_3 extracts SO_4^{2-} significantly. Eqn (4.6) suggests that Na_2CO_3 solution dissolves $Ca_2SO_{4(s)}$ which is the compound on particle surface and forms Na_2SO_4 that has more solubility than Ca_2SO_4 (Aubert et al., 2007 and Saikia et al., 2017). $Na_2SO_{4(aq)}$ can further dissociate into Na^+ and SO_4^{2-} contributing to higher SO_4^{2-} concentration in extracting solution. Specifically, DI water can dissolve SO_4^{2-} as 7,827.1 mg/kg, while 15,821.8 mg/kg of SO_4^{2-} is found in Na_2CO_3 leachate.

$Na_2CO_{3(aq)} + Ca_2SO_{4(s)}$ → $Na_2SO_{4(aq)} + CaCO_{3(s)}$ Eqn (4.6)

Initial pH of FA-APC and FA-LF is 11.5 and 12.5, respectively. pH slightly increases after 60 min of mixing between 11.6 to 12.8 (as seen in appendix A Table A1 to A11), this suggests that FA-APC and FA-LF have buffer capacity of $CaCO_3$ according to XRD result. Final pH of FA-APC is more acidic than FA-LF due to lower initial pH in every treated solution.

Basic condition during treatment (pH 11-12) contributes to Al removal from FA-APC and FA-LF. This can be represented in the following reaction in Eqn (4.7) (Joseph et al., 2018). Al in FA-APC is better extracted by acidic solution as 0.01M HNO_3 and 0.1M HNO_3 than by basic solution (Na_2CO_3). Al can react with Na or K in the leachate to form structure named Potassic-ferrisadanagaite when Na or K is dominant. Hawthorne and Harlow, 2008 found that Na in treating Na_2CO_3 solution reacted with Al in fly ash forming Potassic-ferrisadanagaite. This reaction decreased Al concentration in the leachate.

$Al + 2OH^- + H_2O$ → $[AlO(OH)_2]^- + H_2$ pH>7 Eqn (4.7)

The concentration of Fe in leachate from FA-APC and FA-LF is 0.0000 mg/kg because the overall pH of the system is in a basic condition (pH>7). Fe is better dissolve in acidic than in a basic condition. Fe^{2+} and Fe^{3+} ions in FA-APC and FA-LF particles may dissolve shortly after adding acid solution. However, Fe^{2+} and Fe^{3+} will start to precipitate to form of Fe(II) hydroxide and Fe(III) hydroxide due to an increasing pH in the system (Weibel et al., 2017). Mg removal in leachate from the 0.01M HNO_3 is 0.3820 mg/kg. Other treated solutions have Mg concentration around 0.0048 mg/kg.

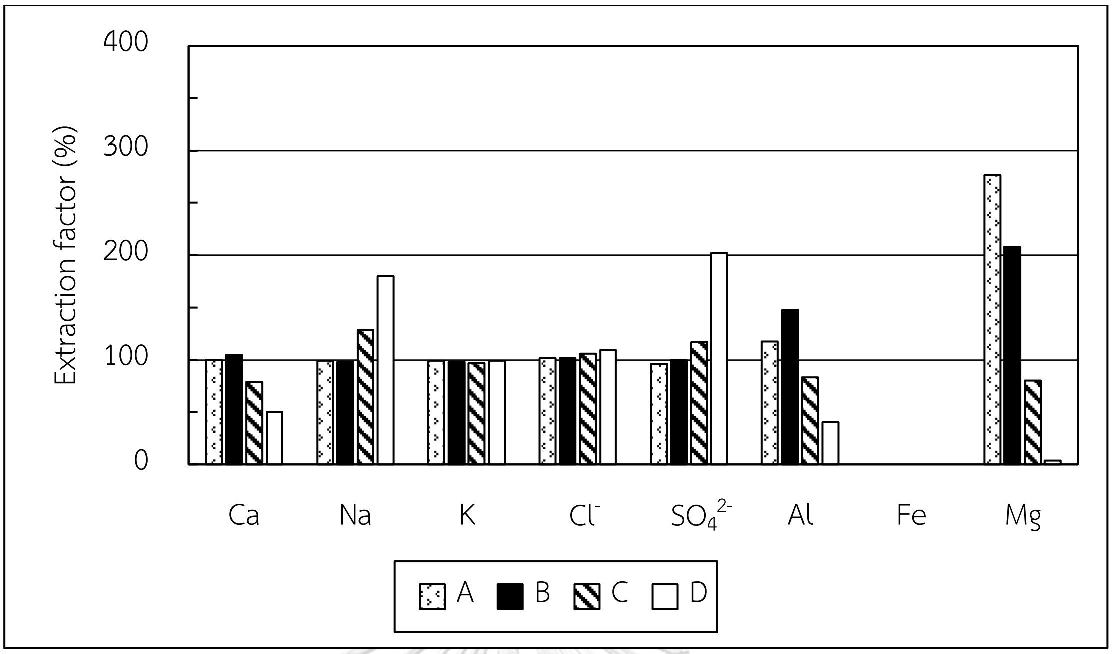

Fig 4.4 Concentration percentage of Ca, Na, K, Cl^-, SO_4^{2-}, Al, Fe and Mg from FA-APC by: A) 0.01M HNO_3, B) 0.1M HNO_3, C) 0.1M Na_2CO_3, D) 0.25M Na_2CO_3 at 1-hr extraction

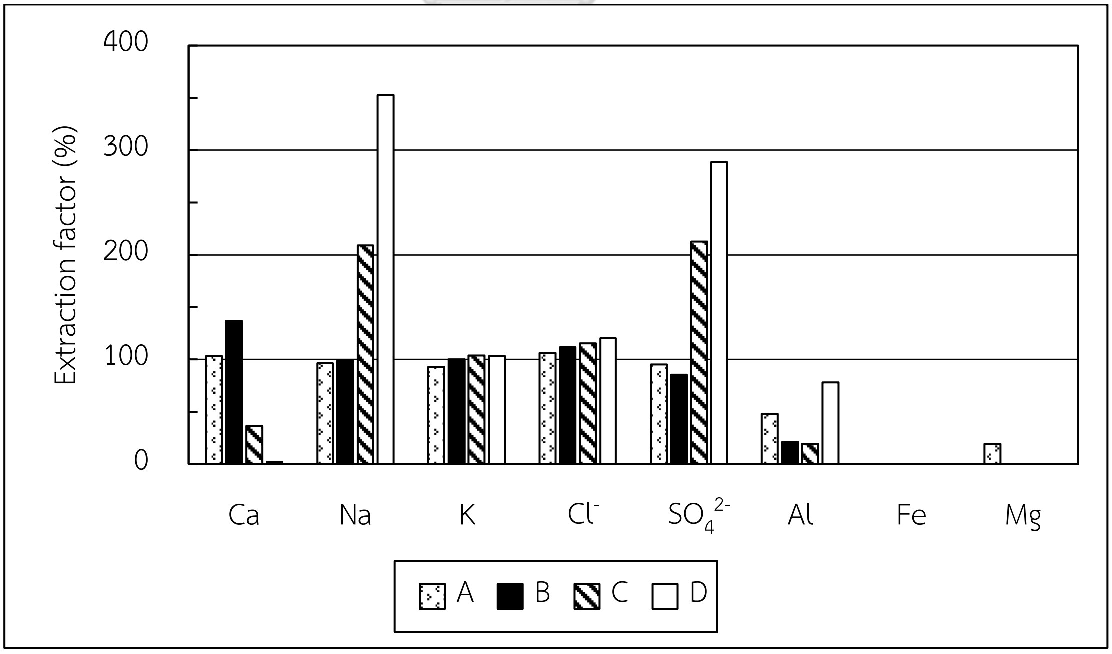

Fig 4.5 Concentration percentage of Ca, Na, K, Cl^-, SO_4^{2-}, Al, Fe and Mg from FA-LF by: A) 0.01M HNO_3, B) 0.1M HNO_3, C) 0.1M Na_2CO_3, D) 0.25M Na_2CO_3 at 1-hr extraction

Table 4.8 Concentration and extraction percentage of Ca, Na, K, Cl^-, SO_4^{2-}, Al, Fe and Mg in leachate from FA-APC at 1-hr extraction time

Element		FA-APC treated by				
		DI water	0.01M HNO_3	0.1M HNO_3	0.1M Na_2CO_3	0.25M Na_2CO_3
Ca	Concentration (mg/kg)	63,715.0 ± 422.2	63,655.8 ± 1,531	66,486.6 ± 666.9	50,326.8 ± 1,023	32,109.9 ± 327.7
	% extraction	100	99.91	104.35	78.99	50.39
Na	Concentration (mg/kg)	57,628.2 ± 1,028	56,986.5 ± 1,280	56,471.5 ± 228.3	73,918.9 ± 1,855	103,708.1 ± 3,439
	% extraction	100	98.89	97.99	128.27	179.96
K	Concentration (mg/kg)	40,216.8 ± 744.5	39,874.2 ± 936.2	39,467.5 ± 136.3	38,889.8 ± 1,793	39,892.6 ± 973.5
	% extraction	100	99.15	98.14	96.70	99.19
Cl^-	Concentration (mg/kg)	251,136.6 ± 6,853	254,909.1 ± 2,518	254,833.1 ± 2,396	265,596.9 ± 17,951	274,799.6 ± 2,459
	% extraction	100	101.50	101.47	105.75	109.42
SO_4^{2-}	Concentration (mg/kg)	7,827.1 ± 286.8	7,497.4 ± 501.5	7,828.2 ± 287.6	9,164.3 ± 289.4	15,821.8 ± 285.3
	% extraction	100	95.79	100.01	117.08	202.14
Al	Concentration (mg/kg)	3.4 ± 0.2	4.0 ± 0.2	5.0 ± 0.4	2.8 ± 0.0	1.4 ± 0.1
	% extraction	100	117.26	147.31	82.98	40.47
Fe	Concentration (mg/kg)	<0.05	<0.05	<0.05	<0.05	<0.05
	% extraction	0.0	0.0	0.0	0.0	0.0
Mg	Concentration (mg/kg)	0.138 ± 0.005	0.382 ± 0.279	0.287 ± 0.109	0.110 ± 0.009	0.004 ± 0.004
	% extraction	100	276.68	208.24	79.89	3.47

Table 4.9 Concentration and extraction percentage of Ca, Na, K, Cl^-, SO_4^{2-}, Al, Fe and Mg in leachate from FA-LF at 1-hr extraction time

Element		FA-LF treated by				
		DI water	0.01M HNO_3	0.1M HNO_3	0.1M Na_2CO_3	0.25M Na_2CO_3
Ca	Concentration (mg/kg)	17,295.3 ± 214.7	17,889.7 ± 581.1	23,708.6 ± 18.15	6,325.1 ± 189.9	412.2 ± 2.859
	% extraction	100	103.44	137.08	36.57	2.38
Na	Concentration (mg/kg)	14,032.4 ± 23.76	13,574.3 ± 290.9	13,849.6 ± 240.9	29,296.9 ± 1,606	49,496.8 ± 539.7
	% extraction	100	96.73	98.70	208.78	352.73
K	Concentration (mg/kg)	11,427.5 ± 562.2	10,621.8 ± 639.7	11,428.9 ± 1,036	11,845.6 ± 370.1	11,753.9 ± 948.3
	% extraction	100	92.95	100.01	103.66	102.85
Cl^-	Concentration (mg/kg)	55,030.5 ± 811.5	58,582.7 ± 852.1	61,564.7 ± 1,964	63,616.9 ± 1,120	66,275.6 ± 1,048
	% extraction	100	106.45	111.87	115.60	120.43
SO_4^{2-}	Concentration (mg/kg)	6,555.7 ± 182.1	6,241.5 ± 556.3	5,617.1 ± 317.6	13,955.8 ± 111.9	18,926.3 ± 413.7
	% extraction	100	95.21	85.68	212.88	288.70
Al	Concentration (mg/kg)	1.97 ± 0.27	0.95 ± 0.97	0.42 ± 0.06	0.38 ± 0.02	1.54 ± 1.00
	% extraction	100	48.00	21.15	19.32	78.33
Fe	Concentration (mg/kg)	<0.05	<0.05	<0.05	<0.05	<0.05
	% extraction	0.0	0.0	0.0	0.0	0.0
Mg	Concentration (mg/kg)	0.197 ± 0.084	0.038 ± 0.063	<0.05	<0.05	<0.05
	% extraction	100	19.52	0.0	0.0	0.0

4.2.2 Concentration of chloride and sulfate in FA-APC and FA-LF by microwave digestion

According to Fig 4.6-4.7 and Table 4.10-4.11, the digestion factor (%) is calculated by using the concentration of element in untreated FA-APC and FA-LF after microwave digestion as a baseline according Eqn (4.8).

$$\% \text{ digestion } = \frac{\left[\left(\frac{\text{mg}}{\text{kg}}\right)\text{in treated MSWI FA}\right]\times 100}{\left[\left(\frac{\text{mg}}{\text{kg}}\right)\text{ in untreated MSWI FA}\right]} \qquad \text{Eqn (4.8)}$$

This microwave digestion result is calculated from pseudo-digestion because acids used indigestion method does not include HF solution to avoid glass corrosion in analytical instrument. Therefore, some elements such as silica or silica components may not totally be digested.

Ca in treated FA-APC increases from 184,582.3 mg/kg to 277,005.7 mg/kg after treatment process. Funari et al., 2017 also found that Ca concentration after water treatment increased from 142,000 mg/kg to 240,200 mg/kg. In contrast, Ca in treated FA-LF remains constant between 221,613.4 and 252,550.6 mg/kg when compared with untreated FA-LF.

For soluble salts such as Na, K, Cl^-, and Al, it is found that all of elements concentration decreases significantly (<50%) in treated FA-APC and FA-LF. For example, Na concentration decreases from 62,376.5 to 14,675.2 mg/kg with DI water-treated FA-APC. This is because during the treatment process, treated solutions dissolved these salts from fly ash particles. Thus, the available concentrations in fly ash decreases resulting in lower concentration of these salts from microwave digestion process.

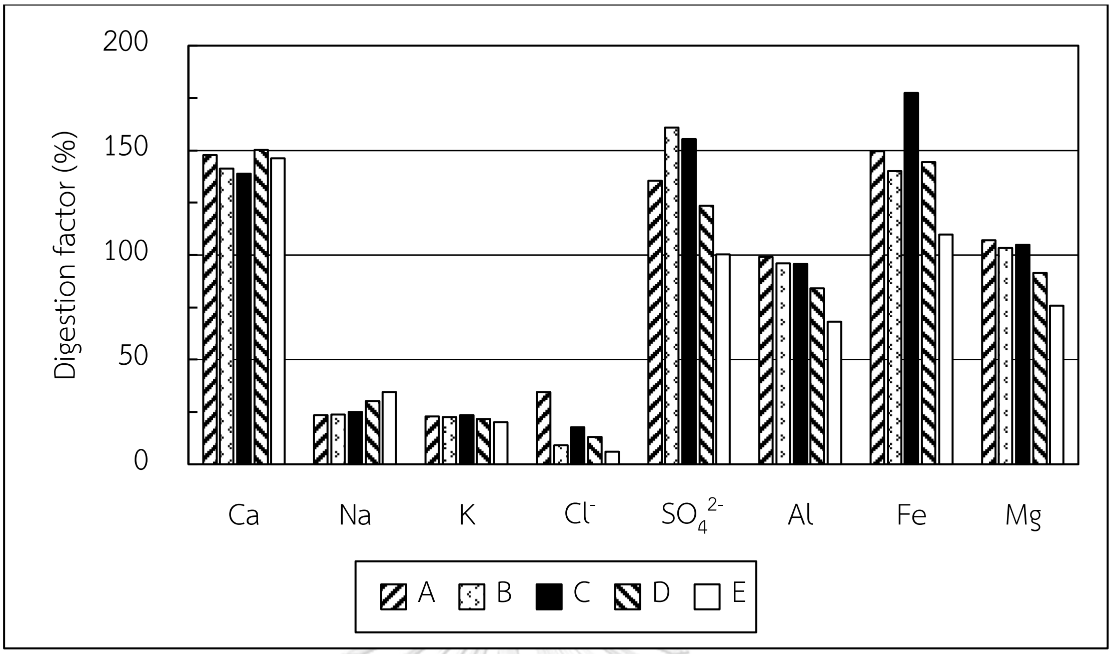

Fig 4.6 Concentration percentage of Ca, Na, K, Cl^-, SO_4^{2-}, Al, Fe and Mg from microwave digestion in FA-APC treated by: A) DI water, B) 0.01M HNO_3, C) 0.1M HNO_3, D) 0.1M Na_2CO_3, E) 0.25M Na_2CO_3 at 1-hr extraction

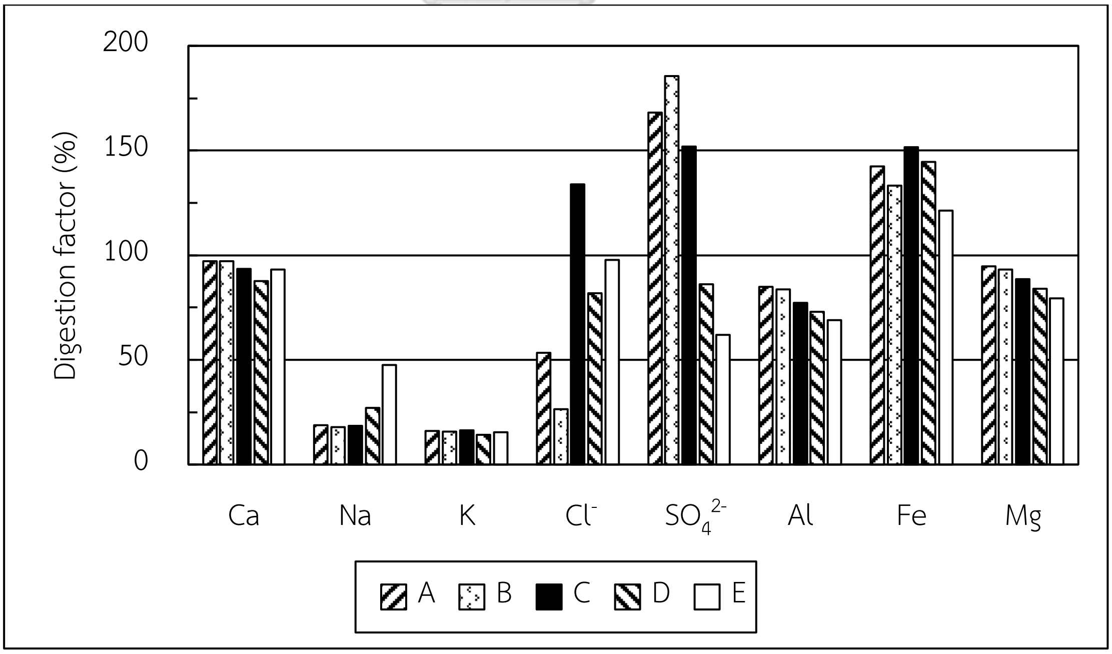

Fig 4.7 Concentration percentage of Ca, Na, K, Cl^-, SO_4^{2-}, Al, Fe and Mg from microwave digestion in FA-LF treated by: A) DI water, B) 0.01M HNO_3, C) 0.1M HNO_3, D) 0.1M Na_2CO_3, E) 0.25M Na_2CO_3 at 1-hr extraction

Table 4.10 Concentration of Ca, Na, K, Cl$^-$, SO_4^{2-}, Al, Fe and Mg from FA-APC by microwave digestion

Element		FA-APC treated by					
		Untreated FA-APC	DI water	0.01M HNO_3	0.1M HNO_3	0.1M Na_2CO_3	0.25M Na_2CO_3
Ca	Concentration (mg/kg)	184,582.3 ± 10,903	272,636.2 ± 1,817	261,019.4 ± 6,305	256,387.1 ± 6,255	277,005.7 ± 538.5	269,721.9 ± 1,019
	% digestion	100	147.70	141.41	138.90	150.07	146.12
Na	Concentration (mg/kg)	62,376.5 ± 3,824	14,675.2 ± 6.5	14,872.5 ± 930.8	15,697.4 ± 291.9	18,928.5 ± 204.0	21,556.6 ± 2,534
	% digestion	100	23.53	23.84	25.16	30.34558	34.55
K	Concentration (mg/kg)	47,709.3 ± 3,461	10,960.7 ± 186.2	10,768.0 ± 684	11,170.0 ± 265.6	10,366.7 ± 127.9	9,640.5 ± 123.1
	% digestion	100	22.97	22.56	23.41	21.72	20.20
Cl$^-$	Concentration (mg/kg)	601,063.1 ± 374,132	207,791.3 ± 124,673	55,105.6 ± 40,422	107,164.5 ± 6,810	79,386.3 ± 2,840	36,191.9 ± 5,866
	% digestion	100	34.57	9.17	17.83	13.21	6.02
SO_4^{2-}	Concentration (mg/kg)	24,940.5 ± 3,817	33,778.4 ± 12,088	40,090.3 ± 11,618	38,718.5 ± 3,258	30,855.1 ± 2,931	25,034.1 ± 1,612
	% digestion	100	135.43	160.74	155.24	123.71	100.37
Al	Concentration (mg/kg)	8,337.9 ± 541.3	8,272.1 ± 155.8	7,997.9 ± 510.2	7,985.6 ± 297.9	7,012.6 ± 229.9	5,682.1 ± 158.0
	% digestion	100	99.21	95.92	95.77	84.10	68.14
Fe	Concentration (mg/kg)	3,473.4 ± 1,425	5,195.5 ± 165.5	4,863.8 ± 333.8	6,153.3 ± 872.8	5,015.6 ± 132.8	3,808.7 ± 49.9
	% digestion	100	149.57	140.02	177.44	144.39	109.65
Mg	Concentration (mg/kg)	14,126.2 ± 151.8	15,134.4 ± 339.7	14,593.5 ± 267.4	14,809.5 ± 586.1	12,937.2 ± 446.7	10,705.1 ± 136.8
	% digestion	100	107.13	103.30	104.83	91.583	75.78

Table 4.11 Concentration of Ca, Na, K, Cl^-, SO_4^{2-}, Al, Fe and Mg from FA-LF by microwave digestion

Element		FA-LF treated by					
		Untreated FA-LF	DI water	0.01M HNO_3	0.1M HNO_3	0.1M Na_2CO_3	0.25M Na_2CO_3
Ca	Concentration (mg/kg)	252,550.6 ± 4,434	245,539.6 ± 9,125	245,650.5 ± 9,244	235,780.3 ± 1,398	221,613.4 ± 8,079	235,491.2 ± 5,012
	% digestion	100	97.22	97.27	93.36	87.75	93.25
Na	Concentration (mg/kg)	21,621.1 ± 2,004	4,081.6 ± 90.2	3,889.9 ± 177.6	4,018.7 ± 200.8	5,874.1 ± 653.6	10,287.9 ± 200.5
	% digestion	100	18.88	17.99	18.59	27.17	47.58
K	Concentration (mg/kg)	14,478.7 ± 147.3	2,317.5 ± 1.9	2,270.3 ± 122.9	2,367.8 ± 141.4	2,076.9 ± 288.9	2,218.3 ± 22.9
	% digestion	100	16.01	15.68	16.35	14.35	15.32
Cl^-	Concentration (mg/kg)	252,230.9 ± 13,744	134,241.4 ± 226,545	66,637.32 ± 7,286	337,495.4 ± 90,876	206,203.2 ± 324,291	246,849.3 ± 156,263
	% digestion	100	53.22	26.42	133.80	81.75	97.87
SO_4^{2-}	Concentration (mg/kg)	21,377.9 ± 982	35,952.9 ± 2,049	39,679.2 ± 403.1	32,500.7 ± 4,371	18,430.0 ± 11,511	13,256.2 ± 601.9
	% digestion	100	168.18	185.61	152.03	86.21	62.01
Al	Concentration (mg/kg)	3,201.3 ± 153.4	2,721.6 ± 51.4	2,675.1 ± 42.3	2,470.5 ± 103.1	2,331.1 ± 48.2	2,207.1 ± 11.8
	% digestion	100	85.02	83.56	77.17	72.82	68.94
Fe	Concentration (mg/kg)	4,215.8 ± 454.6	6,006.1 ± 104.0	5,614.6 ± 132.2	6,397.0 ± 487.2	6,094.3 ± 891.5	5,107.4 ± 27.0
	% digestion	100	142.47	133.18	151.74	144.56	121.15
Mg	Concentration (mg/kg)	6,821.8 ± 155	6,461.2 ± 4.3	6,358.9 ± 201.8	6,043.8 ± 146.3	5,720.3 ± 91.7	5,413.5 ± 24.2
	% digestion	100	94.71	93.21	88.60	83.85	79.36

4.3 Heavy metal

4.3.1 Concentration of heavy metal in leachate

Following in Fig 4.8-4.9 and Table 4.12-4.13, the extraction factor (%) is calculated by using the concentration of element in leachate from DI water treatment as a baseline according Eqn (4.9).

$$\% \text{ extraction } = \frac{\left[\left(\frac{\text{mg}}{\text{kg}}\right)\text{in treated solution}\right]\times 100}{\left[\left(\frac{\text{mg}}{\text{kg}}\right)\text{ in deionized water}\right]} \qquad \text{Eqn (4.9)}$$

The main influencing factor on the dissolution of heavy metals is acidic condition (Zhang et al., 2016). During treatment, pH of system increases to basic condition, so some elements may dissolute less. In leachate from acidic solution, heavy metals can dissolve better than in basic solution. For instance, Zn concentration is 7.03 mg/kg and 2.21 mg/kg for FA-APC treated by 0.1M HNO_3 and 0.25M Na_2CO_3,respectively. Moreover, the strength of acidic solution is one of the dissolution factors. For example, 0.1M HNO_3 can dissolve Pb of 364.2 mg/kg, while 0.01M HNO_3 removes 297.8 mg/kg from FA-APC.

Zn, Pb and Cd concentration are found highest in leachate from FA-APC by HNO_3 solution, but those concentrations are lower in leachate by Na_2CO_3 solution. On the other hand, these element in HNO_3 leachate of FA-LF are found lower than in leachate from DI water. Cu concentration in HNO_3 and Na_2CO_3 leachate of FA-APC and FA-LF is represented in lower concentration when compared with leachate from DI water because DI water remove Cu of 1.44 mg/kg for FA-APC, while other treated solutions can remove Cu less than 1.0 mg/kg. For FA-LF, the result shows that DI water leaches Cu from FA-LF as of 0.1245 mg/kg, while other treated solutions can leach. Cr is the least leached by DI water compared to other solutions.

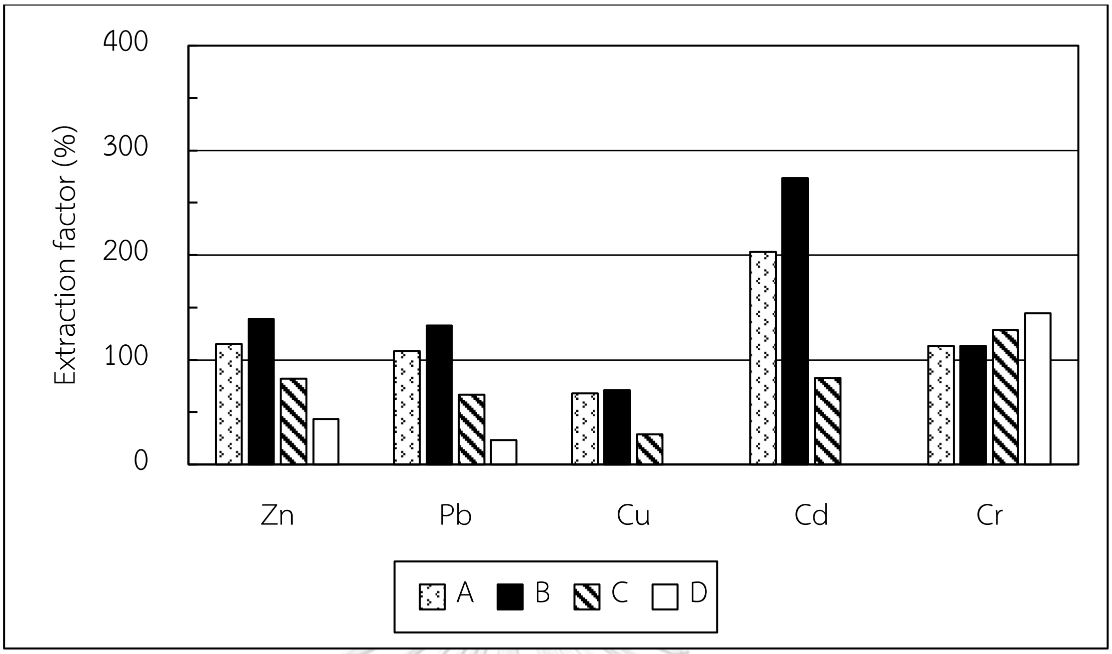

Fig 4.8 Concentration percentage of Zn, Pb, Cu, Cd and Cr from FA-APC by:
A) 0.01M HNO_3, B) 0.1M HNO_3, C) 0.1M Na_2CO_3, D) 0.25M Na_2CO_3 at 1-hr extraction

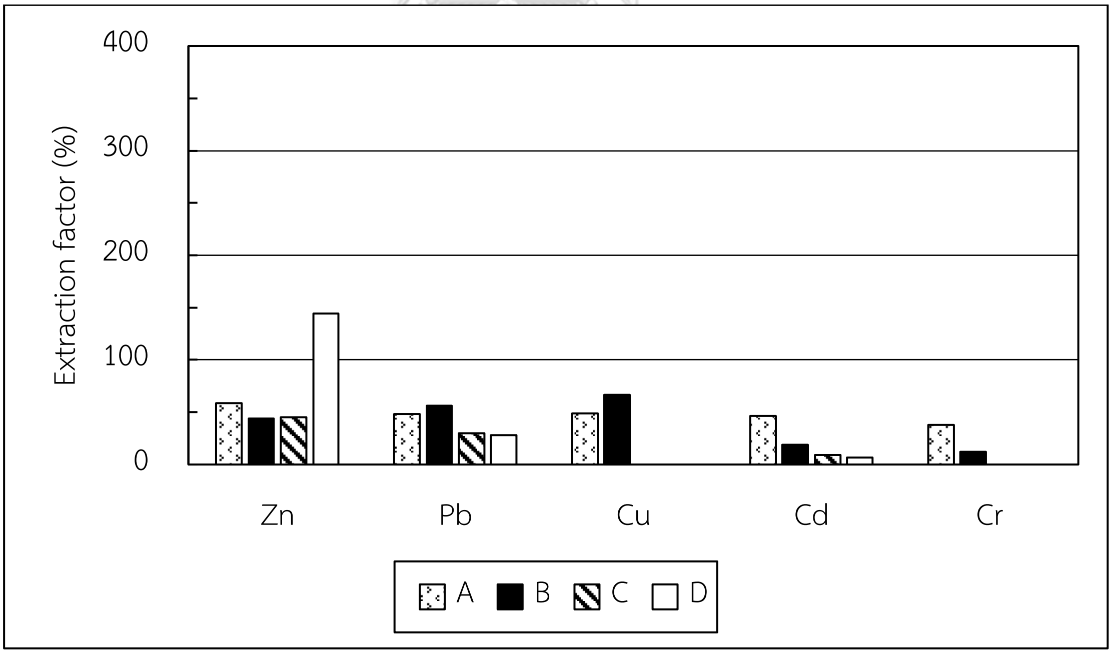

Fig 4.9 Concentration percentage of Zn, Pb, Cu, Cd and Cr from FA-LF by:
A) 0.01M HNO_3, B) 0.1M HNO_3, C) 0.1M Na_2CO_3, D) 0.25M Na_2CO_3 at 1-hr extraction

Table 4.12 Concentration and extraction percentage of Zn, Pb, Cu, Cd and Cr in leachate from FA-APC at 1-hr extraction time

Element		FA-APC treated by				
		DI water	0.01M HNO_3	0.1M HNO_3	0.1M Na_2CO_3	0.25M Na_2CO_3
Zn	Concentration (mg/kg)	5.06 ± 0.03	5.81 ± 0.29	7.03 ± 0.25	4.15 ± 0.02	2.21 ± 0.15
	% extraction	100	114.85	138.83	82.05	43.65
Pb	Concentration (mg/kg)	274.9 ± 7.1	297.8 ± 25.0	364.2 ± 54.1	183.2 ± 7.44	64.7 ± 5.13
	% extraction	100	108.33	132.49	66.65	23.53
Cu	Concentration (mg/kg)	1.44 ± 0.15	0.98 ± 0.07	1.02 ± 0.09	0.41 ± 0.03	<0.05
	% extraction	100	67.97	70.86	28.57	0.00
Cd	Concentration (mg/kg)	0.024 ± 0.000	0.048 ± 0.014	0.065 ± 0.006	0.019 ± 0.002	<0.05
	% extraction	100	202.91	273.78	82.52	0.00
Cr	Concentration (mg/kg)	0.892 ± 0.068	1.009 ± 0.010	1.012 ± 0.091	1.148 ± 0.025	1.290 ± 0.029
	% extraction	100	113.11	113.45	128.61	144.60

Table 4.13 Concentration and extraction percentage of Zn, Pb, Cu, Cd and Cr in leachate from FA-LF at 1-hr extraction time

Element		FA-LF treated by				
		DI water	0.01M HNO_3	0.1M HNO_3	0.1M Na_2CO_3	0.25M Na_2CO_3
Zn	Concentration (mg/kg)	1.192 ± 0.261	0.702 ± 0.319	0.522 ± 0.027	0.538 ± 0.054	1.724 ± 0.999
	% extraction	100	58.92	43.83	45.19	144.60
Pb	Concentration (mg/kg)	5.779 ± 0.256	2.784 ± 0.147	3.254 ± 0.046	1.735 ± 0.097	1.609 ± 0.163
	% extraction	100	48.17	56.31	30.02	27.85
Cu	Concentration (mg/kg)	0.124 ± 0.018	0.061 ± 0.105	0.083 ± 0.144	<0.05	<0.05
	% extraction	100	48.82	66.69	0.00	0.00
Cd	Concentration (mg/kg)	0.101 ± 0.004	0.047 ± 0.053	0.019 ± 0.000	0.009 ± 0.000	0.007 ± 0.002
	% extraction	100	46.55	18.78	9.16	6.65
Cr	Concentration (mg/kg)	0.087 ± 0.011	0.010 ± 0.010	0.033 ± 0.057	<0.05	0.010 ± 0.010
	% extraction	100	37.80	12.10	0.00	0.00

4.3.2 Concentration of heavy metal in FA-APC and FA-LF by microwave digestion

According to Fig 4.10-4.11 and Table 4.14-4.15, the digestion factor (%) is calculated by using the concentration of element in untreated FA-APC and FA-LF after microwave digestion as a baseline according Eqn (4.10).

$$\% \text{ digestion} = \frac{\left[\left(\frac{\text{mg}}{\text{kg}}\right)\text{in treated MSWI FA}\right]\times 100}{\left[\left(\frac{\text{mg}}{\text{kg}}\right)\text{ in untreated MSWI FA}\right]} \qquad \text{Eqn (4.10)}$$

Zn, Pb, Cu, Cd and Cr concentration in treated FA-APC and FA-LF is higher than in untreated FA-APC and FA-LF. For example, Zn in FA-APC treated by DI water is 8,897.8 mg/kg that is higher than 4,699.0 mg/kg of Zn in untreated FA-APC. Cd concentration in all treated FA-LF shows high level at 1,518.5 mg/kg when compared with untreated FA-LF at 127.8 mg/kg. This may be because of the formation of $CdCO_3$ (solid phase) (Zhang et al., 2016), and precipitation on surface of treated FA-LF. However, the concentration of remained heavy metals in FA-APC and FA-LF does not depend on relative removal amount of soluble salt and precipitation, rather it is controlled by type and properties of heavy metals (Wang et al., 2015).

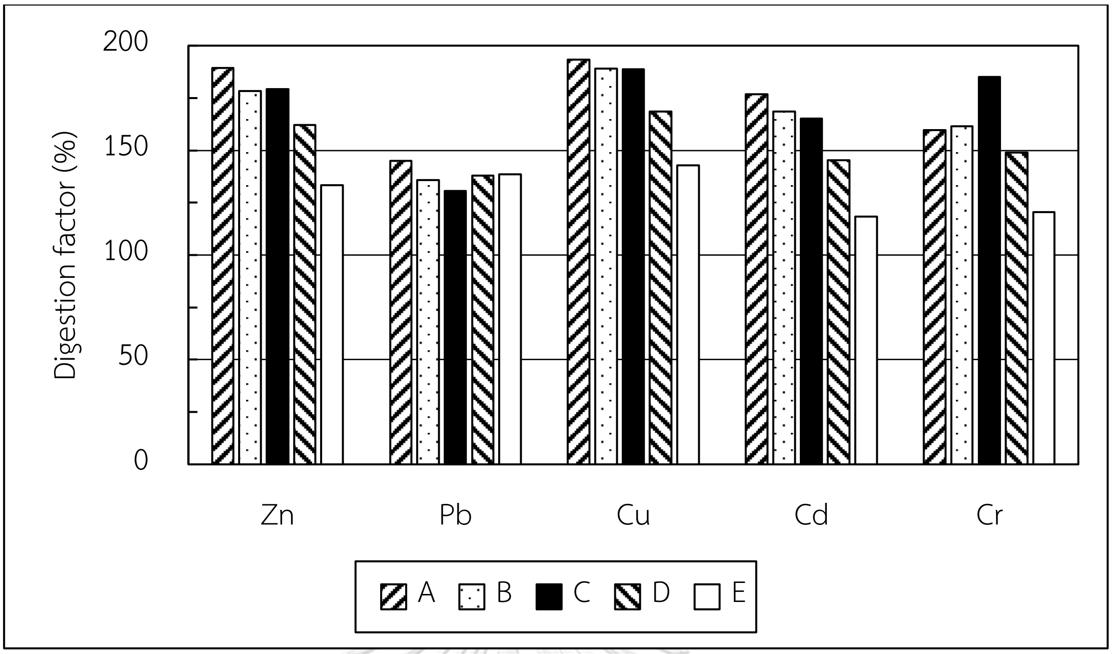

Fig 4.10 Concentration percentage of Zn, Pb, Cu, Cd and Cr from microwave digestion in FA-APC treated by: A) DI water, B) 0.01M HNO_3, C) 0.1M HNO_3, D) 0.1M Na_2CO_3, E) 0.25M Na_2CO_3 at 1-hr extraction

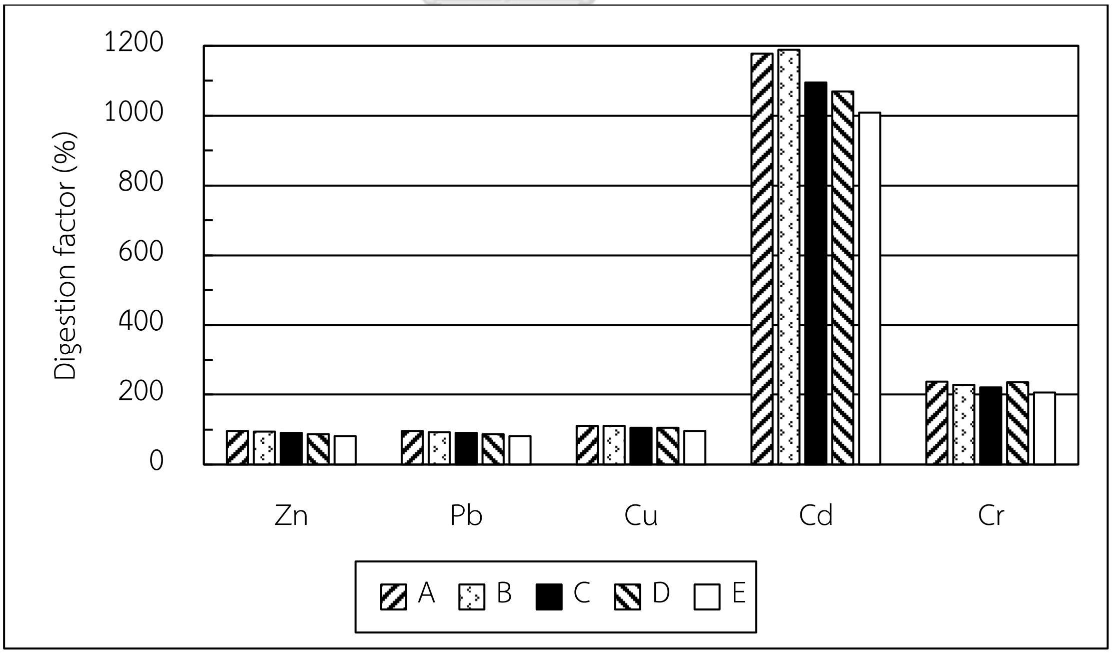

Fig 4.11 Concentration percentage of Zn, Pb, Cu, Cd and Cr from microwave digestion in FA-LF treated by: A) DI water, B) 0.01M HNO_3, C) 0.1M HNO_3, D) 0.1M Na_2CO_3, E) 0.25M Na_2CO_3 at 1-hr extraction

Table 4.14 Concentration of Zn, Pb, Cu, Cd and Cr from FA-APC by microwave digestion

Element		FA-APC treated by					
		Untreated FA-LF	DI water	0.01M HNO_3	0.1M HNO_3	0.1M Na_2CO_3	0.25M Na_2CO_3
Zn	Concentration (mg/kg)	4,699.0 ± 475.2	8,897.8 ± 11.4	8,377.1 ± 53.6	8,420.1 ± 204.1	7,622.2 ± 289.1	6,267.8 ± 95.0
	% digestion	100	189.35	178.27	179.19	162.21	133.39
Pb	Concentration (mg/kg)	1,253.1 ± 14.9	1,817.1 ± 24.2	1,702.2 ± 43.8	1,634.9 ± 51.3	1,728.9 ± 111.1	1,734.9 ± 92.8
	% digestion	100	145.01	135.84	130.46	137.97	138.45
Cu	Concentration (mg/kg)	463.9 ± 52.6	897.3 ± 12.8	877.5 ± 38.5	876.1 ± 17.0	781.7 ± 12.0	663.3 ± 15.8
	% digestion	100	193.43	189.16	188.86	168.52	142.99
Cd	Concentration (mg/kg)	287.5 ± 86.9	508.1 ± 3.2	484.8 ± 9.5	475.2 ± 13.8	417.8 ± 20.5	340.6 ± 2.2
	% digestion	100	176.71	168.58	165.24	145.28	118.45
Cr	Concentration (mg/kg)	33.6 ± 0.4	53.6 ± 0.7	54.3 ± 1.1	62.2 ± 1.5	50.0 ± 3.9	40.4 ± 0.7
	% digestion	100	159.75	161.59	185.20	148.90	120.42

Table 4.15 Concentration of Zn, Pb, Cu, Cd and Cr from FA-LF by microwave digestion

Element		FA-LF treated by					
		Untreated FA-LF	DI water	0.01M HNO_3	0.1M HNO_3	0.1M Na_2CO_3	0.25M Na_2CO_3
Zn	Concentration (mg/kg)	3,523.9 ± 168.5	3,362.9 ± 50.2	3,340.4 ± 99.7	3,188.1 ± 26.4	3,094.9 ± 156.7	2,899.3 ± 51.3
	% digestion	100	95.43	94.79	90.47	87.83	82.27
Pb	Concentration (mg/kg)	742.1 ± 48.5	713.7 ± 6.4	687.4 ± 17.9	675.7 ± 6.0	648.9 ± 46.7	604.5 ± 5.6
	% digestion	100	96.16	92.62	91.04	87.43	81.44
Cu	Concentration (mg/kg)	423.3 ± 5.8	468.8 ± 8.5	471.6 ± 2.4	449.4 ± 4.9	447.4 ± 48.6	407.2 ± 6.1
	% digestion	100	110.73	111.41	106.14	105.67	96.18
Cd	Concentration (mg/kg)	127.8 ± 29.1	1,505.4 ± 4.2	1,518.5 ± 49.7	1,399.2 ± 1.7	1,366.6 ± 69.7	1,290.1 ± 20.0
	% digestion	100	1177.66	1187.94	1094.63	1069.08	1009.22
Cr	Concentration (mg/kg)	43.1 ± 5.0	102.4 ± 1.1	98.7 ± 1.8	95.1 ± 3.2	102.0 ± 1.3	88.6 ± 6.0
	% digestion	100	237.40	228.97	220.55	236.61	205.47

4.4 Efficiency of treated solution for chloride and sulfate removing

4.4.1 Comparison of chemical composition in FA-APC and FA-LF from microwave digestion

From XRF result in Table 4.4, 4.5 and 4.6, the results of chemical composition are shown to study effect of treatment process to FA-APC and FA-LF. In Fig 4.12 and 4.13, the % by wt. of chemical composition in treated FA-APC and FA-LF is calculated to compare with untreated FA-APC and FA-LF by using the concentration of element and % by wt. from XRF result in untreated FA-APC and FA-LF after microwave digestion as a baseline according Eqn (4.11).

$$\% \text{ by wt.} = \frac{\left[\left(\frac{mg}{kg}\right) \text{in treated MSWI FA}\right] \times \% \text{ by wt. in untreated MSWI FA from XRF result}}{\left[\left(\frac{mg}{kg}\right) \text{ in untreated MSWI FA}\right]} \quad \text{Eqn (4.11)}$$

Concentration of Na, K and Cl^- in treated FA-APC and FA-LF decrease after treatment process because all of the treated solutions remove these elements from untreated FA-APC and FA-LF. For example, Na in FA-APC treated by DI water is 3.3% by wt. is lower than 13.9% by wt. of Na in untreated FA-APC. Cl^- concentration is 29.3% by wt. for untreated FA-APC which decreases after treatment process to 1.8% by wt. for 0.25M Na_2CO_3. This is because these elements remove from soluble salts such as NaCl and KCl. Conversely, treated FA-LF has lower concentration of Na and K than untreated FA-LF but Cl^- in treated FA-LF has no pattern growth. For example, Cl^- in treated FA-LF by DI water decreases from 9.3% to 4.9% by wt., while Cl^- in treated FA-LF by 0.1M HNO_3 increase to 12.4% by wt.

However, Ca is not removed after treatment process. Ca concentration in treated FA-APC increases significantly from 32.1% by wt. to 48.2% by wt. This is may be because Ca forms a phase such as calcite ($CaCO_3$) and Portlandite ($Ca(OH)_2$) as seen in XRD result in Table 4.7. However, Ca in treated FA-LF decreases from 44.4% to 39.0% by wt. for untreated and treated FA-LF by 0.1M Na_2CO_3, respectively.

SO_4^{2-} in treated FA-APC and FA-LF increases after treatment process from 4.35% to 7.0% by wt. for untreated FA-APC and FA-APC treated by 0.01M HNO_3, respectively. For example, SO_4^{2-} in treated FA-LF by 0.01M HNO_3 increases from 4.35% to 8.1% by wt. In contrast, SO_4^{2-} in treated FA-LF by 0.1M Na_2CO_3 and 0.25M Na_2CO_3 decreases from 4.35% for untreated FA-LF to 3.8% by wt. and 2.7% by wt. for treated FA-LF by 0.1M Na_2CO_3 and 0.25M Na_2CO_3, respectively.

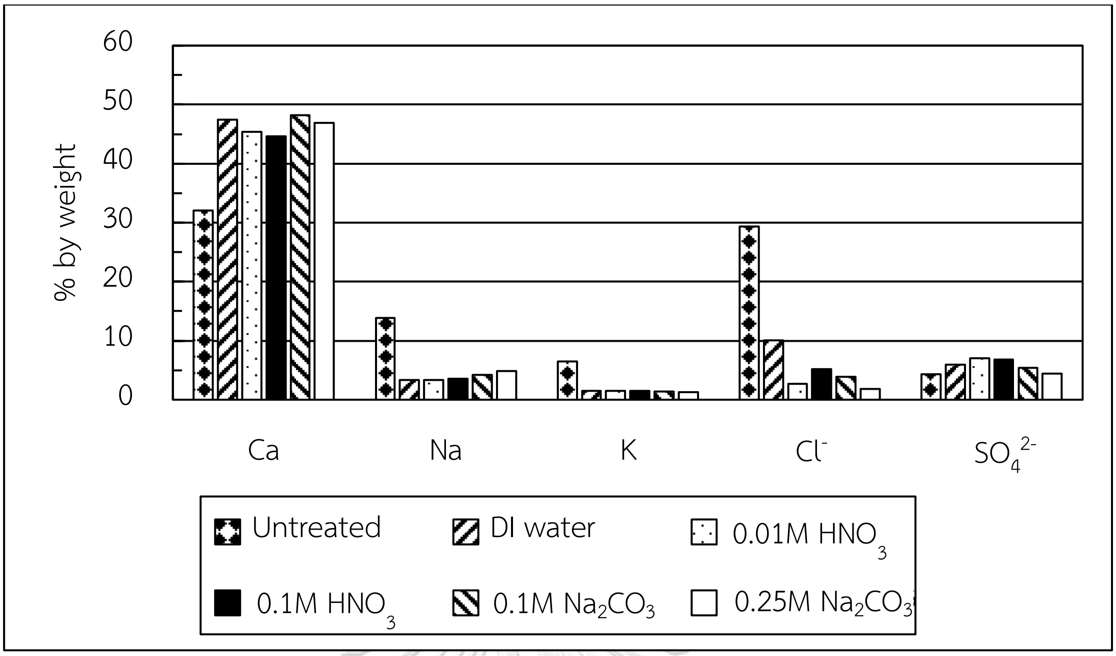

Fig 4.12 Comparison of chemical composition in untreated and treated FA-APC and yields calculated from % XRF of untreated FA-APC

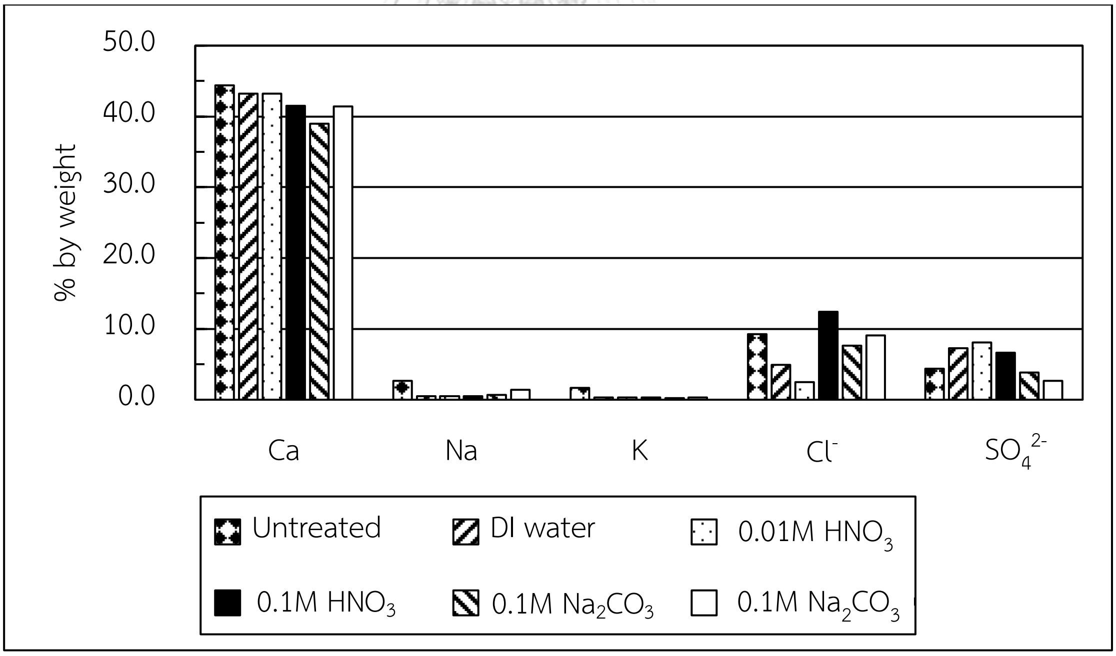

Fig 4.13 Comparison of chemical composition in untreated and treated FA-LF and yields are calculated from % XRF of untreated FA-LF

4.4.2 Removal rate (%R) after treatment process

From ICP-OES result in Table 4.8, 4.9, 4.10 and 4.11, the results of concentration of Ca, Na, K, Cl^- and SO_4^{2-} are shown to study the effect of treated solution types on these elements removal from FA-APC and FA-LF. In Fig 4.14 and 4.15, the percent of removal of concentration in leachate (%R LC) from FA-APC and FA-LF is calculated by using the concentration of element in leachate and untreated FA-APC and FA-LF as a baseline according Eqn (4.12).

$$\%R\ LC = \frac{\left[\left(\frac{mg}{kg}\right)\text{in leachate}\right]}{\left[\left(\frac{mg}{kg}\right)\text{ in untreated MSWI FA}\right]}\times 100 \qquad \text{Eqn (4.12)}$$

For percent of removal of concentration in treated FA-APC and FA-LF (%R MW) from microwave digestion is calculated to compare with untreated FA-APC and FA-LF by using the concentration of element from microwave digestion result in untreated and treated FA-APC and FA-LF according Eqn (4.13) (Funari et al., 2017).

$$\%R\ MW = 1- \frac{\left[\left(\frac{mg}{kg}\right)\text{in treated MSWI FA}\right]}{\left[\left(\frac{mg}{kg}\right)\text{ in untreated MSWI FA}\right]}\times 100 \qquad \text{Eqn (4.13)}$$

In Fig 4.14, high content of soluble salts such as NaCl and KCl is removed from untreated FA-APC. %R MW of Na and K is lower than %R LC. This result suggests that element concentrations leached by treated solutions are higher than those from microwave digestion. For example, %R LC of K is more than 80% by wt. in all leachate, and %R MW of K in DI water is lowest percentage at 77.0% by wt. Conversely, %R LC MW of Cl^- is higher than %R LC. For instance, %R MW of Cl^- in 0.01M HNO_3 and 0.25M Na_2CO_3 are 90.8% by wt. and 94.0% by wt., respectively, while %R MW in DI water is 10.1% by wt. This can be explained that DI water has low efficiency for Cl^- removal and more than 90% by wt. of Cl^- is removed by treated solution.

In contrast, %R LC of Cl^- in FA-LF is around 20% by wt., and %R MW of Cl^- does not depend on solution type and concentration as seen in Fig 4.15. For example, %R MW is 46.8% by wt. and 73.6% by wt. for DI water and 0.01M HNO_3, respectively. However, leachate with 0.25M Na_2CO_3 has %R MW equal -33.8% by wt., and %R MW of 0.1M Na_2CO_3 is 18.2% by wt. while %R MW of 0.25M Na_2CO_3 is 2.1% by wt.

Na and K in all leachates from FA-APC in Fig 4.14 stay at same level around 70.0% by wt. for %R MW of Na. and 76.0% by wt. for %R MW of K, which is similar to %R LC. For example, %R LC of Na is more than 70% by wt. and %R LC of K is around 80% by wt. In Fig 4.15, %R LC of Na and K in FA-LF is around 60% by wt., and %R MW is around 80% by wt. This relates to %R MW of Cl^- which is more than 90% by wt., and Na and K dissolve from NaCl and KCl (Yang et al., 2017).

Ca in all sample increases after treatment process therefore %R LC from leachate cannot show real efficiency of Ca removal. %R MW of Ca is around -45.0% by wt. showing that Ca increases from treatment process (Funari et al., 2017). On the other hand, Ca in FA-LF decreases with %R LC is around 6.0% by wt., and %R MW is 2.8% by wt. for DI water and 0.01M HNO_3 and is around 10% by wt. for 0.1M HNO_3 and Na_2CO_3.

In Fig 4.14, SO_4^{2-} in all samples increases after treatment, and %R LC of SO_4^{2-} is around 30 to 60% by wt. while %R MW is between -0.4% by wt. and -60.7% by wt. For example, %R MW of treated FA-APC by Na_2CO_3 is -0.4% by wt. and -60.7% by wt. for 0.01M HNO_3 that explains efficiency of Na_2CO_3 for SO_4^{2-} removal is higher than 0.01M HNO_3.

In Fig 4.15, SO_4^{2-} in treated FA-LF by DI water and HNO_3 increases after treatment process with %R LC is around 1.3% by wt. and %R MW is -68.2% by wt., and -85.6% by wt. and -52.0% by wt. for DI water, 0.01M HNO_3 and 0.1M HNO_3, respectively. This shows %R MW does not depend on concentration of treated solution. However, Na_2CO_3 has best efficiency for SO_4^{2-} removal with %R LC around 60 to 80% by wt., while %R MW depend on concentration of Na_2CO_3, %R MW in 0.1M Na_2CO_3 is 13.8% by wt. and in 0.25M Na_2CO_3 is 38.0% by wt.

From removal rate and efficiency result, all of treated solution remove Cl^- more than 50% from FA-APC when calculated from %R MW. Cl^- concentration decreases after the treatment process. For SO_4^{2-} concentration, Na_2CO_3 removes SO_4^{2-} more than other treated solutions when compared with other solutions. This is because Na_2CO_3 react with $CaSO_4$ to form Na_2SO_4 which is more soluble.

DI water is considered to be best treated solution because it can remove Ca, Na, K, Cl^- and SO_4^{2-} as high as other basic or acidic solutions as seen in Fig 4.14-4.15. Moreover, DI water gives %R LC, %R MW and highest compressive strength for mortar in Fig 4.16.

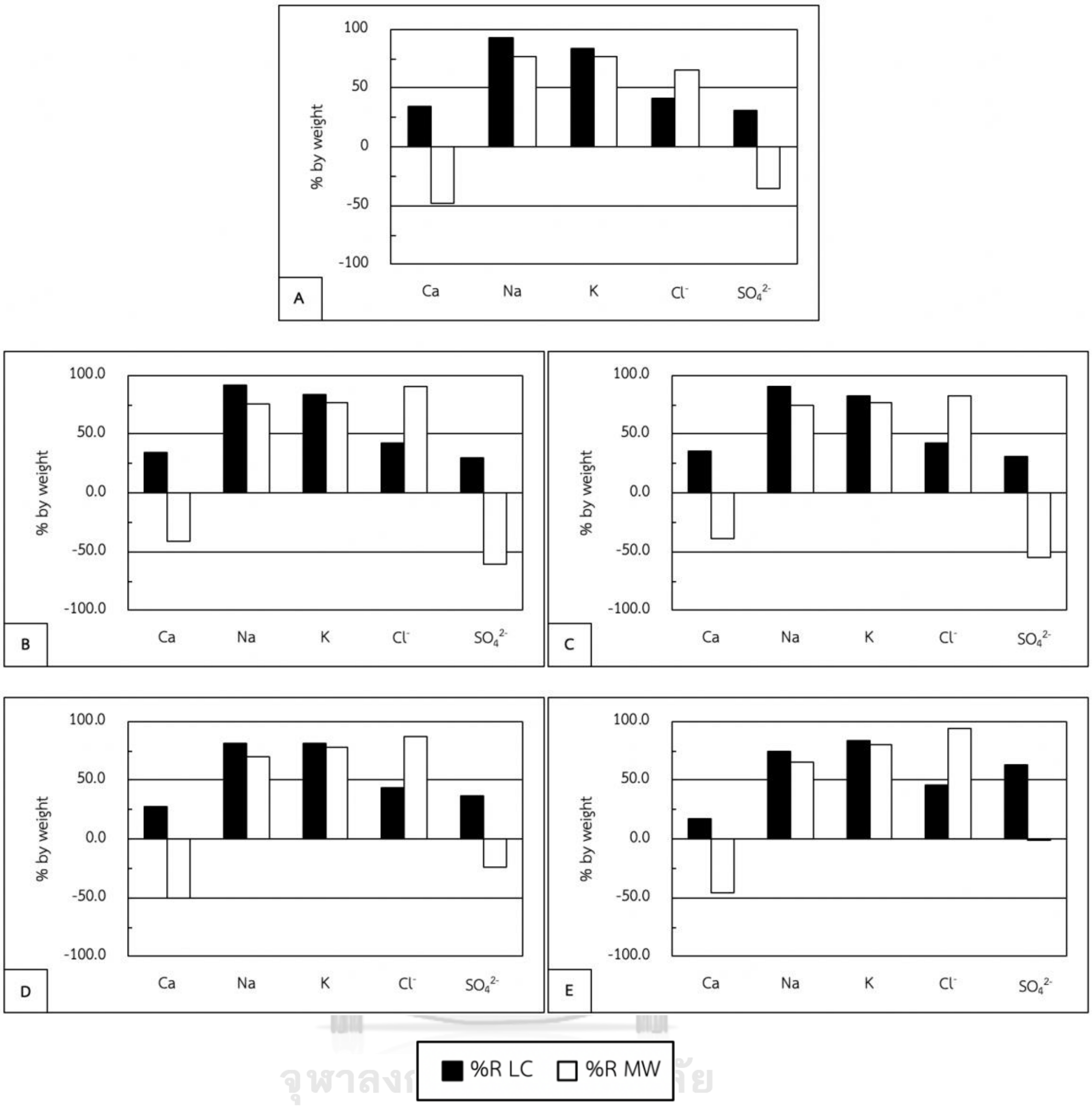

Fig 4.14 Removal rate (%R) after treatment process of FA-APC by (A) DI water, (B) 0.01M HNO_3, (C) 0.1M HNO_3, (D) 0.1M Na_2CO_3 and (E) 0.25M Na_2CO_3:

(1) %R calculated from concentration in leachate (%R LC)

(2) %R calculated from concentration in FA-APC from microwave digestion (%R MW)

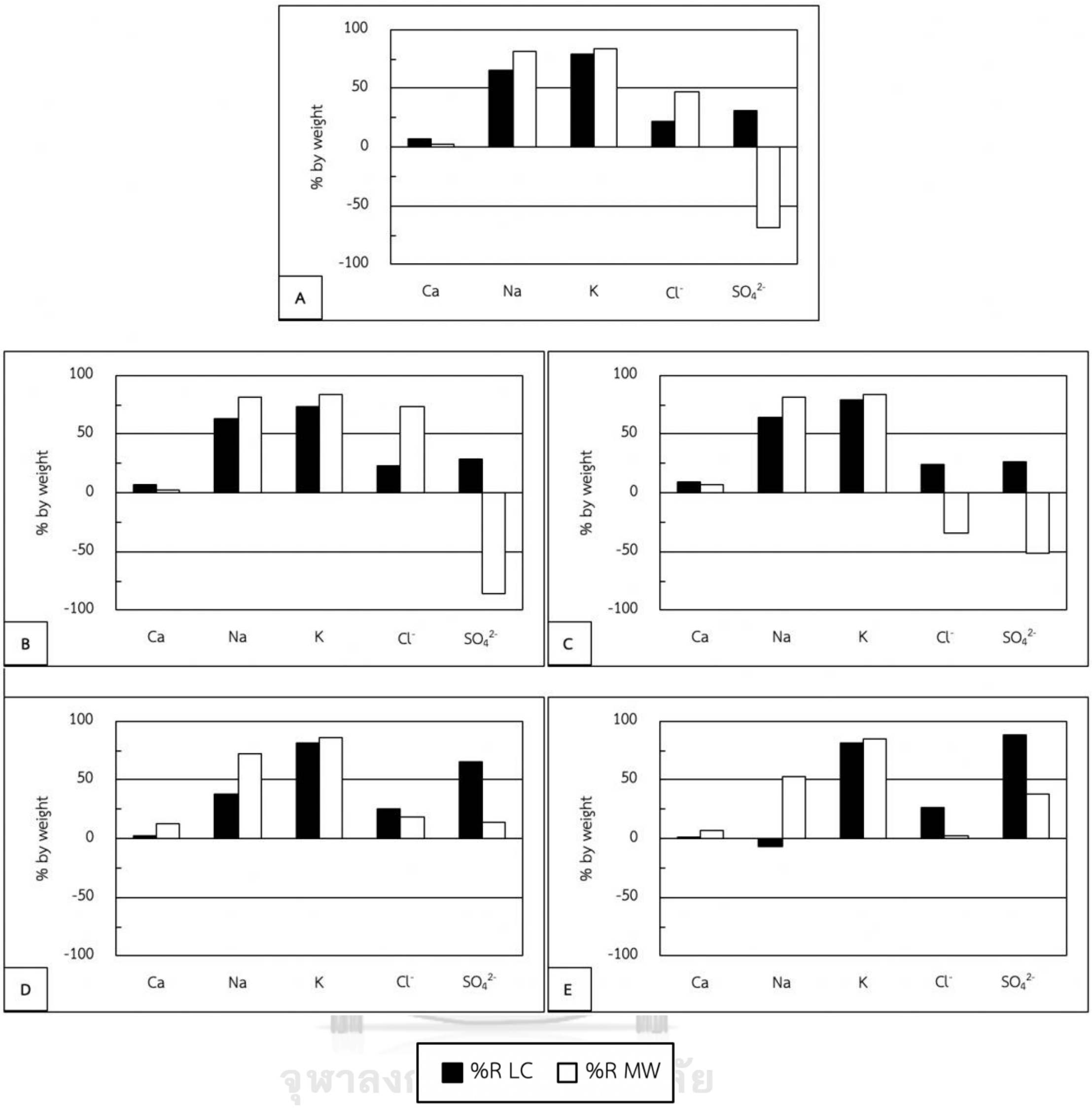

Fig 4.15 Removal rate (%R) after treatment process of FA-LF by (A) DI water, (B) 0.01M HNO_3, (C) 0.1M HNO_3, (D) 0.1M Na_2CO_3 and (E) 0.25M Na_2CO_3:

(1) %R calculated from concentration in leachate (%R LC)

(2) %R calculated from concentration in FA-LF from microwave digestion (%R MW)

4.5 Compressive strength of mortar

Compressive strength results are calculated from Table E1-E15 in appendix E. Following Fig 4.17, the result shows the compressive strength of mortar from untreated FA-APC has lowest strength compared with mortar from treated FA-APC. Treatment process can improve strength of mortar. Similar result was shown in other works (Sancharoen, 2003 and Saikia et al., 2015). For FA-APC, DI water is the best treated solution in improving mortar strength. Specifically, compressive strength of 5%-FA-APC-replaced mortar increases from 24.25 to 29.22 MPa with DI water as treated solution. It is also found that at every FA-APC percent replacement the compressive strength increases after FA-APC was treated by treated solutions as seen in Fig 4.17, except for 15% and 20% replacement with 0.25M Na_2CO_3 as treated solution. Moreover, an increase in HNO_3 concentration results in higher compressive strength. For example, at 5% replacement the mortar strength increases from 23.54 to 28.15 MPa when treating with 0.01M HNO_3 and 0.1M HNO_3, respectively. On the other hand, higher Na_2CO_3 concentration decreases mortar strength for every FA-APC percent replacement. For instance, strength decreases from 30.10 to 27.99 MPa at 5% replacement with 0.1M Na_2CO_3 and 0.25M Na_2CO_3, respectively. This may be because mortar surface became drier when using more concentrated treated solutions resulting in lower compressive strength as seen in Fig 4.16.

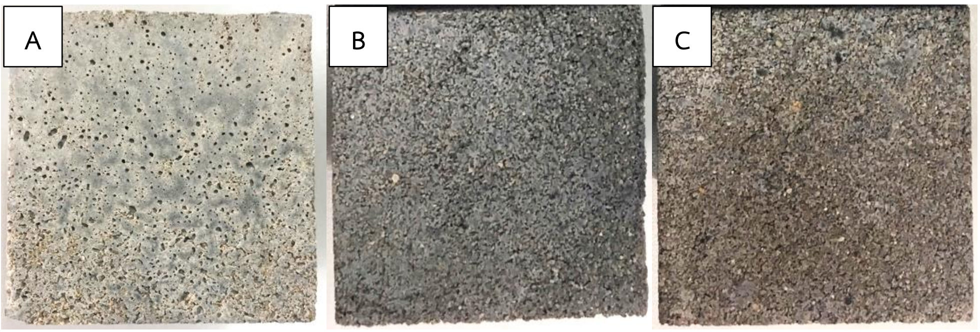

Fig 4.16 General appearance of mortar: (A) without FA-APC, (B) with treated FA-APC by 0.1M Na_2CO_3 and (C) with treated FA-APC by 0.25M Na_2CO_3

Compressive strength of FA-LF mortar in Fig 4.18 suggests that treatment process does not improve strength of fly ash. For example, the highest strength of mortar is from untreated FA-LF at 12.57 MPa at 20% replacement, while treated mortars have strength between 5.87 and 9.25 MPa at the same % replacement. Similar to FA-APC, the concentration on HNO_3 is one of the factors that can improve mortar strength. For example, at 20% replacement the mortar strength increases from 6.51 to 9.25 MPa when treating with 0.01M HNO_3 and 0.1M HNO_3, respectively. However, with Na_2CO_3 as treated solution, mortar strength does not depend on solution concentration for every percent replacement.

The compressive strength of FA-APC and FA-LF to mortars is reduced when FA-APC and FA-LF increase even if FA-APC and FA-LF is treated by treated solution. When FA-APC and FA-LF increase in specimen that decrease the Ca volume from cement and increase pore material in specimen (Lim et al., 2013) that make the mortars has lower density after adding FA-APC and FA-LF as shown in Table 4.16-4.17. The low density has effect to compressive strength because inner structure of mortars has more pore volume and mortars can crack easily.

Moreover, FA-APC and FA-LF do not have high quantity of Si and Al (Chiewchan, 2003) like FA-LN and FA-BT therefore FA-APC and FA-LF have lower strength than these coal fly ashes such as mortar from FA-LN and FA-BT at 5% replacement in Fig 4.19-4.20 have strength 30.40 MPa and 32.25 MPa, respectively while mortar from untreated FA-APC and FA-LF at 5% replacement have strength 24.25 MPa and 17.90 MPa, respectively. Si and Al in coal fly ash can react with $Ca(OH)_2$ released by hydration reaction of cement and form bonding named calcium-silicate hydrate (C-S-H) and calcium-aluminate hydrate (C-A-H) (Thomas, 2007).

Compressive strength of mortar with FA-APC and FA-LF according to TIS 1776-2542 for dry mortar for plastering is compliant with the standard requirement at 2.5 MPa. For example, compressive strength of 5% replacement-DI water-treated FA-APC is 29.22 MPa. The general appearance, deviation from right angle and dimension and tolerance of mortar are shown in Table F1-F4 and Table D1-D15 in appendix D and F, respectively. Treated MSWI FA does not has effect to these characterizations.

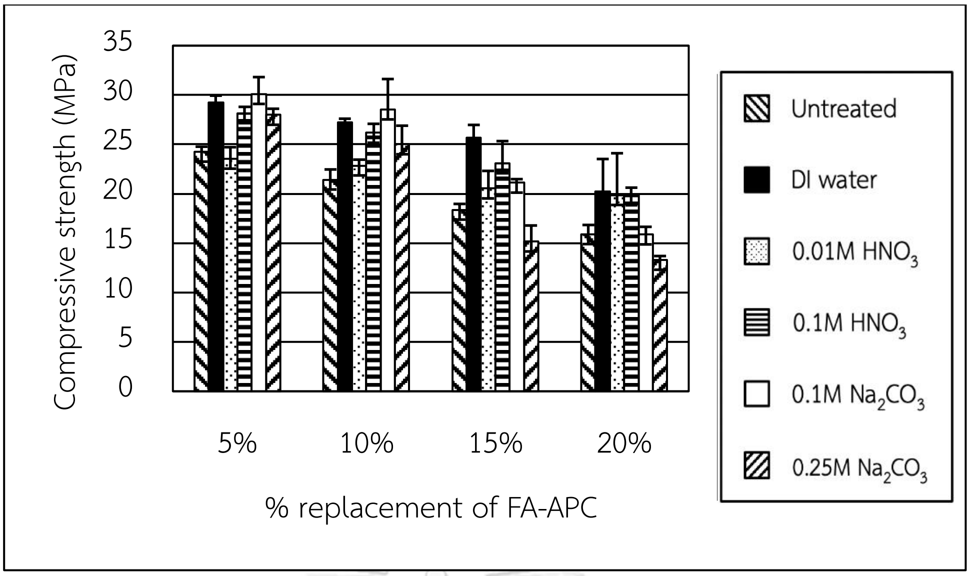

Fig 4.17 Compressive strength of mortar made from raw FA-APC and treated FA-APC by 4 categories of replacement: 5%, 10%, 15% and 20%

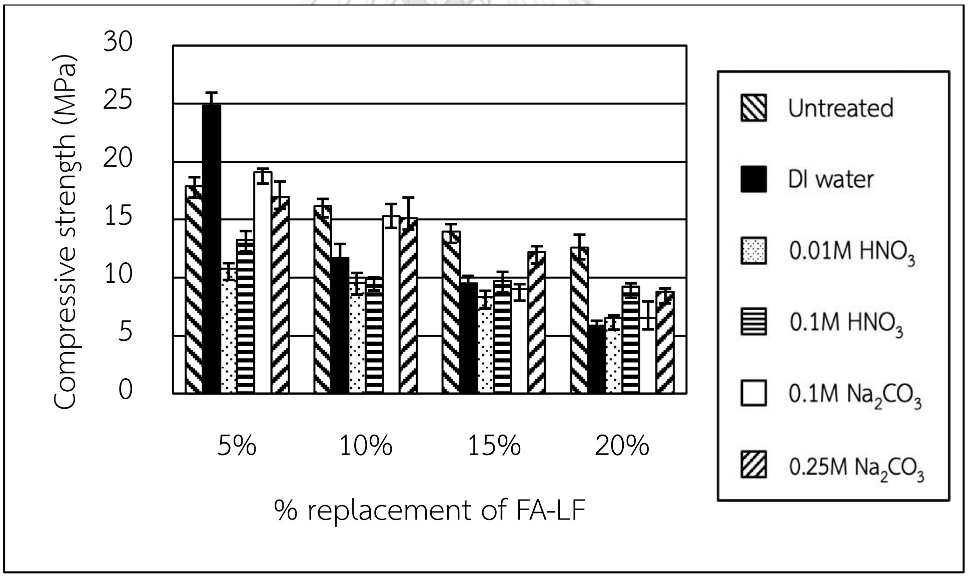

Fig 4.18 Compressive strength of mortar made from raw FA-LF and treated FA-LF by 4 categories of replacement: 5%, 10%, 15% and 20%

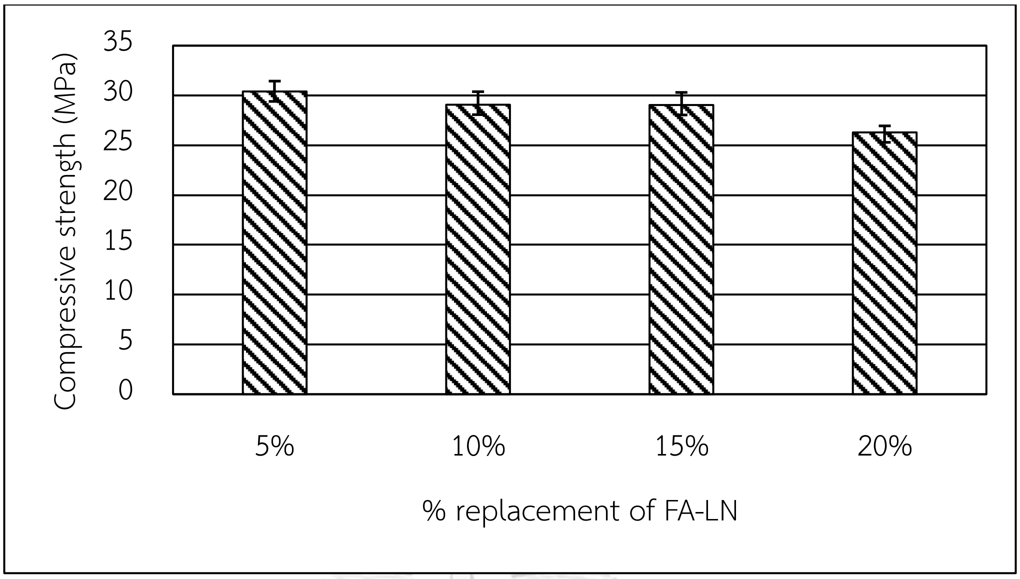

Fig 4.19 Compressive strength of mortar made from untreated FA-LN by 4 categories of replacement: 5%, 10%, 15% and 20%

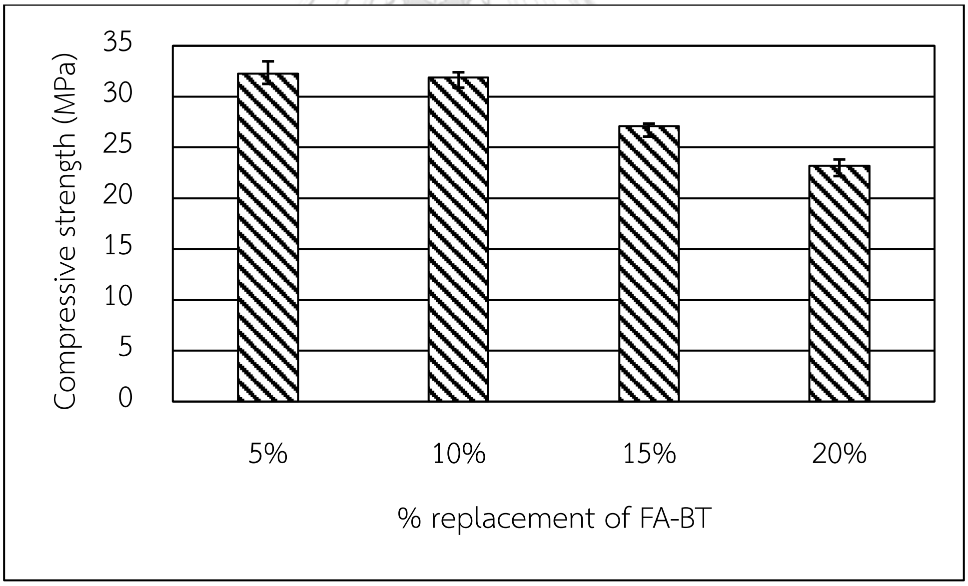

Fig 4.20 Compressive strength of mortar made from untreated FA-BT by 4 categories of replacement: 5%, 10%, 15% and 20%

Table 4.16 Density of FA-APC mortars

Type of mortar	% replacement of fly ash	Density (g/cm^3)
Untreated	5	2.09
	10	2.06
	15	2.06
	20	2.07
DI water	5	2.07
	10	2.06
	15	2.04
	20	1.92
0.01M HNO_3	5	2.02
	10	1.98
	15	1.97
	20	1.92
0.1M HNO_3	5	2.03
	10	2.03
	15	2.00
	20	1.94
0.1M Na_2CO_3	5	2.02
	10	1.93
	15	1.93
	20	1.87
0.25M Na_2CO_3	5	2.02
	10	2.02
	15	1.91
	20	1.90

Table 4.17 Density of FA-LF mortars

Type of mortar	% replacement of fly ash	Density (g/cm^3)
Untreated	5	2.00
	10	1.99
	15	1.96
	20	1.94
DI water	5	2.03
	10	1.83
	15	1.75
	20	1.68
0.01M HNO_3	5	1.83
	10	1.73
	15	1.70
	20	1.69
0.1M HNO_3	5	1.86
	10	1.80
	15	1.80
	20	1.78
0.1M Na_2CO_3	5	1.99
	10	1.95
	15	1.89
	20	1.75
0.25M Na_2CO_3	5	1.97
	10	1.94
	15	1.89
	20	1.84

4.6 Leaching test

In Table 4.18, the result of TCLP testing four elements in untreated fly ash passes the standard except Pb concentration in FA-APC. Specifically, untreated FA-APC has 6.82 mg/L Pb, while limitation is 5.0 mg/L. After solidification process with cement-based treatment, the hazardous element decreases lower the standard concentration. For instance, mortar made with treated FA-APC has Cr around 0.3 mg/L that pass the standard. Therefore, these fly ash samples could be used as construction material in terms of low compressive strength product.

Table 4.18 Concentration of Pb, Cd, Cr and As from TCLP method

Type of sample		Concentration (mg/L)			
		Pb (5.0 mg/L)	Cd (1.0 mg/L)	Cr (5.0 mg/L)	As (5.0 mg/L)
Untreated fly ash					
FA-APC		6.820	<0.005	0.095	<0.005
FA-LF		0.220	<0.005	0.009	<0.005
FA-LN		<0.005	<0.005	0.093	1.979
FA-BT		0.440	<0.005	0.029	0.103
Mortar					
FA-APC	Non-treated	<0.005	<0.005	0.309	<0.005
	DI water	<0.005	<0.005	0.323	0.0027
	0.01M HNO_3	<0.005	<0.005	0.348	<0.005
	0.1M HNO_3	<0.005	<0.005	0.306	<0.005
	0.1M Na_2CO_3	<0.005	<0.005	0.314	<0.005
	0.25M Na_2CO_3	<0.005	<0.005	0.291	<0.005
FA-LF	Non-treated	<0.005	<0.005	0.260	<0.005
	DI water	<0.005	<0.005	0.227	<0.005
	0.01M HNO_3	<0.005	<0.005	0.199	<0.005
	0.1M HNO_3	<0.005	<0.005	0.200	<0.005
	0.1M Na_2CO_3	<0.005	<0.005	0.184	<0.005
	0.25M Na_2CO_3	<0.005	<0.005	0.210	<0.005
FA-LN	Non-treated	<0.005	<0.005	0.246	0.006
FA-BT	Non-treated	<0.005	<0.005	0.269	0.001

CHAPTER 5

CONCLUSION

This detailed laboratory study on different MSWI FA and treated solutions which used FA-APC and FA-LF as raw materials and treatment process to remove Cl^- and SO_4^{2-} from FA-APC and FA-LF by DI water, 0.01M HNO_3, 0.1M HNO_3, 0.1M Na_2CO_3 and 0.25M Na_2CO_3 were investigated. The treated FA-APC and FA-LF were utilized as a binder with cement in solidification and stabilization process, and were tested heavy metals leaching by TCLP method. The following conclusion can be drawn:

1. To answer objective (1) which investigates physical and chemical characterization of MSWI FA:
    - Microstructure of FA-APC and FA-LF are amorphous and show the accumulation of small particles which can further form big particles. FA-LF has particle plate-like structure around particle. This could increase surface area, pore volume and pore diameter of FA-LF.
    - Particle size of FA-LF is bigger than FA-APC because FA-LF has more moisture content which increase number of small particles of FA-LF to compact together.
    - FA-APC and FA-LF have high content of Cl^- and SO_4^{2-}. Dominant phases from XRD analysis are salt of chloride and sulfate. From heavy metal leaching by TCLP method, FA-APC is hazardous waste because it has Pb of 6.82 mg/L which is higher than US EPA 1992 standard (5.0 mg/L)
2. To answer objective (2) which investigates physical and chemical characterization of MSWI FA after treatment process:
    - FA-APC and FA-LF are basic. Adding acidic treated solutions cannot change pH of treated FA because $CaCO_3$ in FA-APC and FA-LF acts as buffer.
    - All of treated solution cannot change microstructure of FA-APC and FA-LF significantly.

  - After treatment process, salt of chloride and sulfate decreases All of the treated solutions can remove Cl^- in equal concentration. Na_2CO_3 can remove SO_4^{2-} in highest level because Na_2CO_3 could transfer $CaSO_4$ to Na_2SO_4 which is more soluble.
  - Heavy metals could be removed by treated solutions even if it is basic condition.
3. To answer objective (3) which investigates effect of treated FA-APC and FA-LF on properties of mortar:
  - Treatment process improves chemical and physical properties of FA-APC for using in mortar.
  - MSWI FA treated with DI water gives the highest efficiency. Used as a binder in mortar, treated FA-APC and FA-LF can improve mortar strength, and meet the requirement of TIS 1776-2542.
  - TCLP results suggested that mortar made with FA-APC and FA-LF could be used to be as dry mortar for plastering following TIS 1776-2542.

Suggestion for the future research

Future research might analyze the mechanism of treatment process to study the formation of leached element in leachate which affect difference of XRD result after treatment process, or analyze the co-precipitation of heavy metal with fly ash samples. For microwave digestion, hydrofluoric acid (HF) may be used for fly ash digestion to analyze total of concentration of elements in fly ash.

In mortar part, future research should study the ratio between water and binder for mortar which has replacement of treated MSWI FA because treated MSWI FA has more surface area and pore volume to react with water. Moreover, a pilot scale could be done using tap water as treated solution to study the possibility of site application.

APPENDIX

APPENDIX A

pH during leaching result

Table A1 pH during leaching of FA-APC by DI water

Sample		pH		
		0 min	30 min	60 min
Treated by DI water	Tube 1	11.7	11.82	11.85
		11.71	11.83	11.86
		11.71	11.83	11.86
	Mean	**11.71**	**11.83**	**11.86**
	Tube 2	11.62	11.81	11.81
		11.7	11.81	11.81
		11.7	11.82	11.81
	Mean	**11.67**	**11.81**	**11.81**
	Tube 3	11.68	11.81	11.8
		11.69	11.82	11.82
		11.69	11.82	11.82
	Mean	**11.69**	**11.82**	**11.81**
	Total Mean	**11.69**	**11.82**	**11.83**

Table A2 pH during leaching of FA-APC by 0.01M HNO_3

Sample		pH		
		0 min	30 min	60 min
Treated by 0.01M HNO_3	Tube 1	11.75	11.8	11.79
		11.76	11.82	11.8
		11.76	11.81	11.81
	Mean	**11.76**	**11.81**	**11.8**
	Tube 2	11.74	11.81	11.81
		11.75	11.81	11.81
		11.75	11.8	11.81
	Mean	**11.75**	**11.81**	**11.81**
	Tube 3	11.73	11.79	11.81
		11.74	11.79	11.81
		11.74	11.78	11.81
	Mean	**11.74**	**11.79**	**11.81**
	Total Mean	**11.75**	**11.80**	**11.81**

Table A3 pH during leaching of FA-APC by 0.1M HNO_3

Sample		pH		
		0 min	30 min	60 min
Treated by 0.1M HNO_3	Tube 1	11.69	11.78	11.78
		11.7	11.81	11.79
		11.7	11.82	11.79
	Mean	**11.70**	**11.80**	**11.79**
	Tube 2	11.72	11.77	11.87
		11.72	11.78	11.88
		11.73	11.8	11.88
	Mean	**11.72**	**11.78**	**11.88**
	Tube 3	11.64	11.79	12.01
		11.65	11.8	12.02
		11.66	11.8	12.03
	Mean	**11.65**	**11.80**	**12.02**
	Total Mean	**11.69**	**11.79**	**11.89**

Table A4 pH during leaching of FA-APC by 0.1M Na_2CO_3

Sample		pH		
		0 min	30 min	60 min
Treated by 0.1M Na_2CO_3	Tube 1	11.85	11.85	12.01
		11.85	11.86	12.02
		11.85	11.86	12.02
	Mean	**11.85**	**11.86**	**12.02**
	Tube 2	11.86	11.86	11.99
		11.86	11.86	12
		11.86	11.87	12
	Mean	**11.86**	**11.86**	**12.00**
	Tube 3	11.81	11.86	12.02
		11.82	11.87	12.02
		11.82	11.87	12.02
	Mean	**11.82**	**11.87**	**12.02**
	Total Mean	**11.84**	**11.86**	**12.01**

Table A5 pH during leaching of FA-APC by 0.25M Na_2CO_3

Sample		pH		
		0 min	30 min	60 min
Treated by 0.25M Na_2CO_3	Tube 1	11.91	11.97	12.09
		11.92	11.97	12.1
		11.93	11.97	12.11
	Mean	**11.92**	**11.97**	**12.1**
	Tube 2	11.94	11.98	12.11
		11.95	12	12.12
		11.95	12.01	12.12
	Mean	**11.95**	**12.00**	**12.12**
	Tube 3	11.89	11.98	12.03
		11.9	12.02	12.04
		11.9	12.03	12.05
	Mean	**11.90**	**12.01**	**12.04**
	Total Mean	**11.92**	**11.99**	**12.09**

Table A6 pH during leaching of FA-LF by DI water

Sample		pH		
		0 min	30 min	60 min
Treated by DI water	Tube 1	12.01	12.07	12.15
		12.03	12.07	12.16
		12.04	12.08	12.18
	Mean	**12.03**	**12.07**	**12.16**
	Tube 2	12.04	12.05	12.15
		12.07	12.09	12.16
		12.08	12.1	12.17
	Mean	**12.06**	**12.08**	**12.16**
	Tube 3	12.06	12.1	12.15
		12.07	12.1	12.16
		12.08	12.12	12.16
	Mean	**12.07**	**12.11**	**12.16**
	Total Mean	**12.05**	**12.09**	**12.16**

Table A7 pH during leaching of FA-LF by 0.01M HNO_3

Sample		pH		
		0 min	30 min	60 min
Treated by 0.01M HNO_3	Tube 1	12.07	12.09	12.11
		12.08	12.09	12.11
		12.06	12.08	12.12
	Mean	**12.07**	**12.09**	**12.11**
	Tube 2	12.1	12.12	12.14
		12.11	12.13	12.16
		12.12	12.13	12.15
	Mean	**12.11**	**12.13**	**12.15**
	Tube 3	12.1	12.13	12.15
		12.11	12.14	12.17
		12.12	12.15	12.16
	Mean	**12.11**	**12.14**	**12.16**
	Total Mean	**12.10**	**12.12**	**12.14**

Table A8 pH during leaching of FA-LF by 0.1M HNO_3

Sample		pH		
		0 min	30 min	60 min
Treated by 0.1M HNO_3	Tube 1	11.88	11.95	12
		11.88	11.96	12.01
		11.87	11.96	12
	Mean	**11.88**	**11.96**	**12.00**
	Tube 2	11.89	11.97	12.02
		11.87	11.95	12
		11.88	11.97	12.01
	Mean	**11.88**	**11.96**	**12.01**
	Tube 3	11.85	11.97	12
		11.85	11.96	12.07
		11.86	11.94	12.05
	Mean	**11.85**	**11.96**	**12.04**
	Total Mean	**11.87**	**11.96**	**12.02**

Table A9 pH during leaching of FA-LF by 0.1M Na_2CO_3

Sample		pH		
		0 min	**30 min**	**60 min**
Treated by 0.1M Na_2CO_3	Tube 1	12.33	12.36	12.5
		12.33	12.37	12.51
		12.34	12.36	12.53
	Mean	**12.33**	**12.36**	**12.51**
	Tube 2	12.32	12.35	12.52
		12.3	12.33	12.51
		12.34	12.37	12.5
	Mean	**12.32**	**12.35**	**12.51**
	Tube 3	12.34	12.35	12.52
		12.34	12.37	12.54
		12.33	12.37	12.52
	Mean	**12.34**	**12.36**	**12.53**
	Total Mean	**12.33**	**12.36**	**12.52**

Table A10 pH during leaching of FA-LF by 0.25M Na_2CO_3

Sample		pH		
		0 min	30 min	60 min
Treated by 0.25M Na_2CO_3	Tube 1	12.59	12.62	12.72
		12.58	12.63	12.72
		12.6	12.64	12.73
	Mean	**12.59**	**12.63**	**12.72**
	Tube 2	12.6	12.61	12.73
		12.59	12.62	12.73
		12.6	12.62	12.74
	Mean	**12.60**	**12.62**	**12.73**
	Tube 3	12.61	12.62	12.73
		12.6	12.64	12.76
		12.62	12.63	12.75
	Mean	**12.61**	**12.63**	**12.75**
	Total Mean	**12.60**	**12.63**	**12.73**

Table A11 pH of MSWI FA

Sample	pH
FA-APC	10.89
	10.90
	10.90
Mean	**10.90**
FA-LF	11.83
	11.84
	11.83
Mean	**11.83**

APPENDIX B

Moisture content of fly ash

Table B1 Moisture content of raw FA-APC

Sample	No.	Weight of crucible (g)	Weight of crucible + ash after drying (g)	Weight of ash (g)	Weight of ash after drying (g)	Moisture content %	Mean %
FA-APC	1	32.5771	33.5518	1.004	0.9731	3.07	3.72
		32.5809					
		32.578					
	Mean	32.5786					
	2	34.0714	35.0467	1.0269	0.9789	4.68	
		34.0659					
		34.0662					
	Mean	34.0678					
	3	34.6398	35.6169	1.0109	0.9764	3.42	
		34.6402					
		34.6416					
	Mean	34.6405					

Table B2 Moisture content of raw FA-LF

Sample	No.	Weight of crucible (g)	Weight of crucible + ash after drying (g)	Weight of ash (g)	Weight of ash after drying (g)	Moisture content %	Mean %
FA-LF	1	34.6538	35.5605	1.0182	0.9105	10.58	12.99
		34.6479					
		34.6483					
	Mean	34.65					
	2	35.6596	36.497	1.0096	0.8403	16.77	
		35.6547					
		35.6559					
	Mean	35.6567					
	3	32.5208	33.4164	1.0123	0.8946	11.62	
		32.5224					
		32.5221					
	Mean	32.5217					

Table B3 Moisture content of raw FA-LN

Sample	No.	Weight of crucible (g)	Weight of crucible + ash after drying (g)	Weight of ash (g)	Weight of ash after drying (g)	Moisture content %	Mean %
FA-LN	1	35.8645	36.8999	1.0402	1.0391	0.10	0.13
		35.8583					
		35.8595					
	Mean	35.8607					
	2	34.1274	35.1556	1.0299	1.0281	0.18	
		34.1272					
		34.128					
	Mean	34.1275					
	3	35.6604	36.6855	1.0263	1.0250	0.12	
		35.6611					
		35.6599					
	Mean	35.6604					

Table B4 Moisture content of raw FA-BT

Sample	No.	Weight of crucible (g)	Weight of crucible + ash after drying (g)	Weight of ash (g)	Weight of ash after drying (g)	Moisture content %	Mean %
FA-BT	1	38.5383	39.5442	1.0124	1.0095	0.29	0.28
		38.5331					
		38.5327					
	Mean	38.5347					
	2	32.5203	33.531	1.0124	1.0102	0.22	
		32.5207					
		32.5214					
	Mean	32.5208					
	3	34.0695	35.0777	1.0117	1.0082	0.34	
		34.0689					
		34.07					
	Mean	34.0694					

APPENDIX C

Density of fly ash

Table C1 Density of raw fly ash

Sample	Initial weight (g)	Final weight (g)	Used weight (g)	Initial point	Final point	Density (g/mL)
FA-APC	41	1.5	39.5	0.2	18.1	2.20
FA-LF	40.5	7	33.5	0.7	18.2	1.91
FA-LN	43.4	2.9	40.5	0.8	18.5	2.28
FA-BT	45	5.8	39.2	0.4	18.5	2.16

APPENDIX D

Dimension and tolerance of mortar

Table D1 Dimension and tolerance of mortar with untreated FA-APC

No.	Width (cm)						Length (cm)						Height (cm)					
	1	2	3	4	Mean	SD	1	2	3	4	Mean	SD	1	2	3	4	Mean	SD
Mortar with untreated FA-APC 5%																		
1	5	5	5	4.9	4.97	0.043	5	5	5	4.85	4.96	0.075	5	5	5	5.05	5.01	0.025
2	5	4.95	4.95	4.9	4.95	0.035	5.1	5	5	5	5.02	0.05	5	5	5	5	5	0
3	5	5	5	5	5	0	5.05	5	5.05	5.05	5.03	0.025	5	5.05	5.05	5.05	5.03	0.025
Mean					**4.97**	**0.026**	Mean				**5.00**	**0.05**	Mean				**5.01**	**0.016**
Mortar with untreated FA-APC 10%																		
1	5	5	5.1	5.1	5.05	0.05	4.95	4.9	4.9	4.9	4.91	0.025	5	4.95	4.95	4.95	4.96	0.025
2	5.15	5.1	5.1	5.1	5.11	0.021	5	5	4.95	4.95	4.97	0.028	5	4.95	5	5.05	5	0.040
3	5.1	5.1	5.1	5.1	5.1	0	5.05	5.05	5	5	5.02	0.028	5.05	5.1	5.1	5.05	5.07	0.028
Mean					**5.08**	**0.023**	Mean				**4.97**	**0.027**	Mean				**5.01**	**0.031**
Mortar with untreated FA-APC 15%																		
1	5.1	5.1	5.1	5.1	5.1	0	5.1	5.05	5.05	5	5.05	0.040	5	5	5	5	5	0
2	4.95	4.95	4.9	4.9	4.92	0.025	5	5	5	5.05	5.01	0.025	4.95	5	5.05	5.05	5.01	0.047
3	5.05	5.05	5.1	5.15	5.08	0.041	5.1	5.05	5.05	5.05	5.06	0.025	5.05	5	4.95	4.95	4.98	0.047
Mean					**5.03**	**0.022**	Mean				**5.04**	**0.030**	Mean				**5**	**0.031**

Table D1-2 Dimension and tolerance of mortar with untreated FA-APC

No.	Width (cm)						Length (cm)						Height (cm)					
	1	**2**	**3**	**4**	**Mean**	**SD**	**1**	**2**	**3**	**4**	**Mean**	**SD**	**1**	**2**	**3**	**4**	**Mean**	**SD**
Mortar with untreated FA-APC 20%																		
1	5.1	5.05	5.05	5.1	5.07	0.025	4.95	4.95	4.9	4.9	4.92	0.028	5	5	4.95	5	4.98	0.025
2	5.05	5.05	5.05	5	5.03	0.021	5	5.05	5.05	5	5.02	0.028	4.95	4.95	4.95	5	4.96	0.025
3	5.1	5.1	5.1	5.1	5.1	0	5	5	5	5	5	0	4.95	4.95	4.95	4.95	4.95	0
Mean					**5.07**	**0.015**	Mean				**4.98**	**0.019**	Mean				**4.96**	**0.016**

Table D2-1 Dimension and tolerance of mortar with treated FA-APC by DI water

No.	Width (cm)						Length (cm)						Height (cm)					
	1	2	3	4	Mean	SD	1	2	3	4	Mean	SD	1	2	3	4	Mean	SD
Mortar with treated FA-APC by DI water 5%																		
1	5	5	5	4.95	4.98	0.021	5.1	5.05	5.05	5	5.05	0.040	5	5	4.95	4.95	4.97	0.028
2	4.95	4.95	5	5	4.97	0.025	5	5	5	5	5	0	4.9	4.9	4.9	4.9	4.9	0
3	5.05	5	5	5	5.01	0.021	5	5	5	5	5	0	5	5	5	5.05	5.01	0.025
Mean					**4.99**	**0.022**	Mean				**5.01**	**0.013**	Mean				**4.96**	**0.017**
Mortar with treated FA-APC by DI water 10%																		
1	5	5	5	5	5	0	5.05	5	5	4.95	5	0.040	5	5	5	5	5	0
2	5.05	5.05	5.05	5.05	5.05	0	5	5	5	5	5	0	5.05	5	5	4.95	5	0.040
3	5	5	5	5	5	0	5	5	5	5	5	0	5	5	5	5	5	0
Mean					**5.01**	**0**	Mean				**5**	**0.013**	Mean				**5**	**0.013**
Mortar with treated FA-APC by DI water 15%																		
1	5.05	5.05	5.05	5.05	5.05	0	5	5	5	5	5	0	5	5	5.05	5.05	5.02	0.028
2	5.1	5.1	5.1	5.1	5.1	0	5	5	5	5	5	0	5	5	5	5	5	0
3	5.05	5.05	5	5	5.02	0.025	5	5	5	5	5	0	5	5	5	5	5	0
Mean					**5.05**	**0.008**	Mean				**5**	**0**	Mean				**5.00**	**0.009**

Table D2-2 Dimension and tolerance of mortar with treated FA-APC by DI water

No.	Width (cm)						Length (cm)						Height (cm)					
	1	**2**	**3**	**4**	**Mean**	**SD**	**1**	**2**	**3**	**4**	**Mean**	**SD**	**1**	**2**	**3**	**4**	**Mean**	**SD**
Mortar with treated FA-APC by DI water 20%																		
1	5	5	5	5	5	0	5.1	5.1	5.1	5.1	5.1	0	5	5	5	5	5	0
2	5	5	5.05	5.05	5.02	0.025	5	5	5	5	5	0	5	5	5	5	5	0
3	4.95	4.95	4.95	5.05	4.97	0.043	5	4.95	4.95	4.95	4.96	0.025	5	5	5	5	5	0
Mean					**5**	**0.022**	Mean				**5.02**	**0.008**	Mean				**5**	**0**

Table D3-1 Dimension and tolerance of mortar with treated FA-APC by 0.01M HNO_3

No.	Width (cm)						Length (cm)						Height (cm)					
	1	2	3	4	Mean	SD	1	2	3	4	Mean	SD	1	2	3	4	Mean	SD
Mortar with treated FA-APC by 0.01M HNO_3 5%																		
1	5	5	5.05	5.05	5.02	0.025	5.05	5.05	5.1	5.1	5.07	0.028	5	5	4.95	4.95	4.98	0.062
2	5	4.95	4.95	4.95	4.96	0.021	5	5	5	5	5	0	5.05	5	5	4.9	5	0
3	5	4.95	4.95	4.95	4.96	0.021	4.9	4.9	5	5.05	4.96	0.075	5	5	5	5	5	0
Mean					**4.98**	**0.022**	Mean				**5.01**	**0.034**	Mean				**4.99**	**0.020**
Mortar with treated FA-APC by 0.01M HNO_3 10%																		
1	4.95	4.95	4.95	4.95	4.95	0	4.9	4.95	5.05	5.1	5	0.091	5.05	5.05	5.05	5.05	5.07	0.028
2	5	5.05	5.05	5.05	5.03	0.021	5.05	5.05	5.05	5.05	5.05	0	5.05	5.05	5.1	5.1	5	0
3	5.05	5.05	5.05	5.05	5.05	0	5	5	5	5	5	0	5	5	5	5	5	0
Mean					**5.01**	**0.007**	Mean				**5.01**	**0.030**	Mean				**5.02**	**0.009**
Mortar with treated FA-APC by 0.01M HNO_3 15%																		
1	5	5	4.95	4.95	4.975	0.025	5	5	5	5	5	0	5	5	5	5	5	0
2	4.95	4.9	4.9	4.85	4.9	0.035	4.95	4.95	4.95	4.95	4.95	0	5	5	5	5	5.01	0.025
3	5.1	5.05	5.05	5.05	5.0625	0.021	5.05	5	5	5	5.01	0.025	5.05	5	5	5	5.01	0.025
Mean					**4.97**	**0.027**	Mean				**4.98**	**0.008**	Mean				**5.00**	**0.016**

Table D3-2 Dimension and tolerance of mortar with treated FA-APC by 0.01M HNO_3

No.	Width (cm)						Length (cm)						Height (cm)					
	1	2	3	4	Mean	SD	1	2	3	4	Mean	SD	1	2	3	4	Mean	SD
Mortar with treated FA-APC by 0.01M HNO_3 20%																		
1	5	4.95	4.95	4.95	4.96	0.021	5	5	5	5	5	0	5	5	5	5	5.02	0.0288
2	5.05	5.05	5.05	5.05	5.05	0	5	5	5	5	5	0	5	5.05	5.05	5	5.03	0.025
3	4.9	4.9	4.9	4.95	4.91	0.021	5	5	5	5	5	0	5	5.05	5.05	5.05	5.03	0.025
Mean					**4.97**	**0.014**	Mean				**5**	**0**	Mean				**5.03**	**0.026**

Table D4-1 Dimension and tolerance of mortar with treated FA-APC by 0.1M HNO_3

No.	Width (cm)						Length (cm)						Height (cm)					
	1	2	3	4	Mean	SD	1	2	3	4	Mean	SD	1	2	3	4	Mean	SD
Mortar with treated FA-APC by 0.1M HNO_3 5%																		
1	5	5	5	5.05	5.01	0.021	5.1	5.1	5.1	5.1	5.1	0	5	5	5	5	5	0
2	4.95	4.95	5	4.95	4.96	0.023	5.1	5.1	5.1	5.1	5.1	0	5	5	5	5	5	0
3	4.95	5	5	5	4.98	0.021	4.9	4.9	4.95	5	4.93	0.047	5	5	5	5	5	0
Mean					**4.98**	**0.022**	Mean				**5.04**	**0.015**	Mean				**5**	**0**
Mortar with treated FA-APC by 0.1M HNO_3 10%																		
1	5	5	5.05	5.05	5.02	0.025	4.95	4.95	4.95	4.95	4.95	0	5	5	5	5	4.95	0
2	5	5	5	5	5	0	5.1	5.1	5.05	5.05	5.07	0.028	4.95	4.95	4.95	4.95	4.97	0.028
3	5	5.05	5.05	5.05	5.03	0.021	5	5	5.05	5.1	5.03	0.047	5	5	4.95	4.95	4.97	0.028
Mean					**5.02**	**0.015**	Mean				**5.02**	**0.025**	Mean				**4.96**	**0.019**
Mortar with treated FA-APC by 0.1M HNO_3 15%																		
1	5	5.05	5.05	5.1	5.05	0.035	4.95	5	5	5	4.98	0.025	5	5	5	5	5.01	0.025
2	5	5	5	5	5	0	5	5	5	5	5	0	5.05	5	5	5	4.95	0.040
3	5	5	5	5	5	0	5.05	5.05	5.05	5.05	5.05	0	4.9	4.95	4.95	5	4.95	0.040
Mean					**5.01**	**0.011**	Mean				**5.01**	**0.008**	Mean				**4.97**	**0.035**

Table D4-2 Dimension and tolerance of mortar with treated FA-APC by 0.1M HNO_3

No.	Width (cm)						Length (cm)						Height (cm)					
	1	2	3	4	Mean	SD	1	2	3	4	Mean	SD	1	2	3	4	Mean	SD
Mortar with treated FA-APC by 0.1M HNO_3 20%																		
1	5.05	5.05	5.05	5.05	5.05	0	4.9	4.9	4.9	4.95	4.91	0.025	5	5	5	5	4.98	0.025
2	5.05	5.05	5.05	5.05	5.05	0	5	5	5.05	5.05	5.02	0.028	5	5	5	4.95	5	0
3	5.05	5	4.95	4.9	4.97	0.055	5.1	5.1	5.1	5.1	5.1	0	5	5	5	5	5	0
Mean					**5.02**	**0.018**	Mean				**5.01**	**0.017**	Mean				**4.99**	**0.008**

Table D5-1 Dimension and tolerance of mortar with treated FA-APC by 0.1M Na_2CO_3

No.	Width (cm)						Length (cm)						Height (cm)					
	1	2	3	4	Mean	SD	1	2	3	4	Mean	SD	1	2	3	4	Mean	SD
Mortar with treated FA-APC by 0.1M Na_2CO_3 5%																		
1	5	5	5	5	5	0	5	5	5.05	5.05	5.02	0.028	5	5.05	5.05	5.05	5	0
2	5.1	5.1	5.05	5.05	5.07	0.025	5	5	5.05	5.05	5.02	0.028	5	5	5	5	5	0
3	5	5	5	5	5	0	4.9	4.9	4.9	4.95	4.91	0.025	5	5	5	5	5	0
Mean					**5.02**	**0.008**	Mean				**4.98**	**0.027**	Mean				**5**	**0**
Mortar with treated FA-APC by 0.1M Na_2CO_3 10%																		
1	5	5	5	5	5	0	5.05	5.05	5.05	5.05	5.05	0	5.05	5.05	5.05	5.05	5.05	0.040
2	5	5	5	5	5	0	5	5	4.95	4.95	4.975	0.028	5	5.05	5.05	5.1	5.025	0.064
3	5	5	5	5	5	0	5	5	5.05	5.05	5.025	0.028	5.1	5.05	5	4.95	5.025	0.064
Mean					**5**	**0**	Mean				**5.01**	**0.019**	Mean				**5.03**	**0.056**
Mortar with treated FA-APC by 0.1M Na_2CO_3 15%																		
1	5	4.95	4.95	4.95	4.96	0.021	5	5.05	5.05	5.05	5.03	0.025	5	5	5	5	5	0
2	5	5	5	5	5	0	5.05	5	5	5	5.01	0.025	5	5	5	5	5	0
3	4.95	4.95	5	5	4.97	0.025	5.05	5.05	5.05	5.05	5.05	0	5	5	5	5	5	0
Mean					**4.97**	**0.015**	Mean				**5.03**	**0.016**	Mean				**5**	**0**

Table D5-2 Dimension and tolerance of mortar with treated FA-APC by 0.1M Na_2CO_3

No.	Width (cm)						Length (cm)						Height (cm)					
	1	2	3	4	Mean	SD	1	2	3	4	Mean	SD	1	2	3	4	Mean	SD
Mortar with treated FA-APC by 0.1M Na_2CO_3 20%																		
1	5	5	5	5	5	0	5.05	5.05	5.05	5.05	5.05	0	5	5	5	5	5.05	0
2	5	5	5	5	5	0	5.05	5.05	5.05	5.05	5.05	0	5.05	5.05	5.05	5.05	5	0
3	5	5	5	5	5	0	4.95	4.95	4.95	5	4.96	0.025	5	5	5	5	5	0
Mean					5	0	Mean				5.02	0.008	Mean				5.01	0

Table D6-1 Dimension and tolerance of mortar with treated FA-APC by 0.25M Na_2CO_3

No.	Width (cm)						Length (cm)						Height (cm)					
	1	2	3	4	Mean	SD	1	2	3	4	Mean	SD	1	2	3	4	Mean	SD
Mortar with treated FA-APC by 0.25M Na_2CO_3 5%																		
1	5	5	5	5	5	0	5	5	5	5	5	0	5	5	5	5	5	0
2	4.95	5	5	5	4.98	0.021	4.95	5	5	5	4.98	0.025	5	5	5	5	5	0
3	5	5	5	5	5	0	5.05	5	5	5	5.01	0.025	5	5	5	5	5	0
Mean					**4.99**	**0.007**	Mean				**5**	**0.016**	Mean				**5**	**0**
Mortar with treated FA-APC by 0.25M Na_2CO_3 10%																		
1	4.9	4.95	5	5	4.96	0.041	5.05	5.05	5.05	5.05	5.05	0	5	5	5	5	5.02	0.028
2	5	5	5	5	5	0	5.1	5.05	5.05	5.05	5.06	0.025	5	5	5.05	5.05	5	0
3	5	5	5	5	5	0	5	5	4.95	4.95	4.97	0.028	5	5	5	5	5	0
Mean					**4.98**	**0.013**	Mean				**5.02**	**0.017**	Mean				**5.00**	**0.009**
Mortar with treated FA-APC by 0.25M Na_2CO_3 15%																		
1	5	5	5	5	5	0	5	5	5	5	5	0	5	5	5	5	5	0
2	5	5	5	5	5	0	5	5	5	5	5	0	5	5	5	5	5	0
3	5	5	5	5	5	0	5	5	5	5	5	0	5	5	5	5	5	0
Mean					**5**	**0**	Mean				**5**	**0**	Mean				**5**	**0**

Table D6-2 Dimension and tolerance of mortar with treated FA-APC by 0.25M Na_2CO_3

No.	Width (cm)						Length (cm)						Height (cm)					
	1	2	3	4	Mean	SD	1	2	3	4	Mean	SD	1	2	3	4	Mean	SD
Mortar with treated FA-APC by 0.25M Na_2CO_3 20%																		
1	4.95	4.95	4.95	4.95	4.95	0	5	5	5	5.05	5.01	0.025	4.9	4.95	4.95	4.95	5.01	0.025
2	4.8	4.9	4.9	4.9	4.87	0.043	5.05	5.05	5.05	5.05	5.05	0	5	5	5	5.05	4.98	0.025
3	4.95	4.95	5	5.05	4.98	0.041	5	5	5	5	5	0	4.95	5	5	5	4.98	0.025
Mean					**4.93**	**0.028**	Mean				**5.02**	**0.008**	Mean				**4.99**	**0.025**

Table D7-1 Dimension and tolerance of mortar with untreated FA-LF

No.	Width (cm)						Length (cm)						Height (cm)					
	1	2	3	4	Mean	SD	1	2	3	4	Mean	SD	1	2	3	4	Mean	SD
Mortar with untreated FA-LF 5%																		
1	5	5	5.1	4.95	5.01	0.054	5	5	5	5.05	5.01	0.025	5.05	5	4.95	4.95	4.98	0.047
2	4.95	5	5.1	5	5.01	0.054	4.95	4.95	4.95	5	4.96	0.025	5	4.95	5	5	4.98	0.025
3	5	4.95	5	5	4.98	0.021	5	5	4.95	5.1	5.01	0.062	5	5	5	4.95	4.98	0.025
Mean					**5.00**	**0.043**	Mean				**4.99**	**0.037**	Mean				**4.98**	**0.032**
Mortar with untreated FA-LF 10%																		
1	5	5.1	5.1	5	5.05	0.05	5	5	4.95	4.8	4.93	0.094	5	4.95	4.95	4.95	4.96	0.025
2	5.1	5	5	4.95	5.01	0.054	4.95	5	5	5.05	5	0.040	5	5	5	5.05	5.01	0.025
3	4.95	5	5	5.1	5.01	0.054	5	4.95	5	5.05	5	0.040	5.05	5.1	5.1	5.05	5.07	0.028
Mean					**5.02**	**0.052**	Mean				**4.97**	**0.058**	Mean				**5.01**	**0.026**
Mortar with untreated FA-LF 15%																		
1	5	5	5	5	5	0	4.95	5	5	5	4.98	0.025	4.95	4.95	5	5.05	4.98	0.047
2	4.95	4.95	5	5.05	4.98	0.041	5	5	4.95	4.95	4.97	0.028	5	5	5	5.05	5.01	0.025
3	5	5	5.05	5.05	5.02	0.025	5.05	5.05	5	5	5.02	0.028	5	5	4.95	5	4.98	0.025
Mean					**5.00**	**0.022**	Mean				**4.99**	**0.027**	Mean				**4.99**	**0.032**

Table D7-2 Dimension and tolerance of mortar with untreated FA-LF

No.	Width (cm)						Length (cm)						Height (cm)					
	1	2	3	4	Mean	SD	1	2	3	4	Mean	SD	1	2	3	4	Mean	SD
Mortar with untreated FA-LF 20%																		
1	5	5.05	5	5	5.0125	0.021	5	4.95	4.9	4.9	4.93	0.047	5	5	5	5	5	0
2	5	4.95	5	5.05	5	0.035	5	5.05	5	5	5.01	0.025	5.05	5	5	5	5.01	0.025
3	5.1	4.95	4.95	5	5	0.061	5	5	5	5	5	0	5	5	5	5	5	0
Mean					**5.00**	**0.039**	Mean				**4.98**	**0.024**	Mean				**5.00**	**0.008**

Table D8-1 Dimension and tolerance of mortar with treated FA-LF by DI water

No.	Width (cm)						Length (cm)						Height (cm)					
	1	2	3	4	Mean	SD	1	2	3	4	Mean	SD	1	2	3	4	Mean	SD
Mortar with treated FA-LF by DI water 5%																		
1	5	5	5.05	5.05	5.02	0.025	5	5	5	5.1	5.02	0.05	4.9	4.95	4.95	4.95	4.93	0.025
2	5	5	5	4.95	4.98	0.021	5	5	5	5	5	0	5	5	5.05	5.05	5.02	0.028
3	5.05	5	4.95	4.95	4.98	0.041	4.9	4.95	5	5.05	4.97	0.064	4.95	5	5	5	4.98	0.025
Mean					**5**	**0.029**	**Mean**				**5**	**0.038**	**Mean**				**4.98**	**0.026**
Mortar with treated FA-LF by DI water 10%																		
1	4.95	4.95	4.95	5	4.96	0.021	5.1	5.1	5.05	5	5.06	0.047	5	5	5	4.95	4.98	0.025
2	5	5	5.05	5.05	5.02	0.025	5	5	5	5	5	0	5.05	5.05	5.05	5.1	5.06	0.025
3	5.05	5.05	5.05	5.05	5.05	0	5	4.95	4.95	4.9	4.95	0.040	4.95	5	5	5	4.98	0.025
Mean					**5.01**	**0.015**	**Mean**				**5.00**	**0.029**	**Mean**				**5.01**	**0.025**
Mortar with treated FA-LF by DI water 15%																		
1	5.1	5.1	5.1	5.1	5.1	0	5	5	4.95	5	4.98	0.025	4.95	5	5	5.05	5	0.040
2	5.1	5.1	5.1	5.1	5.1	0	5	5.05	5.05	5.05	5.03	0.025	5	5	5.05	5.1	5.03	0.047
3	4.95	4.95	4.95	5	4.96	0.021	5.05	5.1	5.1	5.1	5.08	0.025	5	5	5	5	5	0
Mean					**5.05**	**0.007**	**Mean**				**5.03**	**0.025**	**Mean**				**5.01**	**0.029**

Table D8-2 Dimension and tolerance of mortar with treated FA-LF by DI water

No.	Width (cm)						Length (cm)						Height (cm)					
	1	2	3	4	Mean	SD	1	2	3	4	Mean	SD	1	2	3	4	Mean	SD
Mortar with treated FA-LF by DI water 20%																		
1	5	4.95	4.95	5	4.97	0.025	4.95	5	5	5	4.98	0.025	5	5	5	5	5	0
2	5	5.05	5.05	5.05	5.03	0.021	5	4.95	5	5	4.98	0.025	5	5	5	5	5	0
3	4.95	5	4.95	5	4.97	0.025	5.05	5.05	5.1	5.05	5.06	0.025	5	5	5	5	5	0
Mean					**4.99**	**0.023**	Mean				**5.01**	**0.025**	Mean				**5**	**0**

Table D9-1 Dimension and tolerance of mortar with treated FA-LF by 0.01M HNO_3

No.	Width (cm)						Length (cm)						Height (cm)					
	1	2	3	4	Mean	SD	1	2	3	4	Mean	SD	1	2	3	4	Mean	SD
Mortar with treated FA-LF by 0.01M HNO_3 5%																		
1	4.95	5	5	5	4.98	0.021	5	5	5.05	5.05	5.02	0.028	5	5	5	5.05	5.01	0.025
2	5	5	5	5	5	0	5.1	5.05	5	5	5.03	0.047	4.95	5	4.95	4.95	4.96	0.025
3	5.05	5.05	5.05	5.05	5.05	0	5	5	4.95	4.95	4.97	0.028	5	5.05	5	5.05	5.02	0.028
Mean					**5.01**	**0.007**	Mean				**5.01**	**0.035**	Mean				**5**	**0.026**
Mortar with treated FA-LF by 0.01M HNO_3 10%																		
1	5.05	5	5	5.1	5.03	0.041	5	4.95	4.95	4.95	4.96	0.025	5.1	5.1	5.05	5	5.06	0.047
2	5	5	5.05	5.05	5.02	0.025	5	5	5	5.05	5.01	0.025	5.05	5.05	5.05	5	5.03	0.025
3	4.95	5	5.05	5	5	0.035	4.95	4.95	5	5	4.97	0.028	4.95	5	5	5	4.98	0.025
Mean					**5.02**	**0.033**	Mean				**4.98**	**0.026**	Mean				**5.02**	**0.032**
Mortar with treated FA-LF by 0.01M HNO_3 15%																		
1	5.05	5	5.05	5	5.02	0.025	5	5	4.95	4.95	4.97	0.028	5	5	5	5	5	0
2	5.05	5.05	5.05	5.05	5.05	0	5	5	5	5.05	5.01	0.025	5	5	4.95	4.95	4.97	0.028
3	5.05	5	4.95	5	5	0.035	4.95	5	5	5	4.98	0.025	5.1	5.1	5	5	5.05	0.057
Mean					**5.025**	**0.020**	Mean				**4.99**	**0.026**	Mean				**5.00**	**0.028**

Table D9-2 Dimension and tolerance of mortar with treated FA-LF by 0.01M HNO_3

No.	Width (cm)						Length (cm)						Height (cm)					
	1	2	3	4	Mean	SD	1	2	3	4	Mean	SD	1	2	3	4	Mean	SD
Mortar with treated FA-LF by 0.01M HNO_3 20%																		
1	5.05	5	5	5	5.01	0.021	5	5.05	5.05	5.05	5.03	0.025	5	5	4.95	5	4.98	0.025
2	4.95	4.95	5	5	4.97	0.025	5	5	5.05	5.05	5.02	0.028	5.1	5.05	5	5	5.03	0.047
3	5	5	5.1	5.05	5.03	0.041	4.95	4.95	5	5	4.97	0.028	4.95	4.95	4.95	4.95	4.95	0
Mean					**5.00**	**0.029**	Mean				**5.01**	**0.027**	Mean				**4.99**	**0.024**

Table D10-1 Dimension and tolerance of mortar with treated FA-LF by 0.1M HNO_3

No.	Width (cm)						Length (cm)						Height (cm)					
	1	2	3	4	Mean	SD	1	2	3	4	Mean	SD	1	2	3	4	Mean	SD
Mortar with treated FA-LF by 0.1M HNO_3 5%																		
1	5	5	5.05	5.05	5.02	0.025	4.95	4.95	5	5	4.97	0.028	4.95	5	5	5	4.98	0.025
2	5	5	5	5	5	0	5	5.05	5	4.95	5	0.040	5	5.05	5.05	5	5.02	0.028
3	5.05	5.05	5.05	5.05	5.05	0	5	5	5.1	5.1	5.05	0.057	5	5	5	5	5	0
Mean					**5.02**	**0.008**	Mean				**5.00**	**0.042**	Mean				**5.00**	**0.017**
Mortar with treated FA-LF by 0.1M HNO_3 10%																		
1	5.05	5	4.95	4.95	4.98	0.041	4.9	4.95	5	5	4.96	0.047	5	5	5.05	5.05	5.02	0.028
2	5.05	5.05	5	5	5.02	0.025	5	5	5.05	5	5.01	0.025	5	4.95	4.95	4.95	4.96	0.025
3	5	5	5.05	5	5.01	0.021	5	5.05	5.1	5.15	5.07	0.064	5.1	5.1	5.05	5.05	5.07	0.028
Mean					**5.00**	**0.029**	Mean				**5.01**	**0.045**	Mean				**5.02**	**0.027**
Mortar with treated FA-LF by 0.1M HNO_3 15%																		
1	5.05	5.05	5.05	5.05	5.05	0	5	5	5.05	5.05	5.02	0.028	5.05	5	5	5	5.01	0.025
2	5.05	5.05	5.05	5.05	5.05	0	4.95	4.95	4.95	5.05	4.97	0.05	5	5	5	4.95	4.98	0.025
3	5	5	4.95	4.95	4.97	0.025	5	5	5	5	5	0	5	5.05	5.05	5.05	5.03	0.025
Mean					**5.02**	**0.008**	Mean				**5**	**0.026**	Mean				**5.01**	**0.025**

Table D10-2 Dimension and tolerance of mortar with treated FA-LF by 0.1M HNO_3

No.	Width (cm)						Length (cm)						Height (cm)					
	1	**2**	**3**	**4**	**Mean**	**SD**	**1**	**2**	**3**	**4**	**Mean**	**SD**	**1**	**2**	**3**	**4**	**Mean**	**SD**
Mortar with treated FA-LF by 0.1M HNO_3 20%																		
1	5.05	5	5	5	5.01	0.021	4.95	5	5.05	5.05	5.01	0.047	5	5	5	5	5	0
2	5	5	4.95	4.95	4.97	0.025	5.05	5	5	5	5.01	0.025	4.95	4.95	5	5	4.97	0.028
3	5.05	5.05	5	5	5.02	0.025	5.05	5	5	5	5.01	0.025	5	5	5	5	5	0
Mean					**5.00**	**0.023**	Mean				**5.01**	**0.032**	Mean				**4.99**	**0.009**

Table D11-1 Dimension and tolerance of mortar with treated FA-LF by 0.1M Na_2CO_3

No.	Width (cm)						Length (cm)						Height (cm)					
	1	2	3	4	Mean	SD	1	2	3	4	Mean	SD	1	2	3	4	Mean	SD
Mortar with treated FA-LF by 0.1M Na_2CO_3 5%																		
1	5	5	5	5	5	0	5.05	5	5	5	5.01	0.025	5	5	5	5	5	0
2	5	5	5	5	5	0	5	4.95	4.95	4.95	4.96	0.025	5	4.95	4.95	4.9	4.95	0.040
3	5	5	5	5	5	0	5	5	5	5	5	0	5	5	5.05	5.05	5.02	0.028
Mean					**5**	**0**	Mean				**4.99**	**0.016**	Mean				**4.99**	**0.023**
Mortar with treated FA-LF by 0.1M Na_2CO_3 10%																		
1	5	5.05	5.05	5.1	5.05	0.035	5	5	5	5.05	5.01	0.025	5.05	5.05	5	5	5.02	0.028
2	5	4.95	4.95	4.95	4.96	0.021	5	5	4.95	4.95	4.97	0.028	4.95	5	5	5	4.98	0.025
3	4.95	5	5	5.05	5	0.035	5	5	5.05	5	5.01	0.025	4.95	5	5	5	4.98	0.025
Mean					**5.00**	**0.030**	Mean				**5**	**0.026**	Mean				**5**	**0.026**
Mortar with treated FA-LF by 0.1M Na_2CO_3 15%																		
1	5	5.05	5.05	5.05	5.03	0.021	5	5	5	5	5	0	5	5	5	5.05	5.01	0.025
2	5	5	5.05	5.05	5.02	0.025	4.95	4.95	5	5.05	4.98	0.047	5	5	5	5	5	0
3	4.95	4.95	4.95	5	4.96	0.021	5.05	5	5	5	5.01	0.025	4.95	4.95	4.95	5	4.96	0.025
Mean					**5.00**	**0.022**	Mean				**5**	**0.024**	Mean				**4.99**	**0.016**

Table D11-2 Dimension and tolerance of mortar with treated FA-LF by 0.1M Na_2CO_3

No.	Width (cm)						Length (cm)						Height (cm)					
	1	2	3	4	Mean	SD	1	2	3	4	Mean	SD	1	2	3	4	Mean	SD
Mortar with treated FA-LF by 0.1M Na_2CO_3 20%																		
1	5	5	5	5	5	0	5.05	5	5	5	5.01	0.025	5	5	5.05	5.05	5.02	0.028
2	5	4.95	4.95	4.95	4.96	0.021	5	5	5	5	5	0	5.1	5.1	5.1	5.1	5.1	0
3	5	5	5	5.05	5.01	0.021	5.05	5	5	5	5.01	0.025	5	4.95	4.95	4.95	4.96	0.025
Mean					**4.99**	**0.014**	Mean				**5.00**	**0.016**	Mean				**5.02**	**0.017**

Table D12-1 Dimension and tolerance of mortar with treated FA-LF by 0.25M Na_2CO_3

No.	Width (cm)						Length (cm)						Height (cm)					
	1	2	3	4	Mean	SD	1	2	3	4	Mean	SD	1	2	3	4	Mean	SD
Mortar with treated FA-LF by 0.25M Na_2CO_3 5%																		
1	5	5	5	5	5	0	5	5	5.05	5.05	5.025	0.028	5	5	5	5	5	0
2	5	5	5.05	5.05	5.02	0.025	4.95	5	5	5	4.9875	0.025	5	5	5	5	5	0
3	5	5	5	5	5	0	5	5	5.05	5.05	5.025	0.028	5	5	5.05	5.05	5.025	0.028
Mean					**5.00**	**0.008**	Mean				**5.01**	**0.027**	Mean				**5.00**	**0.009**
Mortar with treated FA-LF by 0.25M Na_2CO_3 10%																		
1	4.95	5	5	5.05	5	0.035	5	5	5	4.95	4.98	0.025	5	5	5	5	5	0
2	4.95	4.95	5	5	4.97	0.025	5	5	5.05	5.05	5.02	0.028	5	5	5	5	5	0
3	5	5	5	5.05	5.01	0.021	4.95	5	5.05	5.1	5.02	0.064	5	5	5	5	5	0
Mean					**4.99**	**0.027**	Mean				**5.01**	**0.039**	Mean				**5**	**0**
Mortar with treated FA-LF by 0.25M Na_2CO_3 15%																		
1	5	5	5.05	5.05	5.02	0.025	5	5	5.05	5.05	5.02	0.028	5	5	4.95	4.9	4.96	0.047
2	4.95	5	5	4.95	4.97	0.025	5.1	5.05	5	5	5.03	0.047	5.1	5.05	5.05	5	5.05	0.040
3	5.1	5.1	5	5	5.05	0.05	5	5	4.95	4.95	4.97	0.028	4.95	5	5	5.05	5	0.040
Mean					**5.01**	**0.033**	Mean				**5.01**	**0.035**	Mean				**5.00**	**0.043**

Table D12-2 Dimension and tolerance of mortar with treated FA-LF by 0.25M Na_2CO_3

No.	Width (cm)						Length (cm)						Height (cm)					
	1	2	3	4	Mean	SD	1	2	3	4	Mean	SD	1	2	3	4	Mean	SD
Mortar with treated FA-LF by 0.25M Na_2CO_3 20%																		
1	4.95	4.95	4.95	5	4.96	0.021	4.95	5	5	5	4.98	0.025	5	5	5	5	5	0
2	5	5	5	5.05	5.01	0.021	5	5	5	5	5	0	5.05	5.05	5.05	5	5.03	0.025
3	4.95	5	5	5	4.98	0.021	5.05	5	5	5	5.01	0.025	5	5	5	5	5	0
Mean					**4.98**	**0.021**	Mean				**5**	**0.016**	Mean				**5.01**	**0.008**

Table D13 Dimension and tolerance of mortar without MSWI FA

No.	Width (cm)						Length (cm)						Height (cm)					
	1	**2**	**3**	**4**	**Mean**	**SD**	**1**	**2**	**3**	**4**	**Mean**	**SD**	**1**	**2**	**3**	**4**	**Mean**	**SD**
1	4.85	5	4.9	5	4.93	0.064	5	5	4.95	4.9	4.96	0.047	5	4.9	4.9	5	4.95	0.057
2	5	5.1	5.1	5.1	5.07	0.043	5	5	5	4.95	4.98	0.025	5	5	5	5.1	5.02	0.05
3	5	5.05	5.05	5.1	5.05	0.035	4.9	4.8	4.8	4.9	4.85	0.057	4.9	5	4.95	5	4.96	0.047
Mean					**5.02**	**0.047**	Mean				**4.93**	**0.043**	Mean				**4.97**	**0.051**

Table D14-1 Dimension and tolerance of mortar with FA-LN

No.	Width (cm)						Length (cm)						Height (cm)					
	1	2	3	4	Mean	SD	1	2	3	4	Mean	SD	1	2	3	4	Mean	SD
Mortar with FA-LN 5%																		
1	5	5	5	5	5	0	5.05	5	5	5	5.01	0.025	4.95	4.95	5	5	4.97	0.028
2	5	5	5	5	5	0	5	5	5.05	5.05	5.02	0.028	5	5	5.05	5.1	5.03	0.047
3	5	5	5	5	5	0	4.95	5	5	5	4.98	0.025	5	5	5	5	5	0
Mean					**5**	**0**	Mean				**5.00**	**0.026**	Mean				**5.00**	**0.025**
Mortar with FA-LN 10%																		
1	5	5	5	5.05	5.01	0.021	5	5.05	5.05	5.05	5.03	0.025	5	4.9	4.9	5	4.95	0.057
2	4.95	5	4.95	4.95	4.96	0.021	5	5	5	5.05	5.01	0.025	5	5	5	5.1	5.02	0.05
3	5.1	5.05	5.05	5.05	5.06	0.021	4.95	4.95	4.95	4.95	4.95	0	4.9	5	4.95	5	4.96	0.047
Mean					**5.01**	**0.021**	Mean				**5**	**0.016**	Mean				**4.97**	**0.051**

Table D14-2 Dimension and tolerance of mortar with FA-LN

No.	Width (cm)						Length (cm)						Height (cm)					
	1	2	3	4	Mean	SD	1	2	3	4	Mean	SD	1	2	3	4	Mean	SD
Mortar with FA-LN 15%																		
1	5	5	4.95	4.95	4.97	0.025	5	5	5	5	5	0	5.05	5	5	5	5.01	0.025
2	5.1	5.05	5	5.05	5.05	0.040	5.05	5	5	5	5.01	0.025	4.95	5	5.05	5.05	5.01	0.047
3	5.05	5	5	5	5.01	0.021	5	5	5	5	5	0	5	5	5	5	5	0
Mean					**5.01**	**0.029**	Mean				**5.00**	**0.008**	Mean				**5.00**	**0.024**
Mortar with FA-LN 20%																		
1	5.05	5.05	5.05	5.05	5.05	0	5	5	5	4.95	4.98	0.025	5.05	5	5	5.05	5.02	0.028
2	5	5	5	5	5	0	5	5	5	5.05	5.01	0.025	5	4.95	5	5	4.98	0.025
3	5.05	5.05	5.05	5	5.03	0.021	4.95	4.95	5	5	4.97	0.028	5	5.05	5	5	5.01	0.025
Mean					**5.02**	**0.007**	Mean				**4.99**	**0.026**	Mean				**5.00**	**0.026**

Table D15-1 Dimension and tolerance of mortar with FA-BT

No.	Width (cm)						Length (cm)						Height (cm)					
	1	2	3	4	Mean	SD	1	2	3	4	Mean	SD	1	2	3	4	Mean	SD
Mortar with FA-BT 5%																		
1	5.1	5.05	5	5	5.03	0.041	5	4.95	4.95	4.9	4.95	0.040	5	5	5	5	5	0
2	5	5	5	5	5	0	5.1	5.05	5.05	5.05	5.06	0.025	5	5	5	5	5	0
3	5	5	5.05	5.1	5.03	0.041	5	5	4.95	5	4.98	0.025	5	5	5	5	5	0
Mean					**5.02**	**0.027**	Mean				**5**	**0.030**	Mean				**5**	**0**
Mortar with FA-BT 10%																		
1	5	5	5	5	5	0	5.1	5.1	5.1	5.1	5.1	0	5	5	5	5	5	0
2	5	5	5	5	5	0	4.95	4.9	4.95	4.95	4.93	0.025	5	5	5	5	5	0
3	5	5	5	5	5	0	5	5	4.95	4.9	4.96	0.047	5	5	5	5	5	0
Mean					**5**	**0**	Mean				**5**	**0.024**	Mean				**5**	**0**
Mortar with FA-BT 15%																		
1	5.05	5.05	5.05	5.05	5.05	0	5	4.95	4.95	4.95	4.96	0.025	5.05	5.05	5	4.95	5.01	0.047
2	5	5	5	5.05	5.01	0.021	5	5	5	5	5	0	5	5	5	4.95	4.98	0.025
3	5.05	5.05	5.05	5	5.03	0.021	5	5	5	5	5	0	5	4.95	4.95	4.9	4.95	0.040
Mean					**5.03**	**0.014**	Mean				**4.98**	**0.008**	Mean				**4.98**	**0.037**

Table D15-2 Dimension and tolerance of mortar with FA-BT

No.	Width (cm)						Length (cm)						Height (cm)					
	1	2	3	4	Mean	SD	1	2	3	4	Mean	SD	1	2	3	4	Mean	SD
Mortar with FA-BT 20%																		
1	5.1	5.05	5.05	5.05	5.06	0.021	5	4.95	4.95	4.95	4.96	0.025	5	5	5	5	5	0
2	5	5	4.95	4.95	4.97	0.025	4.95	4.95	4.95	4.95	4.95	0	4.95	5	5.05	5.1	5.02	0.064
3	5.05	5.05	5	5	5.02	0.025	4.95	4.9	4.9	4.9	4.91	0.025	5	5	5	5	5	0
Mean					**5.02**	**0.023**	Mean				**4.94**	**0.016**	Mean				**5.00**	**0.021**

APPENDIX E

Compressive strength of mortar

Table E1 Compressive strength of mortar with untreated FA-APC

% replacement of fly ash	No.	Force (KN)	Area (mm^2)	Force (N)	Compressive strength (N/mm^2 or MPa)	Mean	SD
5%	1	58.80	2468	58800	23.81	**24.25**	**0.514**
	2	61.74	2487	61740	24.82		
	3	60.76	2518	60760	24.12		
10%	1	50.96	2480	50960	20.54	**21.43**	**1.031**
	2	53.90	2543	53900	21.19		
	3	57.82	2562	57820	22.56		
15%	1	49.00	2575	49000	19.02	**18.38**	**0.590**
	2	44.10	2468	44100	17.86		
	3	47.04	2575	47040	18.26		
20%	1	42.14	2499	42140	16.85	**15.90**	**0.936**
	2	40.18	2531	40180	15.87		
	3	38.22	2550	38220	14.98		

Table E2 Compressive strength of mortar with treated FA-APC by DI water

% replacement of fly ash	No.	Force (KN)	Area (mm^2)	Force (N)	Compressive strength (N/mm^2 or MPa)	Mean	SD
5%	1	71.54	2518	71540	28.40	**29.22**	**0.714**
	2	73.50	2487	73500	29.54		
	3	74.48	2506	74480	29.71		
10%	1	68.60	2500	68600	27.44	**27.22**	**0.380**
	2	67.62	2525	67620	26.78		
	3	68.60	2500	68600	27.44		
15%	1	68.60	2525	68600	27.16	**25.70**	**1.268**
	2	63.70	2550	63700	24.98		
	3	62.72	2512	62720	24.96		
20%	1	44.10	2550	44100	17.29	**20.20**	**3.317**
	2	49.00	2512	49000	19.50		
	3	58.80	2468	58800	23.81		

Table E3 Compressive strength of mortar with treated FA-APC by 0.01M HNO_3

% replacement of fly ash	No.	Force (KN)	Area (mm^2)	Force (N)	Compressive strength (N/mm^2 or MPa)	Mean	SD
5%	1	58.80	2550	58800	23.05	**23.54**	**1.177**
	2	61.74	2481	61740	24.88		
	3	55.86	2462	55860	22.68		
10%	1	54.88	2475	54880	22.17	**22.86**	**0.599**
	2	58.80	2543	58800	23.11		
	3	58.80	2525	58800	23.28		
15%	1	55.86	2487	55860	22.45	**20.53**	**1.789**
	2	49.00	2425	49000	20.20		
	3	48.02	2537	48020	18.92		
20%	1	48.02	2481	48020	19.35	**19.87**	**4.236**
	2	40.18	2525	40180	15.91		
	3	59.78	2456	59780	24.33		

Table E4 Compressive strength of mortar with treated FA-APC by 0.1M HNO_3

% replacement of fly ash	No.	Force (KN)	Area (mm^2)	Force (N)	Compressive strength (N/mm^2 or MPa)	Mean	SD
5%	1	73.50	2556	73500	28.75	**28.15**	**0.651**
	2	71.54	2533	71540	28.24		
	3	67.62	2462	67620	27.45		
10%	1	62.72	2487	62720	25.21	**26.17**	**0.912**
	2	66.64	2537	66640	26.26		
	3	68.60	2537	68600	27.03		
15%	1	60.76	2487	60760	24.42	**23.08**	**2.258**
	2	51.94	2537	51940	20.46		
	3	61.74	2537	61740	24.32		
20%	1	47.04	2480	47040	18.96	**19.84**	**0.783**
	2	51.94	2537	51940	20.46		
	3	50.96	2537	50960	20.08		

Table E5 Compressive strength of mortar with treated FA-APC by 0.1M Na_2CO_3

% replacement of fly ash	No.	Force (KN)	Area (mm^2)	Force (N)	Compressive strength (N/mm^2 or MPa)	Mean	SD
5%	1	71.54	2512	71540	28.47	**30.10**	**1.718**
	2	81.34	2550	81340	31.89		
	3	73.50	2456	73500	29.92		
10%	1	72.52	2525	72520	28.72	**28.53**	**3.087**
	2	78.40	2487	78400	31.51		
	3	63.70	2512	63700	25.35		
15%	1	51.94	2499	51940	20.77	**21.12**	**0.367**
	2	53.90	2506	53900	21.50		
	3	52.92	2512	52920	21.06		
20%	1	42.14	2525	42140	16.68	**15.87**	**0.779**
	2	38.22	2525	38220	15.13		
	3	39.2	2481	39200	15.79		

Table E6 Compressive strength of mortar with treated FA-APC by 0.25M Na_2CO_3

% replacement of fly ash	No.	Force (KN)	Area (mm^2)	Force (N)	Compressive strength (N/mm^2 or MPa)	Mean	SD
5%	1	71.54	2500	71540	28.61	**27.99**	**0.622**
	2	69.58	2487	69580	27.97		
	3	68.60	2506	68600	27.37		
10%	1	58.80	2506	58800	23.46	**25.00**	**1.894**
	2	68.64	2531	68640	27.11		
	3	60.76	2487	60760	24.42		
15%	1	41.16	2500	41160	16.46	**15.16**	**1.632**
	2	39.20	2500	39200	15.68		
	3	33.32	2500	33320	13.328		
20%	1	32.34	2481	32340	13.03	**13.31**	**0.390**
	2	32.34	2461	32340	13.13		
	3	34.30	2493	34300	13.75		

Table E7 Compressive strength of mortar with untreated FA-LF

% replacement of fly ash	No.	Force (KN)	Area (mm^2)	Force (N)	Compressive strength (N/mm^2 or MPa)	Mean	SD
5%	1	47.04	2512	47040	18.72	**17.90**	**0.752**
	2	44.10	2487	44100	17.728		
	3	43.12	2499	43120	17.24		
10%	1	40.18	2493	40180	16.11	**16.19**	**0.590**
	2	42.14	2506	42140	16.81		
	3	39.20	2506	39200	15.64		
15%	1	33.32	2493	33320	13.36	**13.98**	**0.626**
	2	36.26	2481	36260	14.61		
	3	35.28	2525	35280	13.97		
20%	1	28.42	2474	28420	11.48	**12.57**	**1.120**
	2	31.36	2506	31360	12.51		
	3	34.30	2500	34300	13.72		

Table E8 Compressive strength of mortar with treated FA-APC by DI water

% replacement of fly ash	No.	Force (KN)	Area (mm^2)	Force (N)	Compressive strength (N/mm^2 or MPa)	Mean	SD
5%	1	62.72	2525	62720	24.83	**24.82**	**1.120**
	2	64.68	2493	64680	25.93		
	3	58.80	2481	58800	23.69		
10%	1	32.34	2512	32340	12.87	**11.72**	**1.171**
	2	26.46	2512	26460	10.53		
	3	29.40	2499	29400	11.76		
15%	1	25.48	2543	25480	10.01	**9.50**	**0.647**
	2	22.54	2569	22540	8.77		
	3	24.50	2524	24500	9.70		
20%	1	14.7	2481	14700	5.92	**5.87**	**0.399**
	2	15.68	2512	15680	6.24		
	3	13.72	2518	13720	5.44		

Table E9 Compressive strength of mortar with treated FA-APC by 0.01M HNO_3

% replacement of fly ash	No.	Force (KN)	Area (mm^2)	Force (N)	Compressive strength (N/mm^2 or MPa)	Mean	SD
5%	1	26.46	2506	26460	10.55	**10.79**	**0.451**
	2	26.46	2518	26460	10.50		
	3	28.42	2512	28420	11.31		
10%	1	25.48	2499	25480	10.19	**9.53**	**0.861**
	2	21.56	2518	21560	8.55		
	3	24.50	2487	24500	9.84		
15%	1	21.56	2499	21560	8.62	**8.34**	**0.515**
	2	19.60	2531	19600	7.74		
	3	21.56	2493	21560	8.64		
20%	1	16.66	2525	16660	6.59	**6.51**	**0.219**
	2	16.66	2499	16660	6.66		
	3	15.68	2506	15680	6.25		

Table E10 Compressive strength of mortar with treated FA-APC by 0.1M HNO_3

% replacement of fly ash	No.	Force (KN)	Area (mm^2)	Force (N)	Compressive strength (N/mm^2 or MPa)	Mean	SD
5%	1	35.28	2499	35280	14.11	**13.24**	**0.763**
	2	32.34	2500	32340	12.93		
	3	32.34	2550	32340	12.68		
10%	1	24.50	2475	24500	9.89	**9.88**	**0.146**
	2	24.50	2518	24500	9.72		
	3	25.48	2543	25480	10.01		
15%	1	26.46	2518	26460	10.50	**9.74**	**0.745**
	2	22.54	2500	22540	9.01		
	3	24.50	2525	24500	9.70		
20%	1	23.52	2512	23520	9.36	**9.25**	**0.261**
	2	23.52	2493	23520	9.43		
	3	22.54	2518	22540	8.94		

Table E11 Compressive strength of mortar with treated FA-APC by 0.1M Na_2CO_3

% replacement of fly ash	No.	Force (KN)	Area (mm^2)	Force (N)	Compressive strength (N/mm^2 or MPa)	Mean	SD
5%	1	48.02	2506	48020	19.16	**19.11**	**0.272**
	2	48.02	2481	48020	19.35		
	3	47.04	2500	47040	18.81		
10%	1	36.26	2531	36260	14.32	**15.28**	**1.062**
	2	37.24	2468	37240	15.08		
	3	41.16	2506	41160	16.42		
15%	1	22.54	2518	22540	8.94	**9.00**	**0.429**
	2	21.56	2506	21560	8.60		
	3	23.52	2487	23520	9.45		
20%	1	12.74	2506	12740	5.08	**6.54**	**1.410**
	2	19.60	2481	19600	7.89		
	3	16.66	2512	16660	6.63		

Table E12 Compressive strength of mortar with treated FA-APC by 0.25M Na_2CO_3

% replacement of fly ash	No.	Force (KN)	Area (mm^2)	Force (N)	Compressive strength (N/mm^2 or MPa)	Mean	SD
5%	1	46.06	2512	46060	18.33	**16.92**	**1.368**
	2	42.14	2506	42140	16.81		
	3	39.20	2512	39200	15.60		
10%	1	34.30	2493	34300	13.75	**15.13**	**1.767**
	2	36.26	2499	36260	14.50		
	3	43.12	2518	43120	17.11		
15%	1	29.40	2525	29400	11.64	**12.21**	**0.494**
	2	31.36	2506	31360	12.51		
	3	31.36	2512	31360	12.48		
20%	1	22.54	2475	22540	9.10	**8.78**	**0.285**
	2	21.56	2506	21560	8.60		
	3	21.56	2499	21560	8.62		

Table E13 Compressive strength of mortar without MSWI FA

% replacement of fly ash	No.	Force (KN)	Area (mm^2)	Force (N)	Compressive strength (N/mm^2 or MPa)	Mean	SD
0%	1	92.12	2450	92120	37.59	**36.39**	**1.729**
	2	94.08	2531	94080	37.16		
	3	84.28	2449	84280	34.41		

Table E14 Compressive strength of mortar with FA-LN

% replacement of fly ash	No.	Force (KN)	Area (mm^2)	Force (N)	Compressive strength (N/mm^2 or MPa)	Mean	SD
5%	1	78.40	2506	78400	31.28	**30.40**	**1.038**
	2	73.50	2512	73500	29.25		
	3	76.44	2493	76440	30.65		
10%	1	70.56	2525	70560	27.94	**29.07**	**1.307**
	2	71.54	2487	71540	28.76		
	3	76.44	2505	76440	30.50		
15%	1	70.56	2487	70560	28.36	**29.04**	**1.263**
	2	71.54	2531	71540	28.26		
	3	76.44	2506	76440	30.49		
20%	1	64.68	2518	64680	25.68	**26.29**	**0.655**
	2	65.66	2506	65660	26.19		
	3	67.62	2506	67620	26.98		

Table E15 Compressive strength of mortar with FA-BT

% replacement of fly ash	No.	Force (KN)	Area (mm^2)	Force (N)	Compressive strength (N/mm^2 or MPa)	Mean	SD
5%	1	83.30	2493	83300	33.40	**32.25**	**1.221**
	2	78.40	2531	78400	30.97		
	3	81.34	2512	81340	32.37		
10%	1	81.34	2550	81340	31.89	**31.88**	**0.514**
	2	77.42	2468	77420	31.36		
	3	80.36	2481	80360	32.38		
15%	1	67.62	2506	67620	26.98	**27.07**	**0.272**
	2	68.60	2506	68600	27.37		
	3	67.62	2518	67620	26.84		
20%	1	56.84	2512	56840	22.62	**23.18**	**0.639**
	2	58.80	2462	58800	23.87		
	3	56.84	2468	56840	23.02		

APPENDIX F

Deviation from right angle

Table F1 Deviation from right angle of mortar with FA-APC

No.	Deviation from right angle (mm)			
	5%	10%	15%	20%
Mortar with untreated FA-APC				
1	1.0	1.0	0.0	1.0
2	0.0	1.0	0.0	1.0
3	0.0	2.0	1.0	1.0
Max	**1.0**	**2.0**	**1.0**	**1.0**
Mortar with treated FA-APC by DI water				
1	1.0	1.0	0.0	1.0
2	1.0	0.0	1.0	1.0
3	2.0	0.0	0.0	0.0
Max	**2.0**	**1.0**	**1.0**	**1.0**
Mortar with treated FA-APC by 0.01M HNO_3				
1	2.0	0.0	0.0	1.0
2	0.0	2.0	1.0	1.0
3	0.0	1.0	0.0	0.0
Max	**2.0**	**2.0**	**1.0**	**1.0**
Mortar with treated FA-APC by 0.1M HNO_3				
1	1.0	1.0	0.0	1.0
2	0.0	0.0	1.5	1.0
3	0.0	1.0	1.0	1.0
Max	**1.0**	**1.0**	**1.5**	**1.0**
Mortar with treated FA-APC by 0.25M Na_2CO_3				
1	0.0	0.0	1.0	1.0
2	0.0	2.0	0.0	0.0
3	1.0	1.0	1.0	2.0
Max	**1.0**	**2.0**	**1.0**	**2.0**

Table F2 Deviation from right angle of mortar with FA-LF

No.	Deviation from right angle (mm)			
	5%	10%	15%	20%
Mortar with untreated FA-LF				
1	1.0	0.0	1.0	0.0
2	2.0	1.5	2.0	0.0
3	0.0	0.0	1.0	1.0
Max	**2.0**	**1.5**	**2.0**	**1.0**
Mortar with treated FA-LF by DI water				
1	0.0	0.0	1.5	0.0
2	1.0	1.0	0.0	0.0
3	1.0	1.0	2.0	1.0
Max	**1.0**	**1.0**	**2.0**	**1.0**
Mortar with treated FA-LF by 0.01M HNO_3				
1	0.0	1.0	0.0	1.0
2	1.0	1.0	0.0	1.0
3	1.0	1.0	1.0	1.0
Max	**1.0**	**1.0**	**1.0**	**1.0**
Mortar with treated FA-LF by 0.1M HNO_3				
1	0.0	2.0	1.0	0.0
2	1.0	0.0	1.0	0.0
3	0.0	2.0	0.0	1.0
Max	**1.0**	**2.0**	**1.0**	**1.0**
Mortar with treated FA-LF by 0.25M Na_2CO_3				
1	0.0	0.5	2.0	0.0
2	0.0	0.0	0.0	1.0
3	1.0	0.5	1.0	2.0
Max	**1.0**	**0.5**	**2.0**	**2.0**

Table F3 Deviation from right angle of mortar with FA-LN and FA-BT

No.	Deviation from right angle (mm)			
	5%	**10%**	**15%**	**20%**
Mortar with FA-LN				
1	0.5	0.0	0.0	0.0
2	0.0	1.0	0.0	0.0
3	1.0	0.0	0.0	0.0
Max	**1.0**	**1.0**	**0.0**	**0.0**
Mortar with FA-BT				
1	1.0	0.0	0.0	0.0
2	0.0	0.0	0.0	0.0
3	1.0	1.0	0.0	1.0
Max	**1.0**	**1.0**	**0.0**	**1.0**

Table F4 Deviation from right angle of mortar without fly ash

No.	Deviation from right angle (mm)
	Mortar without fly ash
1	0.0
2	1.0
3	2.0
Max	2.0

APPENDIX G

Statistic

Table G1 ANOVA of K concentration in leachate from FA-LF

Anova: Two-Factor with Replication					
SUMMARY	DI water	0.01 HNO_3	0.1 HNO_3	0.1 Na_2CO_3	0.25 Na_2CO_3
Count	3	3	3	3	3
Sum	34282.5	31865.5	34286.8	35537.0	35261.5
Average	11427.5	10621.8	11428.9	11845.6	11753.8
Variance	316094.4	409229.9	1074452.5	136974.7	899446.5
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*
Columns	**2789204.6**	**4**	**697301.16**	**1.229288**	**0.35852**
Within	5672396.5	10	567239.65		
Total	8461601.2	14			

APPENDIX H

XRD result of fly ash

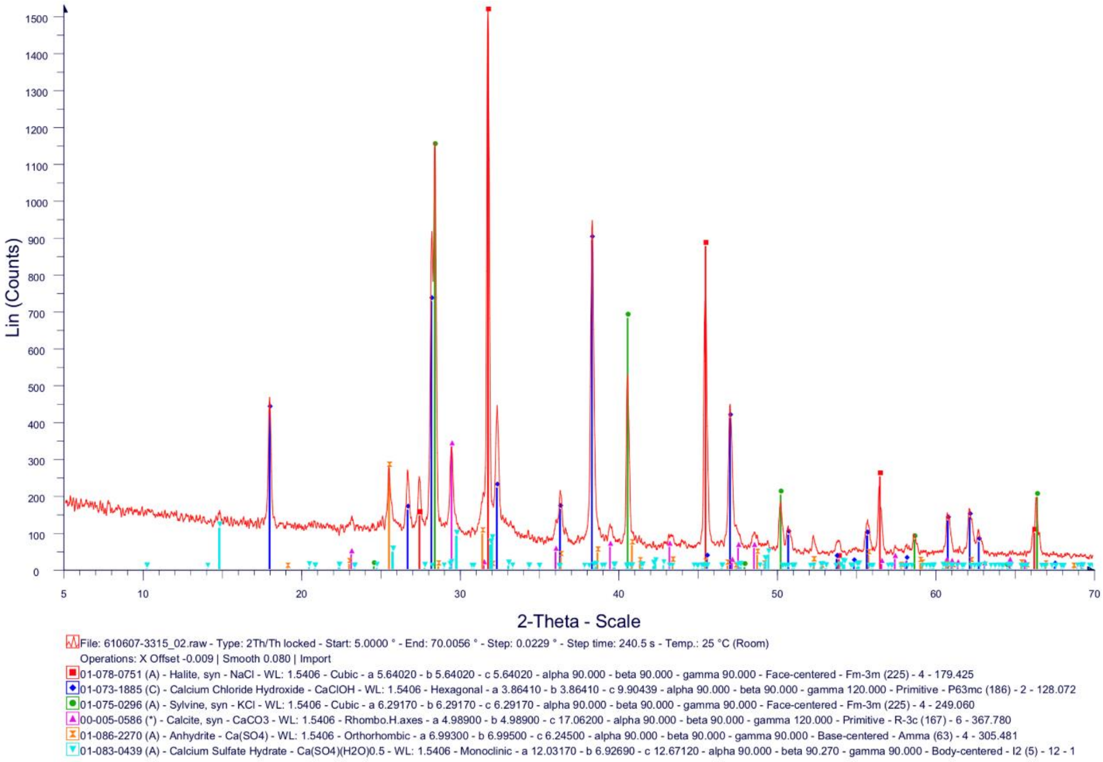

Fig H1 XRD result of untreated FA-APC

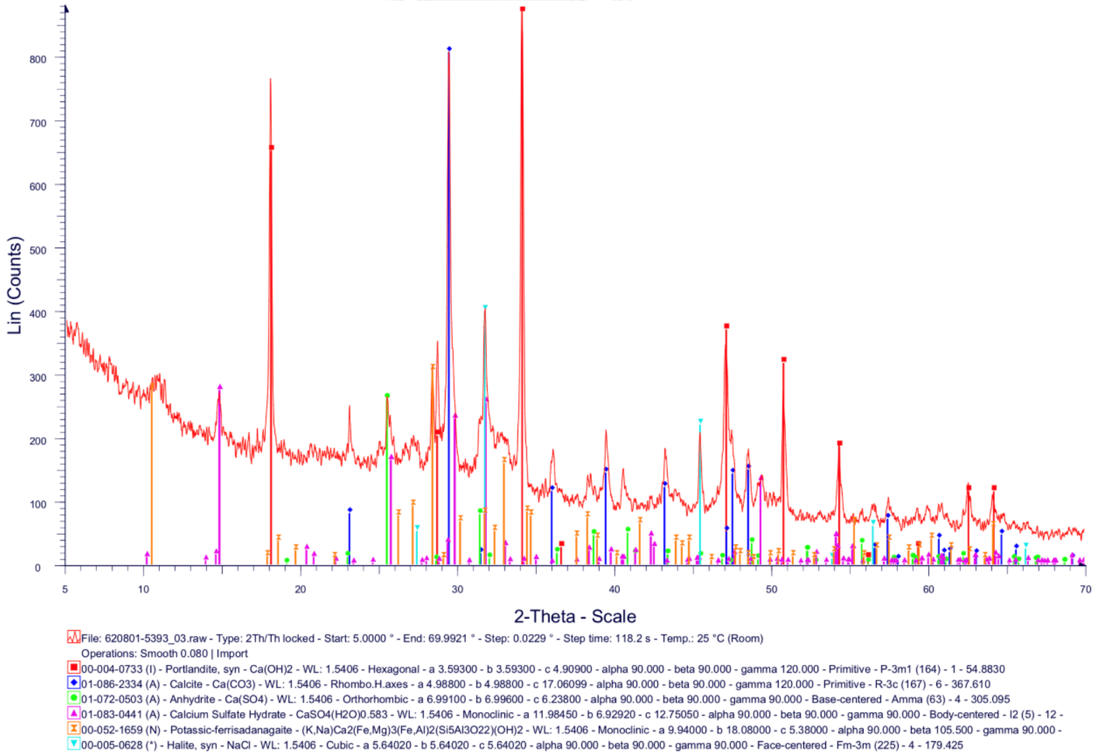

Fig H2 XRD result of treated FA-APC by DI water

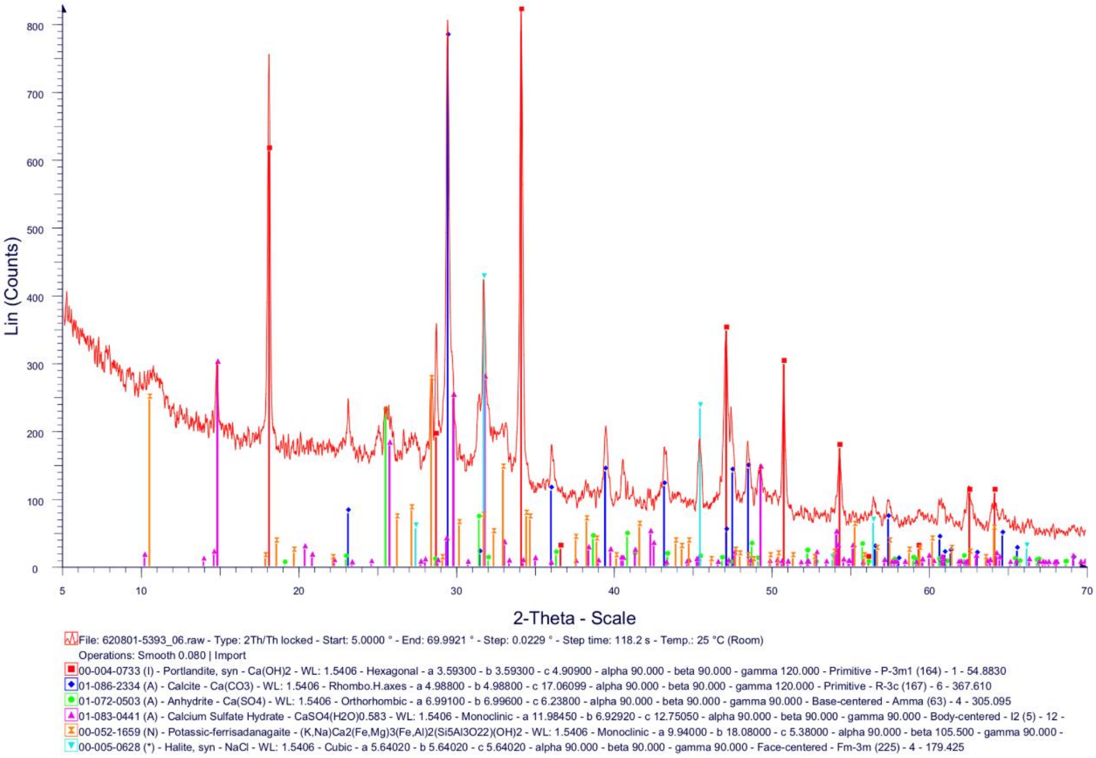

Fig H3 XRD result of treated FA-APC by 0.01M HNO_3

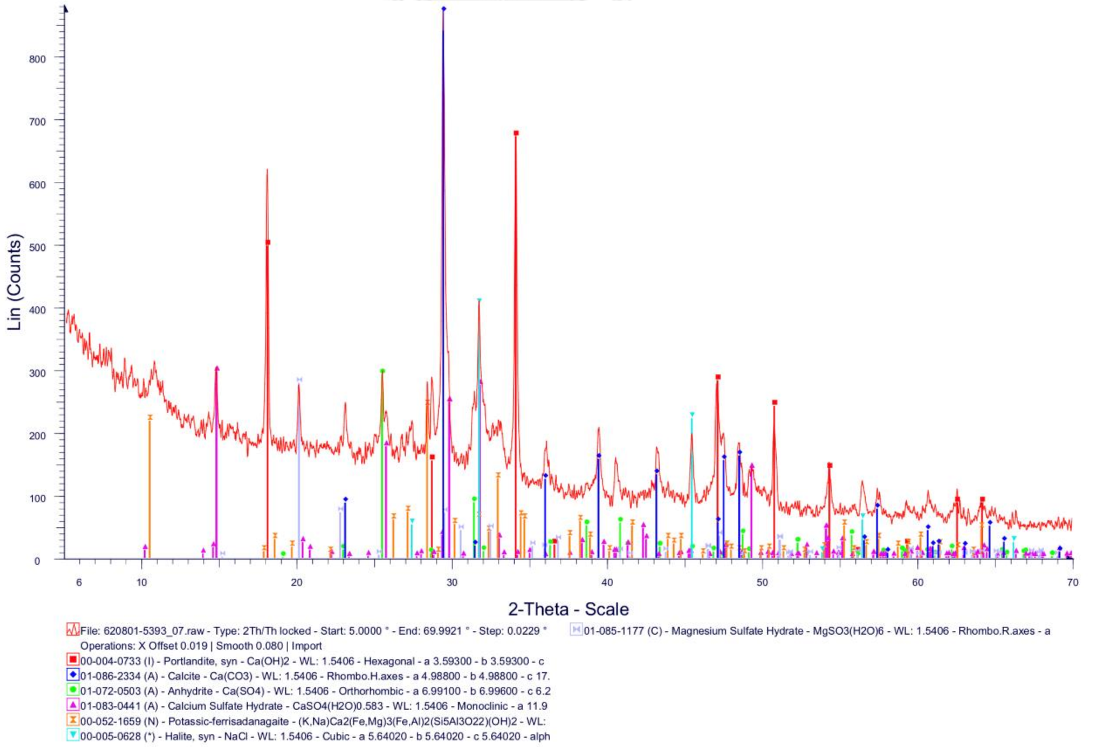

Fig H4 XRD result of treated FA-APC by 0.1M HNO_3

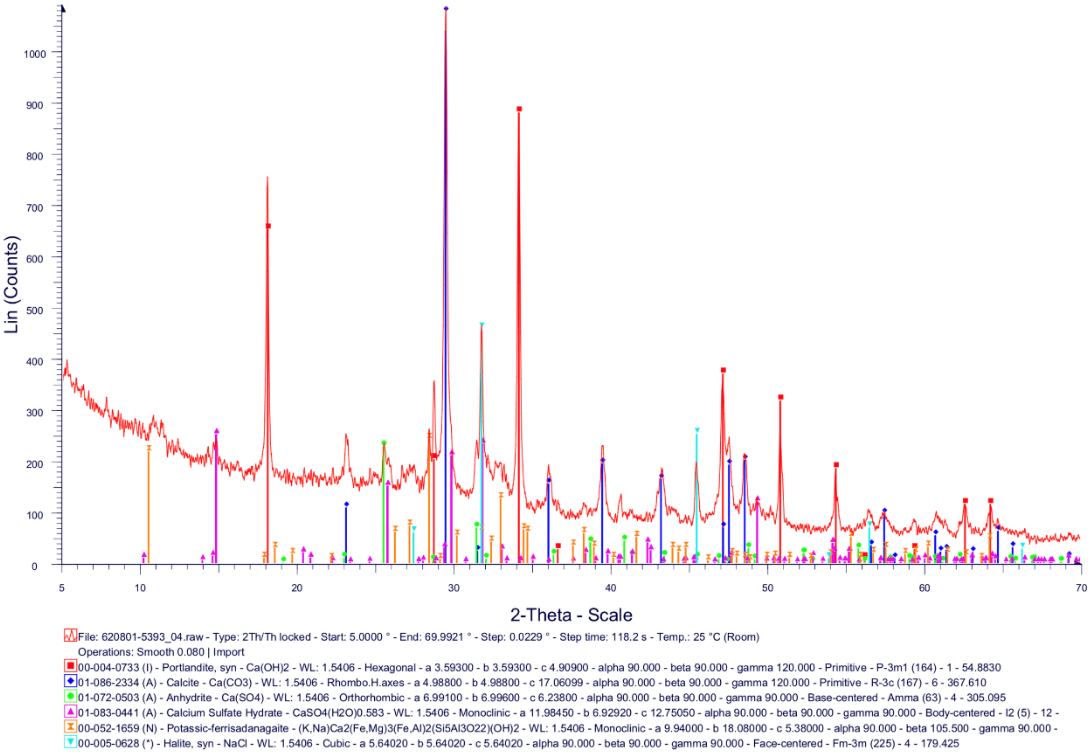

Fig H5 XRD result of treated FA-APC by 0.1M Na_2CO_3

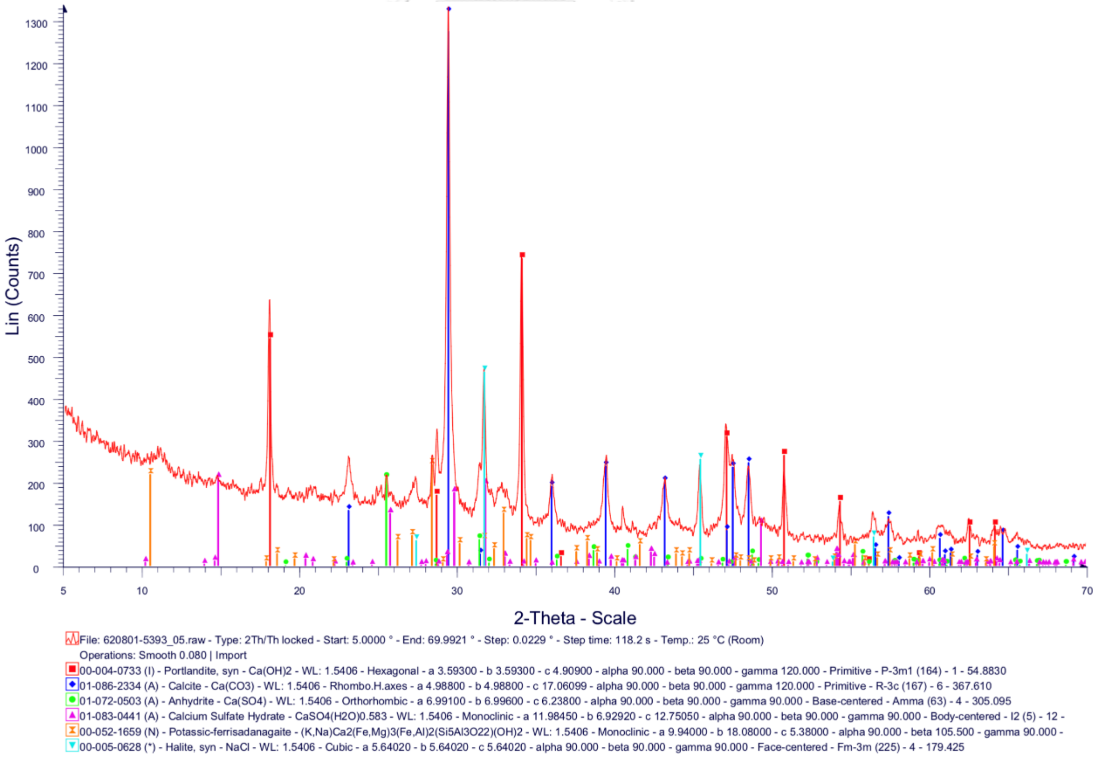

Fig H6 XRD result of treated FA-APC by 0.25M Na_2CO_3

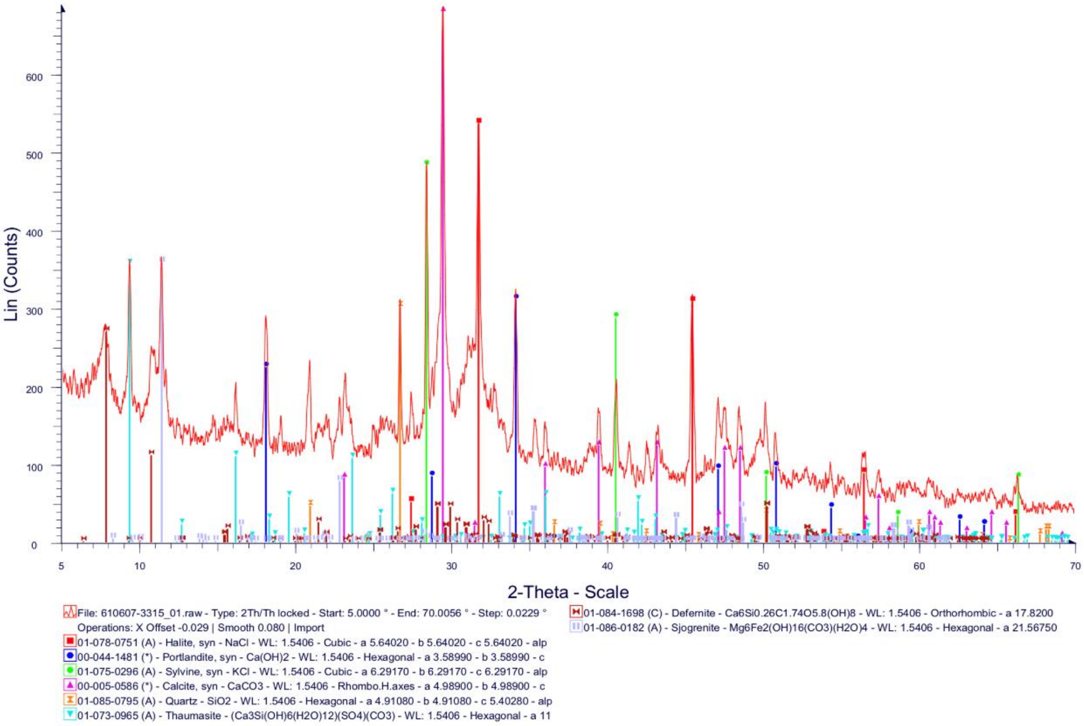

Fig H7 XRD result of untreated FA-LF

Fig H8 XRD result of treated FA-LF by DI water

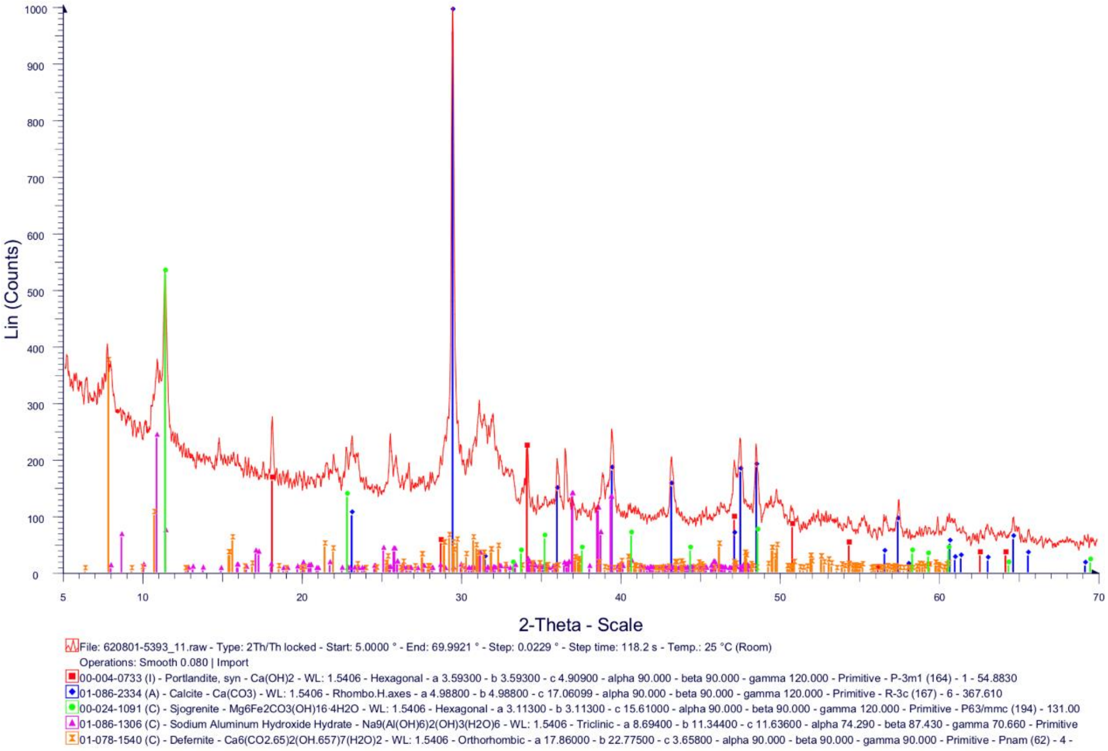

Fig H9 XRD result of treated FA-LF by 0.01M HNO_3

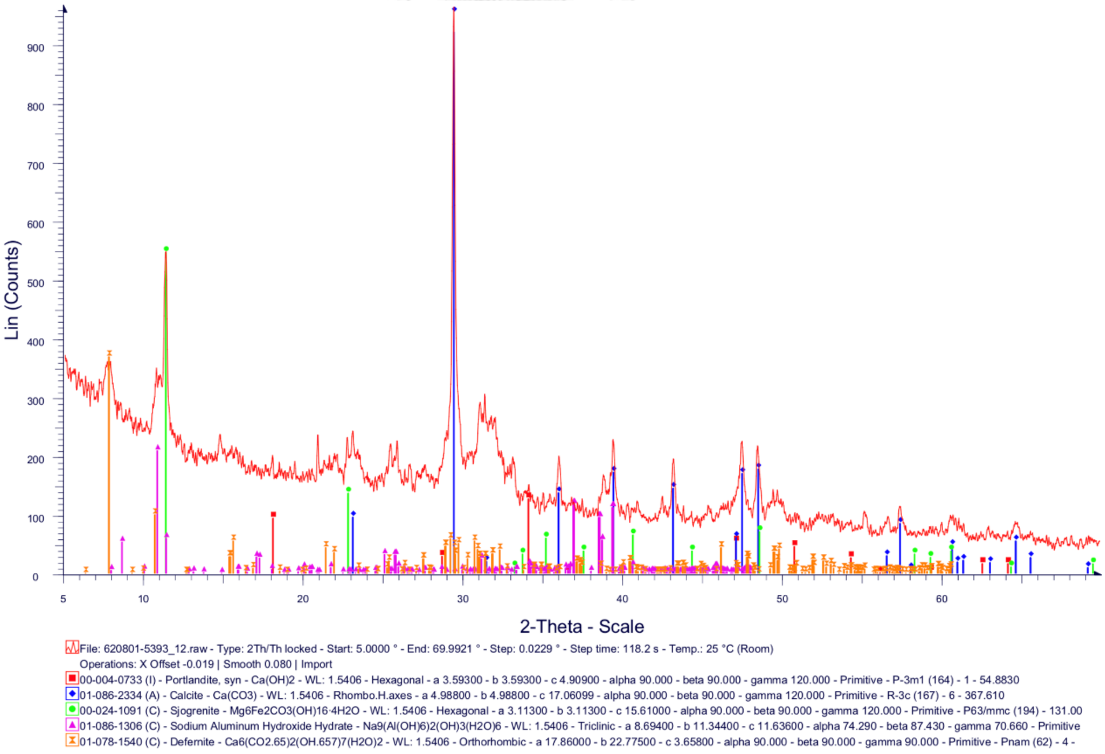

Fig H10 XRD result of treated FA-LF by 0.1M HNO_3

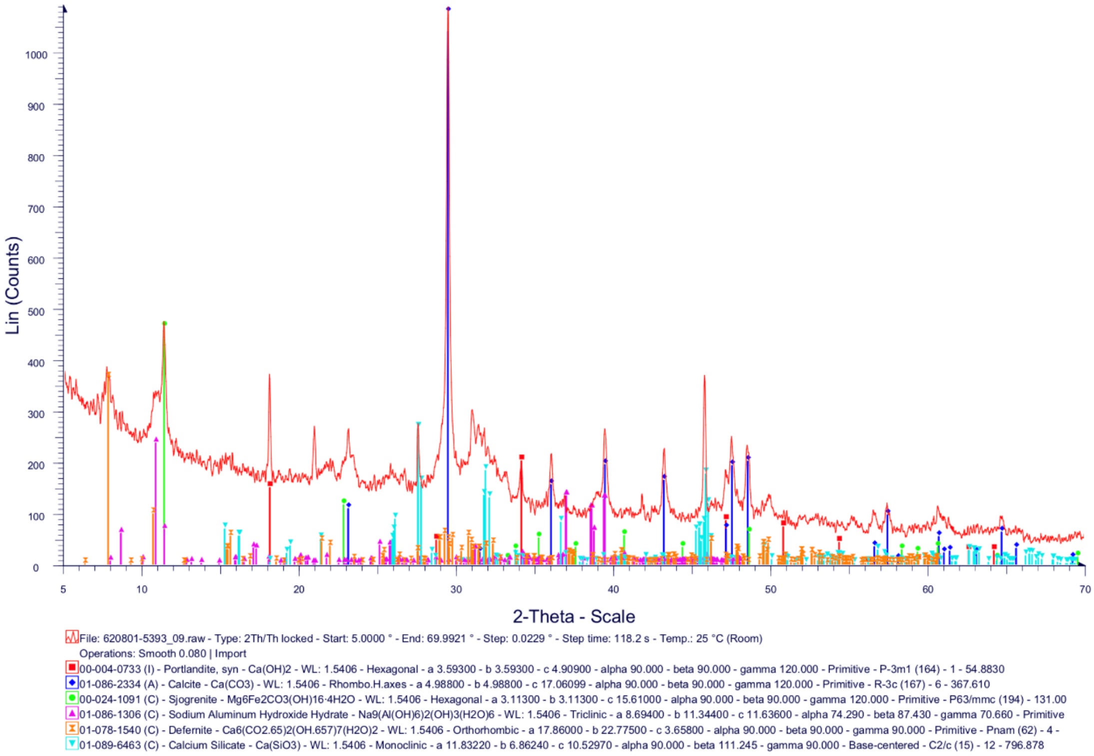

Fig H11 XRD result of treated FA-LF by 0.1M Na_2CO_3

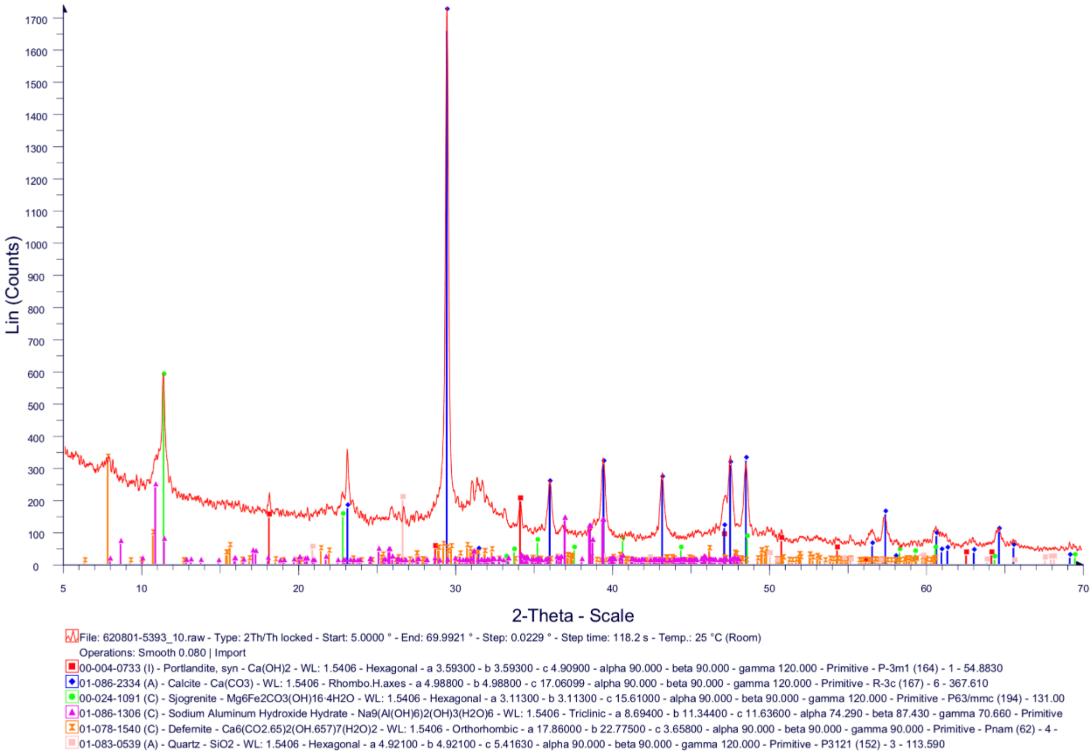

Fig H12 XRD result of treated FA-LF by 0.25M Na_2CO_3

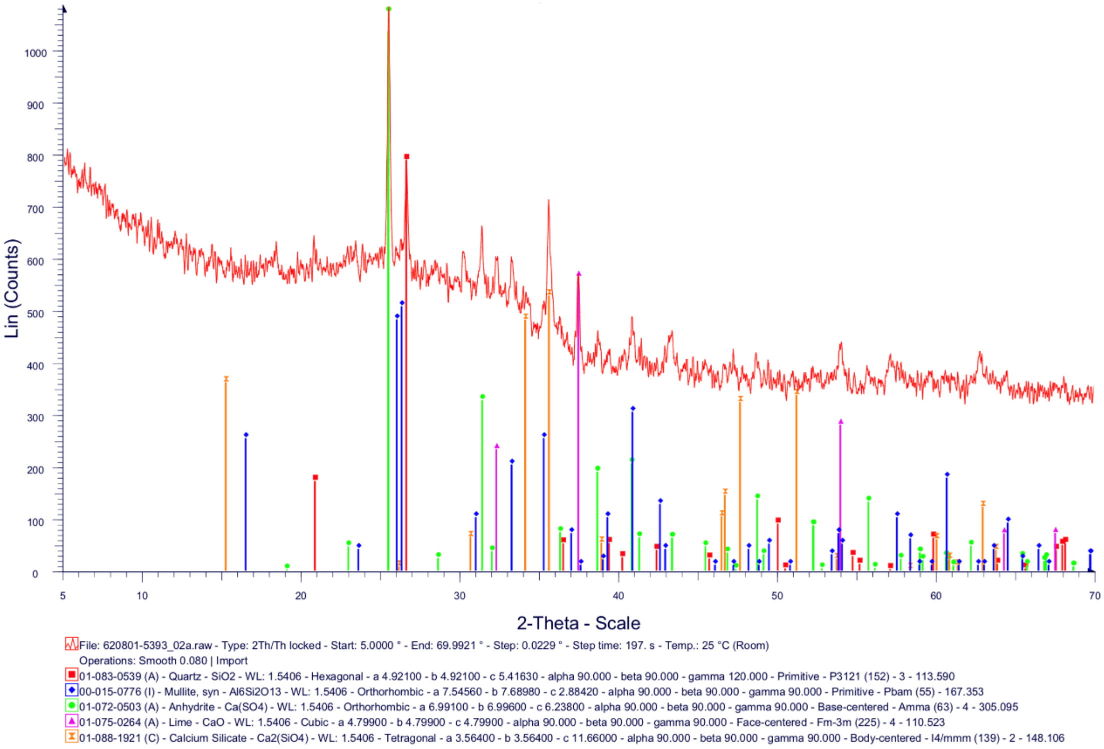

Fig H13 XRD result of raw FA-LN

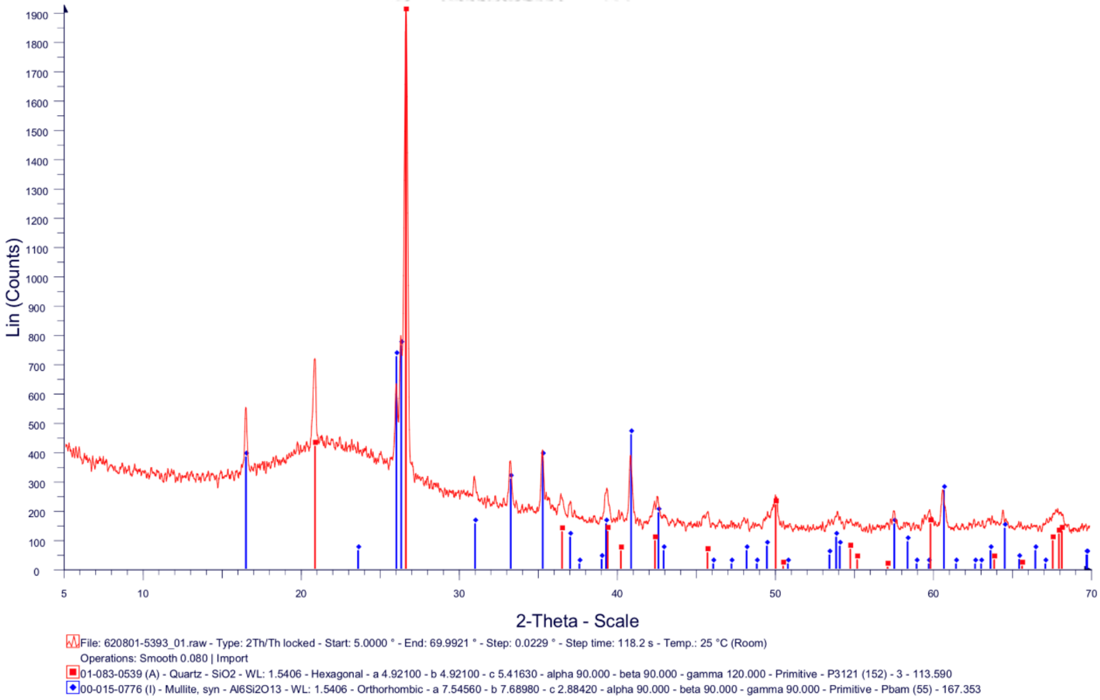

Fig H14 XRD result of raw FA-BT

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