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Reaction, Phases, and Microstructure of Fly Ash-Based Alkali-Activated Materials

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Abstract

The alkaline activator has a significant effect on the microstructure and mechanical properties of fly ash-based alkali activated products. This paper aims to identify the reaction products of fly ash (FA) activated with alkaline activators of different concentrations of Na2O and different SiO2/Na2O ratios. NaOH solution (NA), a mixture of NaOH and sodium silicate solution (MIX) and sodium silicate solution (LG) were used to activate fly ash. Different techniques were used to characterize the reaction products of activated fly ash including X-ray diffraction (XRD) with Rietveld refinements, attenuated total reflectance Fourier transformer infrared (ATR-FTIR), 29Si dipolar-decoupling (DD) magnetic angel spinning/nuclear magnetic resonance (29Si MAS/NMR) and 27Al MAS NMR, field emission scanning electron microscopy (FE-SEM) attached with energy-dispersive X-ray (EDX) analyzer. Also, the fly ash-based alkali activated products were indentation tested using a Vickers indenter.

The results revealed that the main reaction product of alkali activation of fly ash is a sodium aluminosilicate gel (geopolymer) with high Si/Al ratio when sodium silicate was used as alkaline activator, while zeolite appeared as minority phase when fly ash was activated with NaOH solution or a mixture of NaOH and sodium silicate solution. Moreover, Na2O content and SiO2/Na2O ratio in the activator solution influence on the amount of amorphous phase and Q4(mAl) units formed in the alkali activated materials and that reflect on the mechanical properties.

1. Introduction

Since the Great East Japan Earthquake and tsunami in 2011, Japan energy self-sufficiency rate is declined to 7.4% owing shutting down many nuclear power stations (Komiyama and Fujii 2017, 2015). In this situation, importing fossil fuel as alternative to nuclear energy is increased, especially coal, because is the most abundant and widespread fossil fuel in the world and its cost is the lowest among all fossil fuel. Consequently, huge amount of fly ash is generated from coal-fired thermal power plants, which require a sustainable disposal and utilization (Ahmaruzzaman 2010; Meawad et al. 2010). Many research studies have been conducted to use fly ash in the construction sector (Cristelo et al. 2018; Ebrahimi et al. 2017; Eliche-Quesada et al. 2018; Mohammadinia et al. 2016; Yao et al. 2015).

Alkali activation of fly ash by mixing with alkaline solutions (usually alkali metal silicates or hydroxides) produce crystalline or nanocrystalline aluminosilicate compounds. The main role of alkalis is to achieve a high pH to activate the raw materials and to balance the charge on aluminosilicate framework (Duxson et al. 2005). This reaction consists of three main stages, dissolution, re-orientation, and polycondensation (Provis and van Deventer 2007).

In alkali-activation reaction, different parameters influence the reaction rate as well as morphology and properties of reaction product, among which the concentration of sodium oxide (Na2O) and the SiO2/Na2O ratio in the activator solution. It has been reported that zeolite crystalline phases were formed when aluminosilicate materials were activated with NaOH solution followed by hydrothermal treatment (LaRosa et al. 1992; Mondragon et al. 1990; Murayama et al. 2002), while amorphous phase is formed when only sodium silicate solution was used as activator (Duchesne et al. 2010). Consequently, in the case where a mixture of NaOH and sodium silicate solution are used, it is supposing that both crystalline and amorphous phases coexist in alkali activated products.

In this work, the effect of different types of alkali activators, with different sodium oxide contents and SiO2/Na2O ratios, on the nature and composition of the reaction products formed (N–A–S–H gel and/or zeolites). Three solutions (NaOH solution, sodium silicate solution and a mixture of NaOH and sodium silicate solution) were used to activate the fly ash. The fly ash-based alkali activated products were examined using different techniques (XRD, ATR-FTIR, 29Si MAS-NMR, 27Al MAS-NMR and FE-SEM with EDX). Furthermore, the

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mechanical properties of the alkali activated products, were examined by indentation test, and were correlated with the change in the microstructure of the resultant products.

2. Experimental procedure

2.1 Materials

Fly ash used in this study with a Si/Al mole ratio of ~ 2.3 is obtained from (Tohoku Electric Power Engineering & Construction Co. Inc.) and its major chemical composition is listed in Table 1. According to Japan Industrial Standard (JIS) (JIS A-6201 1999) the used fly ash is classified as Class II. The specific surface area and density are 3880 cm²/g and 2.3 g/cm³, respectively.

Reagent-grade sodium hydroxide (Nacalai Tesque, Inc., special grade) and a chemically pure sodium silicate solution (Junsei Chemical Co.), with composition Na₂O 17~19%, SiO₂ 35~38% were used as alkaline activators. NaOH pellets were dissolved in deionized water to obtain 7 mol/l NaOH solution. Sodium silicate is diluted with deionized water (~ 48.9%) in order to decrease its viscosity and permit more easy mixing with fly ash (Matsuda et al., 2018, 2017). All materials were stored overnight in controlled temperature room at 20 ± 2°C prior to mixing.

2.2 Specimens preparation

Fly ash and alkaline activators were mixed with a constant liquid to solid ratio (L/S = 0.3) in a planetary centrifugal mixer machine (Thinky Mixer, ARE-500) for 1 min at 1000 rpm at 20°C then the machine was stopped for 30 s to remove the adhered paste to container and remixed again for additional 1 min at the same speed. The mix proportions of the prepared specimens are tabulated in Table 2. The resultant paste was molded in a stainless-steel mold of 3 × 13 × 135 mm³ and subjected for curing at 80°C for 24 h. The specimens were covered with a plastic film to minimize the water evaporation during curing. After demolding, the specimens sealed with plastic sheets and kept in controlled temperature room at 20 ± 2°C until the testing age. At the desired time, the specimens immersed in isopropanol to stop the reaction then stored in vacuum desiccator for drying (Chen et al., 2014). The samples were grounded using a ball mill and sieved (< 100 µm) for analysis.

2.3 Mechanical Properties

Young’s modulus and Vickers hardness of the specimens were determined from indentation test. A Vickers indenter was attached to a compact tensile compression test machine and a load was applied on double side polished specimen until it reached 20 N and then unloaded. The indentation depth during loading and unloading was monitored by a laser displacement meter (Keyence LK-G30) with 0.0001 mm precision. The test was performed three times for each specimen and the average is calculated.

Young's modulus of the sample was computed from load depth curve (P-h curve) using Sneddon’s equation without direct confirmation of impression size (Pharr 1992).

\[
E = \frac{1}{\beta} \frac{\sqrt{\pi}}{2} \frac{S}{\sqrt{A}}
\]

where,
- \(E\): Young's modulus
- \(S\): contact stiffness
- \(A\): contact area
- \(\beta\): constant depending on the shape of the indenter

Contact stiffness \(S\) is obtained by the following equation, in which the slope of the unloading curve corresponds to a simple elastic recovery.

\[
S = \frac{dP}{dh}
\]

The contact area \(A\) is obtained by the following equation.

\[
A = 4 \frac{\tan \theta}{\cos \theta} h_i^2
\]

\[
h_i = h_{\text{max}} - h_s = h_{\text{max}} - \epsilon \frac{P}{S}
\]

where,
- \(\theta\): the angle between the central axis of the quadrangular pyramid and the side surface
- \(h_{\text{max}}\): the maximum indentation depth
- \(h_s\): the displacement of the surface
- \(\epsilon\): a constant

The following equation was used to calculate Vickers
2.4 Microstructure analysis

The phase composition of powdered samples of raw fly ash and hardened pastes is analyzed using X-ray diffraction (XRD) (D8 Advance, Bruker AXS) with Rietveld analysis. The phases content was determined by adding 10/wt. % corundum powder to the sample as an internal standard. The back-loading technique was used to prepare the specimens and a knife edge collimator was fitted to reduce the air scattering. The pattern was recorded by Cu–$\kappa$ radiation with $\lambda$ of 1.5406 Å and 40 kV tube voltage, 40 mA tube current, 2°/min scan speed, and scan speed 0.5°/min.

The weight fractions of quartz, hematite, magnetite, mullite and albite crystalline phases as well as total amorphous content in fly ash and alkali activated products were quantified using Rietveld analysis (Bish and Howard 1988). The software used for Rietveld analysis was TOPAS Ver. 4.1 (Bruker AXS) and the fundamental parameters approach was used to model the peak shapes (Cheary and Coelho 1992).

Attenuated total reflectance Fourier transform infrared (ATR-FTIR) spectrophotometer (ALPHA, Bruker) with a diamond crystal is used to follow the change in the structure with the activator type. All spectra were obtained by 128 scans and 4 cm$^{-1}$ resolution in wave numbers ranging from 1300 to 500 cm$^{-1}$. A blank measurement is performed to eliminate CO$_2$ peaks from the background.

Bruker Avance-300/MHz spectrometer equipped with a 9.4-T widebore magnet is used to collect the $^{29}$Si dipolar-decoupling (DD) magnetic angle spinning/nuclear magnetic resonance ($^{29}$Si MAS/NMR) spectra. Samples were placed in standard ZrO$_2$ rotors (7 mm) and rotated at MAS rates of up to 5/kHz using a standard cross-polarization (CP)-MAS probe. Number of scans was 5000 with a relaxation delay of 60 s. All spectra were recorded at room temperature and chemical shifts were referenced to hexamethyldisiloxane at $\delta = +9.55$ ppm relative to tetramethysilane. $^{27}$Al MAS NMR spectra were acquired on ECA700 spectrometer (JEOL) with a magnetic field of 16.4 T at room temperature using a CP-MAS probe with outer diameter 3.2 mm and ZrO$_2$ rotors at a spinning frequency of 18 kHz. The total accumulation time was 6400 s with a recycle delay of 0.5 s. Alum (AlK(SO$_4$)$_2$·12H$_2$O) was used as an external reference (0 ppm) for the measurement of chemical shift.

The morphology of the samples was observed through field emission scanning electron microscopy (FE-SEM; JSM-7500F, JEOL). Also, the elemental composition is characterized by energy-dispersive X-ray (EDX) analyzer (JED - 2300 F) attached to FE-SEM. Samples were dried at a temperature of 105°C under degassed conditions (with a minimum pressure of 0.067 Pa for 30 min and then coated with osmium. Fractions from indentation test were mounted on an electrically conductive sheet attached to the sample holders.

3. Results and discussion

3.1 Young's modulus and Vickers hardness

Figure 1 shows the Young’s modulus and Vickers hardness of fly ash-based alkali activated products calculated from the load-indentation depth curve (P-h curve). The values of Young's modulus were 1.76, 5.80 and 11.35 GPa while the Vickers hardness were 4.43, 37.86 and 82.33 HV2 for NA, MIX and LG, respectively. It is noted that an increase in the concentration of secondary silica in the activator solution enhanced the geopolymerization process resulting in an improvement in the mechanical properties. Sodium silicate activated fly ash attained the highest Young’s modulus and Vickers hardness due to the formation of a homogenous and denser aluminosilicate gel (geopolymer) with higher Si/Al ratio in the reaction product.

3.2 X-ray diffraction

The x-ray diffraction patterns of raw fly ash and alkali activated materials are shown in Fig. 2. Raw fly ash...
comprises glassy phase as indicated by a characteristic broad hump around 22° 2θ, as well as crystalline phases as observed by the sharp peaks of quartz, hematite, magnetite and mullite.

It should be noted that no crystalline peaks related to calcium-based phases were observed in raw fly ash pattern. However, this does not exclude the possible presence of amorphous calcium-based phase.

When fly ash was activated with NaOH (NA), a mixture of NaOH and sodium silicate solution (MIX) or sodium silicate solution (LG), the glassy component of fly ash starts to dissolve to form new amorphous alkali aluminosilicate gels which indicated by the apparent slight shift of broad hump of fly ash from 2θ 22° to 25°, 26° and 27° for NA, LG and MIX, respectively (Criado et al. 2007; Guo et al. 2010a, 2010b; Rattanasak and Chindaprasirt 2009).

During the initial dissolution step, it is expected that soluble calcium species are present in the solution phase, which may react with silicate (secondary silica added in MIX and LG) to form calcium silicate hydrate (CSH) and/or calcium aluminate silicate hydrate (CASH) phases, therefore the broad hump may include both geopolymer gel and C–(A)–S–H phases (Chindaprasirt et al. 2009; Guo et al. 2010a, 2010b; Rattanasak and Chindaprasirt 2009).

Sodium aluminosilicate gel together with zeolite, C–(A)–S–H phases as well as unreacted ash are expected to be presented after the activation of fly ash with different alkaline solutions and treatment at 80°C for 24 h. When fly ash was activated with different activator solutions, a significant change in the spectrum of fly ash is observed as the main band shifts to lower wavenumbers due to the formation of a new gel phase containing AlO4 (Rees et al. 2007). The main band (originally located at 1050 cm⁻¹) is shifted to 970 cm⁻¹, while become narrow and increase in its intensity when NaOH is used as an alkaline activator. Also, the shoulder band at 890 cm⁻¹ in fly ash is disappeared and a new shoulder band appeared at 855 cm⁻¹ attributed to Al–OH bond in certain Al-rich structures such as hydroxy-sodalite (previously identified in the XRD). In sample MIX, the main band is found at 990 cm⁻¹ while at 1000 cm⁻¹ in sample LG, this shifting in the main band is dependent on the content of Na2O and soluble silica in the activating solution and attributed to the change in Si/Al ratio in the reaction products.

### Table 3 XRD Rietveld analysis of fly ash and alkali activated products.

| Phase         | Sample | FA  | NA  | MIX | LG  |
|---------------|--------|-----|-----|-----|-----|
| Quartz        |        | 9.293 ± 0.29 | 8.86 ± 0.11 | 8.708 ± 0.72 | 6.978 ± 0.60 |
| Hematite      |        | 0.058 ± 0.16  | 0.061 ± 0.16  | 0.044 ± 0.15  | 0.035 ± 0.11  |
| Magnetite     |        | 0.438 ± 0.52  | 0.311 ± 0.62  | 0.233 ± 0.46  | 0.266 ± 0.42  |
| Mullite       |        | 14.18 ± 0.11  | 12.06 ± 0.16  | 12.31 ± 0.11  | 9.073 ± 0.93  |
| Hydroxy-sodalite |     | 0.00   | 4.06 ± 0.25  | 0.097 ± 0.58  | 0.013 ± 0.42  |
| Amorphous     |        | 75.6 ± 0.29  | 73.83 ± 0.44  | 78.34 ± 0.28  | 83.52 ± 0.29  |
| Total         |        | 99.99  | 99.60 | 78.34 ± 0.28  | 83.52 ± 0.29 |

### 3.3 FTIR

FT-IR spectroscopy can be used to directly identify the molecular structure of fly ash and the alkali-activated products in micrometer scale. The FTIR spectrum of the raw fly ash as well as spectra of reaction products of alkali activation with the solutions described in Table 2 are shown in Fig. 3. The raw fly ash FTIR spectrum shows a broad band centered at around 1050 cm⁻¹ corresponding to asymmetric stretching and a shoulder band at 890 cm⁻¹ assigned to symmetric stretching of vibrations of Si–O–T (T = Si or Al) (Fernández-Jiménez and Palomo 2005; He et al. 2016; Lee and Van Deventer 2003). The shoulders located at 1070, double band at 795 – 775 cm⁻¹ and band at 695 cm⁻¹ rises from the presence of quartz in raw fly ash (Gadsden 1975), in turn, shoulder around 1180 – 1130 cm⁻¹ attributed to octahedral aluminum in mullite (Jin et al. 2002).

Sodium aluminosilicate gel together with zeolite, C–(A)–S–H phases as well as unreacted ash are expected to be presented after the activation of fly ash with different alkaline solutions and treatment at 80°C for 24 h. When fly ash was activated with different activator solutions, a significant change in the spectrum of fly ash is observed as the main band shifts to lower wavenumbers due to the formation of a new gel phase containing AlO4 (Rees et al. 2007). The main band (originally located at 1050 cm⁻¹) is shifted to 970 cm⁻¹, while become narrow and increase in its intensity when NaOH is used as an alkaline activator. Also, the shoulder band at 890 cm⁻¹ in fly ash is disappeared and a new shoulder band appeared at 855 cm⁻¹ attributed to Al–OH bond in certain Al-rich structures such as hydroxy-sodalite (previously identified in the XRD). In sample MIX, the main band is found at 990 cm⁻¹ while at 1000 cm⁻¹ in sample LG, this shifting in the main band is dependent on the content of Na2O and soluble silica in the activating solution and attributed to the change in Si/Al ratio in the reaction products.
In fact, the shift towards lower wavenumber is larger with an increase in the Si/Al ratio.

3.4 Solid state $^{29}$Si and $^{27}$Al MAS NMR

It should be noted that in $^{29}$Si MAS NMR, the differences in peak positions and widths in the spectra are connected to the extent of ordering of Si$^{4+}$ and Al$^{3+}$, and the identification of silicate species is depending on its chemical shifts. Alkali activated aluminosilicate materials comprises different silicate species and an overlap of peaks may arise, preventing a confident interpretation of the $^{29}$Si MAS NMR spectra. Moreover, the quantification of Q$^4$ is difficult, because relaxation time is long. However, since the measurement was performed using the same conditions for every specimen, the relative relation is meaningful.

The $^{29}$Si MAS-NMR spectra of the raw fly ash and the reaction products formed during ash activation under hydrothermal curing condition are shown in Fig. 4. Table 4 presents the chemical shifts of Q sites and relative composition percentage in raw fly ash and alkali-activated products.

Noticeable changes are detected in the spectra imply chemical transformations during alkali activation of fly ash using different alkaline solutions. The spectrum of the original fly ash discloses a broad peak in the range of -80 and -120 ppm, suggesting the presence of different heterogeneous Q$^4$ structures. Six peaks are observed by deconvolution of original fly ash spectrum. The peaks at -80, -93 and -104 ppm are attributed to the vitreous material (Criado et al. 2008; Fernández-Jimenez et al. 2006; Fernández-Jiménez and Palomo 2003). The peak at -86 ppm corresponds to crystalline mullite (Gomes and François 2000; Zhang et al. 2018) while the two peaks at -108 and -112 ppm are assigned to Q$^4$(0Al) in quartz (Criado et al. 2008; Müller-Warmuth 1988).

In the absence of soluble silica, spectrum of NA exhibited peaks at -71, -79, -85, -87, -92, -103, -108 and -111 ± 1 ppm, which are located at approximately the same peak positions of zeolites (Klinowski 1984; Müller-Warmuth 1988; Neuhoff et al. 2003). Peaks at chemical shifts less than -80 ppm are normally attributed to monomeric and dimeric units (Q$^0$ and Q$^1$) due to the dissolution of raw fly ash by alkaline activator. The peak at -85 ppm is assigned to hydroxy-sodalite of Q$^4$(4Al) units (Engelhardt et al. 1989). The peaks appearing at -87, -92 and -103 ppm are attributed to Q$^4$(4Al), Q$^4$(3Al) and Q$^4$(1Al), respectively. The peaks at higher chemical shifts (-108 and -111 ppm) assigned to Q$^4$(0Al) from quartz in residual fly ash and its relative composition reflect the degree of the reaction. The relative composition of this peak is decreased from 45.5% in raw fly ash to 20.9%.

When the alkaline solution containing soluble silica, peaks at -71, -79, -85, -87, -92, -96, -103, -108 and -111 ± 1 ppm are observed. The additional peak at -96 ppm in both MIX and LG spectra is attributed to aluminosilicate gel Q$^4$(2Al) with relative composition of 10 and 18.5 %, respectively. The higher relative composition of this peak indicating a gel with a higher Si/Al ratio in LG. The deconvoluted peak identified at -85 ppm, might belongs to Q$^4$ units in amorphous CSH, produced due to reaction between soluble calcium from fly ash and soluble silica.

![Fig. 4 29Si NMR-MAS spectra of raw fly ash and alkali activated products.](image-url)
form sodium silicate solution. This peak is extremely overlapped with zeolite peak (Buchwald and Dombrowski 2005).

Figure 5 depicts the $^{27}$Al MAS NMR spectra of fly ash as well as the reaction products of alkali-activated fly ash. The spectrum of raw fly ash displays two broad peaks, one centered at +60 ppm, associated with tetrahedral aluminum ($\text{Al}_T$) and another at +9 ppm, ascribed to octahedral aluminum ($\text{Al}_O$). The octahedral aluminum confirming the presence of mullite in raw fly ash (Palomo et al. 2004; Sun et al. 2006).

As can be seen from Fig. 5, the location of $\text{Al}_O$ groups unchanged upon alkaline activation, indicating that mullite in fly ash shows limit contribution in the activation reaction. The peak of $\text{Al}_T$ groups become sharper and slightly shifted to positive chemical shifts, indicating a higher silicon surrounded $\text{Al}_T$ in 3D network after activation. Specimen NA exhibits a significant increment in the peak relative intensity of $\text{Al}_T$ groups.

### 3.5 FE-SEM and EDX

FE-SEM and EDX can provide information about the morphology and elemental composition of alkali-activated products. Figure 6 represents the SEM images of al-

| Sample | $Q^0$ | $Q^+$ | $Q^4$ | $Q^4(4\text{Al})$ | $Q^4(3\text{Al})$ | $Q^4(2\text{Al})$ | $Q^4(1\text{Al})$ | $Q^4(0\text{Al})$ | $Q^4(0\text{Al})$ |
|--------|-------|-------|-------|-------------------|-------------------|-------------------|-------------------|-------------------|-------------------|
| Fly ash| 0.0   | 1.0   | 3.0   | 16.0             | 0.0              | 35.0             | 3.0               | 41.0             |
| LG     | 2.0   | 2.0   | 8.0   | 1.0              | 19.0             | 18.0             | 30.0              | 3.0               | 16.0             |
| MIX    | 5.0   | 3.0   | 12.0  | 1.0              | 30.0             | 10.0             | 25.0              | 4.0               | 9.0               |
| NA     | 5.0   | 4.0   | 11.0  | 4.0              | 32.0             | 0.0              | 22.0              | 5.0               | 16.0             |

Fig. 5 $^{27}$Al MAS NMR spectra of (a) fly ash, (b) LG60, (c) MIX60 and (d) NA60.

Fig. 6 FE-SEM images of (a) NA60, (b) MIX60 and (C) LG60 and (d) EDX analysis.
kali-activated products and the EDX results at marked locations confirming their elemental compositions.

As can be seen, different proportions of unreacted fly ash spheres remain in the matrix of specimens after the activation. Figure 6a shows a reaction product layer with Si/Al ratio of 2.37, embedded fly ash particle, in NaOH activated specimen. Moreover, a crystalline zeolitic material (hydroxy-sodalite as confirmed previously by XRD) is observed on the external surface of unreacted fly ash. The Si/Al ratio of this crystalline zeolite is 4.35. In Fig. 6b, when a mixture of NaOH and sodium silicate solution was used as an activator, needle-shaped crystals were seen on the surface of fly ash particles, which also reported by (Jang and Lee 2016; Yousefi Oderji et al. 2017). Also, it is noted that a lower volume of pores exists. A homogeneous and denser structure is observed when fly ash was activated with sodium silicate solution, Fig. 6c, with no evidence of crystalline phase. This might be explaining why this specimen was achieved the highest mechanical strength.

3.6 Structure – mechanical properties relationship

The variation of the mechanical properties with change of alkaline activator composition can be reconciled with the observed changes in the structure of alkali activated materials, and further related to microstructural aspects. Figures 7 shows a correlation between the young’s modulus of alkali activated materials and amount of amorphous content and Q4(mAl) units (4 ≥ m ≥ 1) units in the alkali activated materials. It can be seen that; the Young’s modulus is enhanced as the amorphous content increased in the alkali activated material. However, the mechanical properties not only depend on the amorphous content, but also on the network structure of the amorphous phase. Theoretically, Si-O-Si linkages are stronger than Si-O-Al and A-O-Al bonds (de Jong and Brown 1980), which means that the strength will increase with Si/Al ratio. As shown in Fig. 7, there is a relationship between the amount of Q4(mAl) units in the gel of the alkali activated materials and the mechanical properties. In agreement with previous work (Criado et al. 2016), the Young’s modulus is increased with increasing in the amount of Q4(1Al) and Q4(2Al) units (higher Si/Al ratio) in the alkali activated materials. On the contrary, an increase in the Q4(3Al) and Q4(4Al) units (low Si/Al ratio) in the alkali activated material, reduce the young’s modulus.

4. Conclusions

Different tests were carried out to investigate the effect of alkaline activators on the composition, microstructure and mechanical properties of alkali-activated fly ash-based pastes. Alkaline activator solutions of different Na2O contents and SiO2/Na2O ratios were used. The sodium silicate activated fly ash attained the highest Young’s modulus and Vickers hardness due to the formation of a homogenous and denser aluminosilicate gel (geopolymer) with high Si/Al ratio in the reaction product. A lower amount of aluminosilicate gel is produced when fly ash was activated with a mixture of NaOH and sodium silicate solution, with presence of some pores. When fly ash hydrothermally activated with NaOH, a hydroxy-sodalite is formed with quartz and mullite phases from unreacted fly ash. Finally, the content of Na2O and the SiO2/Na2O ratio of the activator has a profound effect on phases formed during activation and that reflected on the mechanical properties of alkali activated materials.

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