

## Pure SiO<sub>2</sub> extraction through aluminosilicates synthesis from incinerated solid wastes

Vu Dinh Hieu<sup>1,\*</sup>, BUI Xuan Nam<sup>1</sup>, BUI Hoang Bac<sup>2</sup>, NGO Thi Thanh Nga<sup>3</sup>

<sup>1</sup> Faculty of Mining, Hanoi University of Mining and Geology, Duc Thang, Bac Tu Liem, Hanoi, Vietnam

<sup>2</sup> Faculty of Geology, Hanoi University of Mining and Geology, Duc Thang, Bac Tu Liem, Hanoi, Vietnam

<sup>3</sup> Institute of Hydropower and Renewable Energy, 8/95 Chua Boc, Dong Da, Hanoi, Vietnam

**Abstract.** In this study, Pure SiO<sub>2</sub> solution extraction from incinerated solid wastes following after aluminosilicate synthesis. The optimum conditions for obtaining both the pure SiO<sub>2</sub> solution and the substantial amounts of unique residue material should be 200°C of reaction temperature, 1:30 of sample:NaOH, 2M NaOH, and enough reaction time over 24 hours. The optimization of the pure SiO<sub>2</sub> extraction proposes an effective way for recycling the abundant incinerated solid waste as well as other waste ashes.

Keywords: Solid wastes, Coal fly ash, Synthesis, SiO<sub>2</sub> solution extraction

### 1. Introduction

In Vietnam, many incinerators have been built for disposing waste and also for generating electric power. Incineration is one of effective ways to reduce the great volume and weight of municipal solid waste (MSW). However, in terms of byproduct, incinerating MSW has produced a big amount of solid residual materials daily. The solid residual material is also a waste, called the incinerated solid waste, which is generally hazardous in nature. Due to the limited landfill space and environmental problems, the recycling of this solid waste is a necessary and burning issue.

Recently, several approaches have been made to minimize the environmental impacts from coal fly ash as well as to recycle them effectively. As the main components of the coal fly ash are similar to these of natural zeolites with high amount of SiO<sub>2</sub>, Al<sub>2</sub>O<sub>3</sub>, one of the most common approaches for recycling this ash is converting to different types of zeolite such as phillipsite, zeolite Na-P1, zeolite X and faujasite [1] [2] [3]. Zeolites are useful materials with high ion exchange property and are usually applied to environmental treatment such as uptake of heavy metals from polluted waste water [4] [5] [6].

Similar to coal fly ash, chemical composition of the incinerated solid waste mainly consists of SiO<sub>2</sub> and Al<sub>2</sub>O<sub>3</sub>. Some reports of conversion this type of waste to zeolite have been published. Yang *et al.* successfully synthesized zeolite from the municipal incinerator fly ash [7]. Fan *et al.* synthesized zeolite X and hydroxy-sodalite from waste ash from MSW and coal co-combustion power plant and applied them to Zn<sup>2+</sup> contaminated wastewater treatment [8]. In practice, during processing of zeolite synthesis, Si and Al are the major components extracted from the raw waste ash with other cations such as Na, K, Ca, and Mg to form zeolites. The previous studies were only focused on synthesizing zeolites using some waste raw materials, but not concerned about residual solution after synthesizing zeolites. In general, if some aluminosilicate, such as zeolites, are synthesized from the waste raw material with high Si content, a substantial amount of dissolved Si

\* Corresponding author: [vudinhieu@gmail.com](mailto:vudinhieu@gmail.com)

would be fixed into the structure of synthesized phases with Al and other cations, but the excess of Si would still remain in the residual solution as the only dominant cation. That is, the synthesized aluminosilicates would be a great role filtering the dissolved cations from the solution. The purity and quantity of dissolved Si in the solution should be determined by the type, quantity, and quality of synthesized aluminosilicate, which is depending on the factors, such as the reaction temperature, the ratio of solid/solution, the concentration of NaOH solution, and the reaction time. In this study, the authors considered how to extract the pure SiO<sub>2</sub> solution effectively from the incinerated solid waste following after aluminosilicate synthesis. Several researchers have tried to extract pure SiO<sub>2</sub> from coal fly ash in the previous step for zeolite synthesis [9] [10] [11], but not to get pure SiO<sub>2</sub> as a final product. The pure SiO<sub>2</sub> can be used for industrial applications as fumed silica, raw material for semiconductor, and a source for synthesis of zeolite and other silicates, etc.

In this study, we considered how to extract the pure SiO<sub>2</sub> solution effectively from the incinerated solid waste following after aluminosilicate synthesis. Several researchers have tried to extract pure SiO<sub>2</sub> from coal fly ash in the previous step for zeolite synthesis, but not to get pure SiO<sub>2</sub> as a final product. Therefore, the objective of this study is to establish the optimal condition for the pure SiO<sub>2</sub> extraction and to define the factors, controlling the purity and quantity of the extracted SiO<sub>2</sub>. The results may be applied to effectively recycling a huge amount of the incinerated solid waste from municipal incineration plants as well as other sources of waste ashes.

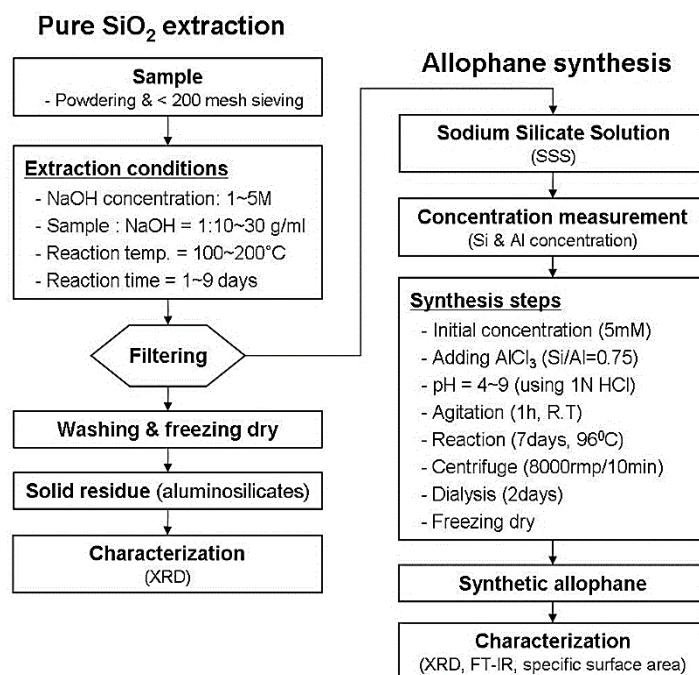
## 2. Experimental

### 2.1. Materials

The incinerated solid waste samples used in this study were collected from a municipal incineration plant of the Uong Bi Thermal Power Plant at Uong Bi City, Quang Ninh Province. These were considered to be representative of the production of that plant. Depending on the cooling methods after incineration, the solid wastes were divided into two types. One was cooled quickly using water (WCS, water cooling sample) and the other was cooled by air condition (ACS, air cooling sample). For each type of sample, it was ground into small particles by using ball-mill grinder for 15 minutes and then mixed thoroughly. The powder with under 75µm (200-mesh sieve) in particle size was used to synthesize zeolite and to extract SiO<sub>2</sub> in next steps. Coal fly ash sample was also obtained from the Cam Pha thermal power plant for comparison.

### 2.2. Pure SiO<sub>2</sub> extraction

The mixture of ground sample (3.3 ~ 30 g) and NaOH solution in determined ratios (1:10, 1:20, and 1:30 g ml<sup>-1</sup>) was reacted at different temperatures (100, 150 and 200 °C) for different reaction time (1 ~ 9 days) in autoclave system. The concentration of NaOH solution is also tested with different cases of 1, 2, and 5 M. 25 experimental cases with different conditions were examined. The reacted solution was then filtered through a membrane of 0.45 µm. The obtained products include the solid residue and the residual Si-rich solution. The solid residues containing the synthesized zeolite-type materials were washed with distilled water several times and dried at 100 °C for 1 day. The concentrations of Si and Al in the extracted solution were determined by using ultraviolet-visible spectroscopy (UV) for checking the purity and quantity of Si in the solution.. The experimental scheme for the SiO<sub>2</sub> extraction process is shown in Figure 1.



**Figure 1.** Schematic diagram showing the procedure for the pure SiO<sub>2</sub> extraction from the incinerated solid wastes through zeolite synthesis.

### 2.3. Characterization

The characteristics of the incinerated solid wastes and synthesized minerals were determined by using various techniques such as X-ray diffraction (XRD) analysis, scanning electron microscope (SEM) with energy dispersive X-ray spectroscopy (EDX), Fourier Transform Infrared (FT-IR) spectroscopy, and specific surface area measurements (BET).

X-ray powder diffraction patterns of the incinerated solid wastes and synthesized minerals were measured using a Mac Science MXP-3 model powder diffractometer with Cu-K $\alpha$  radiation at 40 kV and 30 mA. All samples were scanned from 2 to 70° at a goniometer rate of  $2\theta = 2^\circ\text{min}^{-1}$ . Crystalline phases of materials presenting in the sample were identified by using the software named Joint Committee of Powder Diffraction Standards (JCPDS). The relative percentages of the synthesized minerals were calculated by using FULLPAT method for XRD patterns (Chipera et al., 2002). The morphological properties and major elements of the incinerated solid wastes and synthesized minerals were examined by using the scanning electron microscope (SEM) with energy dispersive X-ray spectroscopy (EDX) [JEOL, JMS 5800]. The FT-IR spectra for the synthesized minerals were obtained in transmission mode on pellets containing a pressed mixture of approximately 1.5 mg of the sample and 100 mg of KBr. The IR spectra were recorded in the range between 4000 and 400  $\text{cm}^{-1}$  (PerkinElmer) with 200 scans. The specific surface area of the products containing zeolites was measured from N<sub>2</sub> gas adsorption at 77 K by using NOVA 3200 BET instrument, Quantachrome Corporation, USA.

### 3. Results and discussion

### 3.1. The incinerated solid waste properties

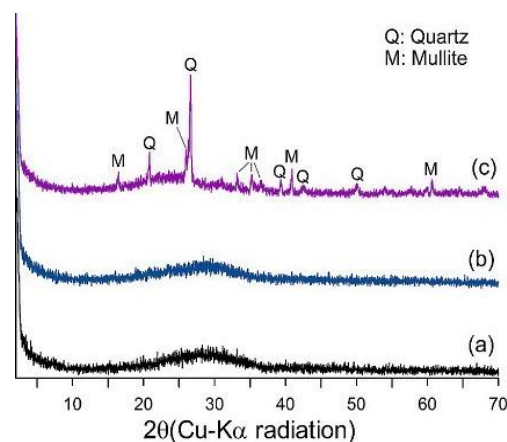
The chemical compositions of the raw samples and coal fly ash are shown in Table 1. The incinerated solid wastes (ACS and WCS) contained mainly SiO<sub>2</sub> (45.68~47.07 wt.%), Al<sub>2</sub>O<sub>3</sub> (10.25~12.40 wt.%), CaO (10.80~16.14 wt.%), and a little amount of oxides of Fe, Mg, Na, Mg, K, P, Ti etc. The high content of CaO may be due to the addition of lime into the incinerator. Some difference in bulk composition between ACS and WCS is probably due to the inhomogeneity of incinerated solid wastes. Coal fly ash was characterized by the relatively high SiO<sub>2</sub> (49.97 wt.%) and the low CaO (3.59 wt.%) contents. The powder of incinerated solid waste with sizes under 75 μm includes solid particles (SEM images are not shown here), which are different from coal fly ash particles with hollow sphere structure [12].

**Table 1.** Objectives of management in mineral operation.

Component	Incinerated solid wastes (wt. %)				Coal fly ash (wt. %)	
	Air cooling		Water cooling			
SiO <sub>2</sub>	45.68		47.07		49.97	
TiO <sub>2</sub>	0.66		0.33		1.38	
Al <sub>2</sub> O <sub>3</sub>	10.25		12.40		21.64	
FeO*	6.20		3.13		8.35	
MgO	2.80		3.66		1.42	
MnO	0.28		0.78		0.23	
CaO	16.14		10.80		3.59	
Na <sub>2</sub> O	7.56		9.07		0.56	
K <sub>2</sub> O	0.99		0.75		2.83	
P <sub>2</sub> O <sub>5</sub>	4.65		5.01		3.64	
V <sub>2</sub> O <sub>5</sub>	0.34		0.64		0.49	
Cr <sub>2</sub> O <sub>3</sub>	1.24		0.85		2.01	
NiO	0.52		1.34		0.74	
ZnO	1.87		1.55		2.39	
PbO	0.80		1.33		0.77	

\* Total Fe treated as FeO.

The XRD pattern of the incinerated solid shows a big hump of between 20 to 35° of 2θ, indicating the presence of a large amount of amorphous phases in the sample (Figure 2a and 2b), while that of coal fly ash indicates that quartz (SiO<sub>2</sub>) and mullite (3Al<sub>2</sub>O<sub>3</sub>·2SiO<sub>2</sub>) are main crystalline phases in the sample (Figure 2c) The BET specific surface area of the incinerated solid wastes powder passed through 200-mesh sieve is around 0.5 m<sup>2</sup> g<sup>-1</sup>.



**Figure 2.** XRD patterns of air cooling sample (ACS) (a), water cooling sample (WCS) (b), and coal fly ash (c)

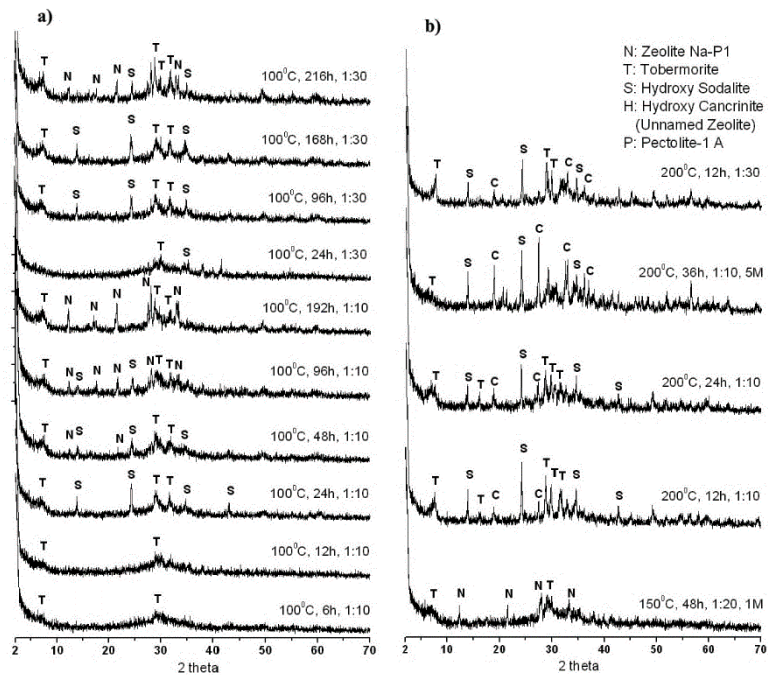
The high content of  $\text{SiO}_2$  in chemical composition and the presence of a substantial amount of amorphous aluminosilicates in the samples strongly support that the incinerated solid wastes should have a great potential as raw materials for effective recycling through aluminosilicate synthesis and pure  $\text{SiO}_2$  extraction.

### 3.2. Characterization of residues

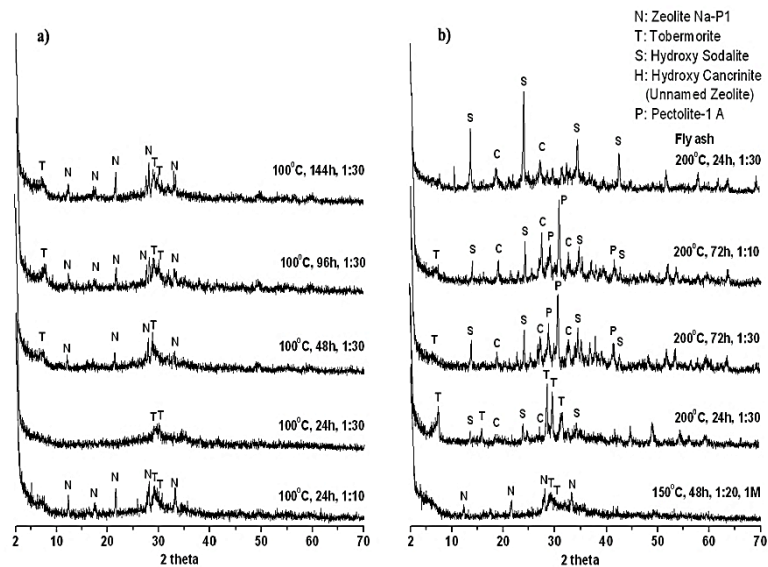
Some crystalline materials were synthesized as by-product residues during the extraction experiments. The type of crystalline phases and the percentage of each type, and the total percentage of the crystalline phases were determined using XRD analysis and considered as the potential factors controlling the purity and quantity of extracted  $\text{SiO}_2$  solution.

These residues were identified by XRD measurements and the patterns were shown in Figure 3 and 4. Hydroxysodalite ( $4\text{Na}_2\text{O} \cdot 3\text{Al}_2\text{O}_3 \cdot 6\text{SiO}_2 \cdot \text{H}_2\text{O}$ ), tobermorite ( $\text{Ca}_5(\text{OH})_2\text{Si}_6\text{O}_{16} \cdot 4\text{H}_2\text{O}$ ), Na-P1 zeolite ( $\text{Na}_6\text{Al}_6\text{Si}_{10}\text{O}_{32} \cdot 12\text{H}_2\text{O}$ ), hydroxycancrinite ( $\text{Na}_{14}\text{Al}_{12}\text{Si}_{13}\text{O}_{51} \cdot 6\text{H}_2\text{O}$ ), and pectolite-1A ( $\text{NaCa}_2\text{HSi}_3\text{O}_9$ ) were identified as the main materials and the relative percentages of the minerals for each experimental condition were listed in Table 2.

Tobermorite, the Ca-rich silicate, was observed as a major component in most conditions for both ACS and WCS (7.8~38.5 %), except the conditions at  $200^\circ\text{C}$  for 72 hours for WCSs (No.22 and 24 in Table 2), where pectolite-1A, another Ca-rich silicate was identified as a dominant phase (20.6~31.7 %), instead of tobermorite. It is likely that tobermorite was transformed to pectolite-1A by increasing the reaction time at  $200^\circ\text{C}$ . The dominant occurrence of the Ca-rich phases should be due to high Ca content in bulk composition. Hydroxysodalite (8.6~22.2 %) and Na-P1 zeolite (3.9~12.4 %) were found in most conditions at  $100^\circ\text{C}$  reaction temperature, while hydroxycancrinite was identified as a dominant component only in the condition at  $200^\circ\text{C}$  for both ACSs (24.4~41.9 %) and WCSs (12.4~31.2 %) (Figure 3~4 and Table 2). The material in experimental condition of No.14 ( $200^\circ\text{C}$ , 1:10 ratio, 5M NaOH, 36 hours) was matched well with typical hydroxycancrinite (PDF 46-1457) as a dominant phase (41.9 %), but the others in the conditions at  $200^\circ\text{C}$  were matched more with hydroxycancrinite-type unnamed phase (PDF 31-1270) as one of major phases (24.4~39.1 % for ACSs and 12.4~31.2 % for WCSs, Table 2).



**Figure 3.** XRD patterns of the synthetic products of air cooling samples (ACSs) at 100°C (a) and 150–200°C (b) with the different experimental conditions.

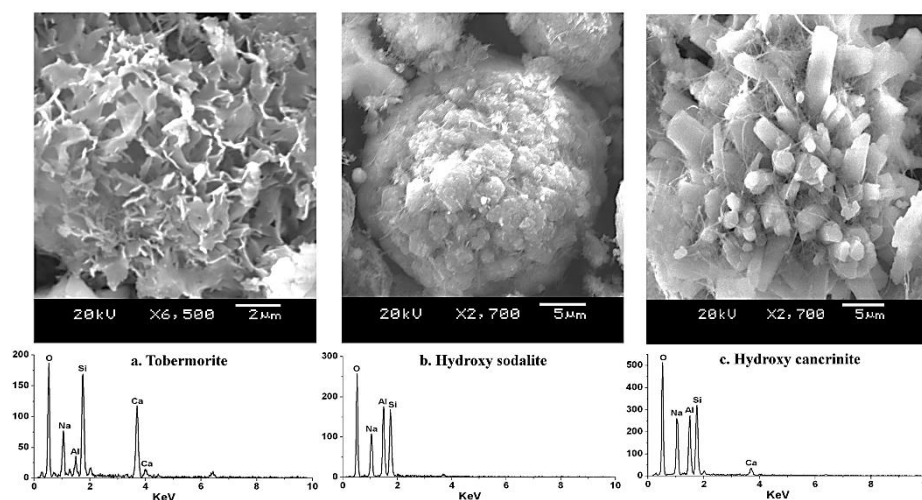


**Figure 4.** XRD patterns of the synthetic products of water cooling samples (WCSs) at 100°C (a) and 150–200°C (b) with the different experimental conditions.

The sums of the percentage of synthesized residues at 200°C (No.12~15 for ACSs and No.22~24 for WCSs in Table 2) were much higher than those at 100~150°C, indicating that the dissolution and crystallization reactions were much more active at 200°C. There was no distinct difference in the sums of the percentage of synthesized minerals between 1:10 and 1:30 of sample:NaOH ratio at 200°C. For the coal fly ash raw material, hydroxycancrinite-type phase (unnamed, PDF No. 31-1270) appeared as a dominant phase (71.6 %) with a little amount of tobermorite (7.8 %) at 200°C, 24 hours, 1:30 of sample:NaOH ratio, and 2M NaOH experimental condition (No.25 in Table 2), probably due to the difference in bulk composition. Most of XRD patterns show a little hump between 20 to 35° of 2θ, indicating that a significant amount of amorphous phases still remained in the sample.

The existence of the synthesized materials in the reacted residues was also confirmed by SEM analysis. Figure 5 shows the scanning electron microscope (SEM) and EDX chemical data of some synthesized materials at the representative conditions. Ca-rich aluminosilicate, tobermorite, was observed in the condition at 200°C, 24 hours, 1:30 ratio, and 2M NaOH for WCS (Figure 5a, No. 23 in Table 2), hydroxysodalite was in the condition at 100°C, 24hours, 1:10 ratio, and 2M NaOH for ACS (Figure 5b, No. 3 in Table 2), and hydroxycancrinite was in the condition at 200°C, 36hours, 1:10 ratio, and 5M NaOH for ACS (Figure 5c, No. 14 in Table 2). In general, most of the obtained synthetic materials showed crystalline forms with various size, but not typical, and the substantial amounts of incinerated solid wastes still remained in the reacted residues, indicating the dissolution and crystallization reactions were not undergone completely under the given alkaline conditions.

The specific surface area of the representative synthetic product containing zeolites is 41 m<sup>2</sup>g<sup>-1</sup> for ACS at 200°C of reaction temperature, 1:30 of sample/NaOH ratio, 12 hours of reaction time, 2M of NaOH concentration, and 54 m<sup>2</sup>g<sup>-1</sup> is for WCS at 200°C of reaction temperature, 1:30 of sample/NaOH ratio, 24 hours of reaction time, 2M of NaOH concentration.



**Figure 5.** SEM images of the synthesized minerals with the EDX chemical data. {(a) tobermorite at 200°C of reaction temperature, 1:30 of sample/NaOH ratio, 24 hours of reaction time, and 2M of NaOH concentration for WCS (No.23 in Table 2); (b) hydroxysodalite at 100°C of reaction temperature, 1:10 of sample/NaOH ratio, 24 hours of reaction time, and 2M of NaOH concentration for ACS (No. 3 in Table 2); (c) hydroxycancrinite at 200°C of reaction temperature, 1:10 of sample/NaOH ratio, 36 hours of reaction time, and 5M of NaOH concentration for ACS (No.14 in Table 2)}.

### 3.3. Pure SiO<sub>2</sub> extraction

The results for all experimental conditions of SiO<sub>2</sub> extraction were summarized in Table 2. The reaction temperature, sample/NaOH solution ratio, reaction time, and the concentration of NaOH solution were considered as the factors controlling the purity and quantity of extracted SiO<sub>2</sub>. The concentrations of Si and Al in the extracted solution and the yields of extracted SiO<sub>2</sub> for each condition were also suggested in Table 2. The weight and the yield of extracted SiO<sub>2</sub> from the solid waste were calculated using the equations as follows.

$$SiO_2 (g) = \frac{Si\ conc.\ in\ solution\ (mg/l)}{1000} \times \frac{60.085(SiO_2\ molecular\ weight)}{28.086(Si\ atomic\ weight)} \times \frac{Solution\ volume\ (ml)}{1000}$$

$$Yield\ of\ SiO_2\ extraction\ (\%) = \frac{Extracted\ SiO_2\ (g)}{Weight\ percent\ of\ SiO_2\ in\ sample \times Sample\ weight\ (g)} \times 100$$

The results revealed that the yields (%) of WCS (6.81 ~ 24.40) were generally higher than those of ACS (3.07 ~ 15.67). For the ACSs, the concentrations of Al were still high (19.4 ~ 59.5 mg/l) until 48 hours reaction time with the low values (about 4%) of SiO<sub>2</sub> yields at 100°C and 1:10 of sample/NaOH ratio (No.1~4 in Table 2), indicating that the conditions were not enough for dissolving the raw sample and for synthesizing aluminosilicates. As mentioned above, the dissolved Al and cations can be removed from the solution by being fixed into the structure of synthesized aluminosilicates during the reaction. The concentrations of Al decreased steeply (<10 mg l<sup>-1</sup>) after reacting for 96 hours, due to relatively enough time for zeolite synthesis (No.5~6 in Table 2). At 100°C and 1:30 of sample/NaOH ratio, the extracted solutions were also pure (low Al concentrations) after reacting for 96 hours, with the steep increase of SiO<sub>2</sub> yields (7.24~14.23 %) (No.7~10 in Table 2). At 200°C and 1:10 of sample/NaOH ratio, Al concentrations were less than 5mg/l in spite of the relatively short reaction time (<36 hours), but the SiO<sub>2</sub> yields were very low (3.1~5.6%) (No.12~14 in Table 2). However, the SiO<sub>2</sub> yield dramatically increased to 15.7% at 1:30 ratio with keeping Al concentration low (5.3 mg l<sup>-1</sup>) (No.15 in Table 2). There is no distinct change in the yield of SiO<sub>2</sub> extraction at 5 M NaOH and 1:10 ratio (3.09 %) (No.14 in Table 2). At 150°C, 1:20, 1M NaOH, and 48 hours conditions, the SiO<sub>2</sub> yield was relatively good (12.7 %) (No.11 in Table 2).

For the WCSs, the concentrations of Al were less than 10 mg l<sup>-1</sup> for most of experimental conditions, except No. 18 (11.6 mg l<sup>-1</sup>, Table 2) at 100°C, 1:30, 48 hours, and 2M NaOH. The SiO<sub>2</sub> yield was 6.81 % at 1:10 and 100°C (No.16 in Table 2), while those were 13.1~16.6 % at 1:30, 100°C, and 24 ~ 144 hours reaction time (No.17~20 in Table 2). There is no distinct change in the yield of SiO<sub>2</sub> extraction at 150 °C, 1:20, 1 M NaOH, and 48 hours conditions (14.0 %) (No.21 in Table 2). The SiO<sub>2</sub> yield was maximum (24.4 %) at 200 °C, 1:30, and 24 hours reaction time (No.23 in Table 2), but that is minimum (8.33 %)



at 200 °C, 1:10, and 72 hours reaction time (No.22 in Table 2). For the coal fly ash, the SiO<sub>2</sub> yield was 13.9 % at 200 °C, 1:30, and 24 hours reaction time (No.25 in Table 2).

### 3.4. Controlling factors pure SiO<sub>2</sub> extraction

The experimental results of this study can be summarized as follows; (1) tobermorite, the Ca-rich silicate, was synthesized as a major component in most conditions for both ACS and WCS, except the conditions at 200 °C for 72 hours for WCSs, where pectolite-1A, another Ca-rich silicate, was identified as a dominant phase, instead of tobermorite, (2) hydroxycancrinite formed as a major phase at 200 °C of reaction temperature, not depending on the sample/NaOH ratio, (3) the SiO<sub>2</sub> yield dramatically increased at 1:30 of sample/NaOH ratio and 200 °C rather than at 1:10 and 100°C with keeping Al concentration low, even at the short reaction time, (4) the SiO<sub>2</sub> yields for WCSs were much higher than for ACSs (Table 2).

**Table 2.** Summary of the experimental conditions, the percentage of synthesized minerals, and the yield of SiO<sub>2</sub> extraction. {<sup>1</sup>Hydroxysodalite (PDF 41-0009), <sup>2</sup>Tobermorite (PDF 19-0050, 19-1364), <sup>3</sup>Zeolite Na-P1 (PDF 39-0219), <sup>4</sup>Hydroxycancrinite (PDF 46-1457), or Unnamed zeolite (PDF 31-1270), and <sup>5</sup>Pectolite-1A (PDF 33-1223). “-” indicates to negligible values, or not detected in XRD patterns}

No.	Reaction conditions	Percentage of synthesized minerals					Solution conc.		SiO <sub>2</sub> solid
	Temp.-Solid-Ratio-Time-NaOH	HS <sup>1</sup>	T <sup>2</sup>	N <sup>3</sup>	H <sup>4</sup>	P <sup>5</sup>	Si	Al	Yield
	[(°C)-(g)-(g/ml)-(h)-(M)]	(%)	(%)	(%)	(%)	(%)	(mg/l)	(mg/l)	(%)
<b>I. Air Cooling Samples (ACs)</b>									
1	100-10-1:10-6-2	-	8.99	-	-	-	745.0	59.5	3.94
2	100-10-1:10-12-2	-	11.35	-	-	-	728.3	48.0	3.85
3	100-10-1:10-24-2	22.16	14.54	-	-	-	774.9	20.2	4.09
4	100-10-1:10-48-2	12.31	13.11	3.86	-	-	716.7	19.4	3.79
5	100-10-1:10-96-2	8.59	9.5	5.9	-	-	770.3	8.3	4.07
6	100-10-1:10-192-2	-	14.77	12.37	-	-	581.5	3.1	3.07
7	100-20-1:30-24-2	-	8.45	-	-	-	491.6	56.9	7.79
8	100-3.3-1:30-96-2	15.36	15.17	-	-	-	888.9	4.3	14.23
9	100-3.3-1:30-168-2	20.01	15.17	-	-	-	456.0	8.4	7.30
10	100-3.3-1:30-216-2	8.58	22.15	8.72	-	-	452.6	4.3	7.24
11	150-25-1:20-48-1	-	13.64	8.86	-	-	1203.0	9.7	12.70
12	200-30-1:10-12-2	-	27.93	-	39.12	-	1056.0	2.4	5.58
13	200-30-1:10-24-2	-	17.55	-	24.37	-	845.7	3.4	4.47
14	200-30-1:10-36-5	-	7.8	-	41.87	-	584.3	-	3.09
15	200-10-1:30-12-2	-	28.81	-	28.44	-	988.7	5.3	15.67
<b>II. Water Cooling Samples (WCSs)</b>									
16	100-10-1:10-24-2	-	14.99	8.84	-	-	1433.5	3.5	6.81
17	100-20-1:30-24-2	-	10.11	-	-	-	1166.4	5.3	16.60
18	100-3.3-1:30-48-2	-	15.71	7.93	-	-	1056.1	11.6	15.20
19	100-3.3-1:30-96-2	-	14.76	8.96	-	-	1043.2	7.2	15.00
20	100-3.3-1:30-144-2	-	14.48	10.11	-	-	910.5	2.0	13.10
21	150-25-1:20-48-1	-	11.64	8.84	-	-	1467.1	3.8	14.00
22	200-30-1:10-72-2	-	-	-	31.16	31.69	1751.3	4.8	8.33
23	200-10-1:30-24-2	-	38.5	-	12.43	-	1709.2	6.2	24.40
24	200-10-1:30-72-2	-	-	-	22.00	20.62	1612.4	3.9	23.00
<b>III. Coal Fly Ash</b>									
25	200-10-1:30-24-2	-	7.82	-	71.66	-	1174.1	4.7	13.90

These results strongly suggest that only for the maximum yield of pure SiO<sub>2</sub> extraction, the conditions with 1:30 of sample/NaOH ratio and 200 °C of reaction temperature should be required. The reaction time was not an essential factor for increasing the yield of pure SiO<sub>2</sub> extraction, but it was an important factor determining the quantity of synthesized zeolite. For example, the percentage of hydroxycancrinite showed a little increase at 72 hours reaction times with no significant change in the yield of SiO<sub>2</sub> extraction (No. 25 in Table 2). The reaction temperature is a critical factor controlling not only the yield of SiO<sub>2</sub> extraction, but the zeolite type (hydroxysodalite and/or Na-P1 zeolite at 100 °C, and hydroxycancrinite at 200 °C) and the quantity (sum of zeolite percentage; 7.9 ~ 22.2% at

100°C, 12.4 ~ 41.9% at 200°C, Table 2). The increase of NaOH concentration should be a factor to improve zeolite synthesis, but to reduce significantly the yield of SiO<sub>2</sub> extraction (No.14 in Table 2). The higher SiO<sub>2</sub> yields for WCSs rather than those for ACSs indicate that the fast cooling of the melted wastes in incinerator is better for the SiO<sub>2</sub> extraction, owing to the increase of amorphous form. The existence of Ca-rich silicates, tobermorite and pectolite-1A, is a critical factor reducing the pure SiO<sub>2</sub> yield by fixing a substantial amounts of Si into the structure, depending on the molar ratio of Ca:Si in the chemical formula. If the lime addition was minimized, the yield of SiO<sub>2</sub> extraction should be increased distinctly, and a single type of zeolite can be synthesized.

On considering all experimental results, the optimum conditions for obtaining both pure SiO<sub>2</sub> and the substantial amounts of unique zeolite should be 200 °C of reaction temperature, 1:30 of sample/NaOH, 2 M NaOH, and enough reaction time over 24 hours.

#### 4. Conclusions

In this study, we have successfully extracted the pure SiO<sub>2</sub> solution from the hazardous incinerated solid wastes using alkaline dissolution method. The experimental results can be summarized by the dramatic increase of pure SiO<sub>2</sub> yield at 1:30 of sample:NaOH ratio and 200°C, even at the short reaction time, and the relatively high SiO<sub>2</sub> yields for WCSs rather than ACSs. The high ratio of sample:NaOH was inevitable for keeping high purity, high concentration, and high yield of SiO<sub>2</sub> solution, though it was not proper for economical extraction. The types of the solid residues precipitated during the reaction had an important role to control purity and yield of the extracted pure SiO<sub>2</sub> solution. While the formation of Ca-rich silicates, tobermorite and pectolite-1A, was a critical factor reducing the yield of the pure SiO<sub>2</sub> solution by fixing a substantial amounts of Si into the structure. Therefore the yield of SiO<sub>2</sub> extraction and the quality of residue materials can be improved distinctly by minimizing the addition of Ca-lime into the incinerator.

In conclusion, the optimum conditions for obtaining both the pure SiO<sub>2</sub> solution and the substantial amounts of unique residue material should be 200°C of reaction temperature, 1:30 of sample:NaOH, 2M NaOH, and enough reaction time over 24 hours. The optimization of the pure SiO<sub>2</sub> extraction proposes an effective way for recycling the abundant incinerated solid waste as well as other waste ashes.

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Opiekun: prof. dr Jadwiga Jarzyna

Recenzent: Taki GÜLER, [takiguler@mu.edu.tr](mailto:takiguler@mu.edu.tr)

lub Ercan POLAT, [epolat@mu.edu.tr](mailto:epolat@mu.edu.tr) (zaczepnęłam z Inżynieria Mineralna, 2017)

Recenzent: Paulina Nowak [paulina-nowak@gkpge.pl](mailto:paulina-nowak@gkpge.pl)