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The effect of different Na₂O and K₂O ratios of alkali activator on compressive strength of fly ash based-geopolymer

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Abstract

Fly ash sourced from Sarawak, Borneo was alkali-activated by a combination of alkali hydroxides (i.e. NaOH, KOH or Ca(OH)₂) and sodium silicate (i.e. industrial or commercial grade Na₂SiO₃) in this research. A comprehensive overview of the compressive strength of geopolymer due to different alkali activator/fly ash and Na₂SiO₃/NaOH (Na₂SiO₃/KOH or Na₂SiO₃/Ca(OH)₂) were studied. The results show that geopolymer made using Sarawak fly ash can be a potential construction material depending on the requirements of workability and compressive strength. The core study of this research was the investigation on the variations of compressive strength due to the oxide molar ratios. The results revealed that higher oxide molar ratios do not necessarily lead to higher compressive strengths. SiO₂/Na₂O, Al₂O₃/Na₂O, SiO₂/K₂O and Al₂O₃/K₂O weight ratios had dissimilar effects on the compressive strength of NaOH- and KOH-based geopolymer. The reduction of SiO₂/Na₂O and Al₂O₃/Na₂O in NaOH- and KOH-based geopolymer using commercial grade Na₂SiO₃ intensively

increased the strength capability. The ratios of $\text{SiO}_2/\text{Na}_2\text{O}$ and $\text{Al}_2\text{O}_3/\text{Na}_2\text{O}$ in $\text{Ca}(\text{OH})_2$ -based geopolymer were the highest, nevertheless, the compressive strength and workability of $\text{Ca}(\text{OH})_2$ -based geopolymer were the weakest in comparison to NaOH - and KOH -based geopolymers. Na_2O was postulated as the major alkali oxide required for the strength development rather than K_2O in both NaOH - and KOH -based geopolymer. However, K_2O in KOH -based geopolymer may govern the strength development when Na_2O is low in the mixture.

Keywords

Geopolymer, Sarawak fly ash, alkali activator/ash, mixture proportions, compressive strength

1. Introduction

In Malaysia, there are a total of 6 power stations in the country. 4 power stations situate in Peninsula Malaysia namely, Tanjung Bin Power Station in Johor ($700 \text{ MW} \times 3$ units), Jimah Power Station in Negeri Sembilan ($700 \text{ MW} \times 2$ units), Sultan Azlan Shah Power Station in Manjung ($700 \text{ MW} \times 3$ units) and Sultan Salahuddin Abdul Aziz Power Station in Kapar ($752 \text{ MW} \times 2$ units) [1, 2]. 2 power stations are located in Sarawak, Borneo namely, Sejingkat Power Station in Kuching ($50 \text{ MW} \times 2$ units and $55 \text{ MW} \times 2$ units) and Mukah Power Station in Mukah ($135 \text{ MW} \times 2$ units).

The consumption of coal for annual combustion is approximately 1 million tons at Sejingkat Power Station. The production of fly ash is approximately 7 to 10% out of the annual coal consumption. Most of the captured fly ash is disposed into the ash ponds nearby and only some of the fly ash has been utilised for construction purposed. As the

environmental issue becomes global concern, it is crucial to widen the application of this industrial waste in order to reduce the disposal rate.

There are several types of alkali activators that can be used to activate fly ash. For example, sodium hydroxide (NaOH) [3-8], potassium hydroxide (KOH) [3, 4], sodium silicate (Na_2SiO_3) [3-8], potassium silicate (K_2SiO_3) [3, 4], calcium hydroxide ($\text{Ca}(\text{OH})_2$) [9-11] etc. The combined use of NaOH and Na_2SiO_3 is the most common practice in term of cost effectiveness to produce geopolymer with good compressive strength than the solely use of alkali silicate or hydroxide.

The ratio of alkali activator/ash can be a critical parameter to the strength development [12]. High alkali activator/ash increases the viscosity and difficulty in compaction [13]. The workability and compressive strength decrease by further increment of the alkali activator/ash and $\text{Na}_2\text{SiO}_3/\text{NaOH}$ [8]. Hardjito and Rangan [14] suggested that $\text{Na}_2\text{SiO}_3/\text{NaOH}=2.5$ by mass is suitable for fly ash-based geopolymer synthesis in term of cost effective and consistency of the results. The change of Si content and Na^+ ion due to different ratios of alkali activators have significant effect on the geopolymerisation as well as the strength development [15]. The increase of Si content increases the $\text{SiO}_2/\text{Al}_2\text{O}_3$ ratio resulting in more formation of Si-O-Si bonds [16], which are stronger than Si-O-Al and Al-O-Al bonds [17], thus leading to strength gain.

Xu and Deventer [18] claim that KOH-based geopolymer obtains higher compressive strength compared with NaOH-based geopolymer. Although NaOH solution exhibits higher extent of mineral dissolution, better geopolymerisation in KOH solution enhances the strength development. However, Palomo, Grutzeck [4] reported that KOH-based geopolymer does not certainly lead to the highest compressive strength. NaOH-

based geopolymer may obtain higher compressive strength than KOH-based geopolymer when the curing temperature, curing age or alkali activator/ash is varied. Duxson, Mallicoat [19] concluded that the Si/Al is a significant parameter on the study of effect of alkali cation from the alkali activators on the compressive strength.

Na₂O and K₂O ratios of alkali activator are different in various mixture ratios. It has been reported in term of SiO₂/Na₂O and Al₂O₃/Na₂O elsewhere. However, limited study on the ratio of K₂O has been reported. The increment of silicate solution increases the ratio of SiO₂/Na₂O [9, 20]. Geopolymer tends to be less stable at low SiO₂/Na₂O than at high SiO₂/Na₂O [20]. The highest compressive strength is obtained at intermediate ratio of SiO₂/Na₂O [7]. However, it declines simultaneously with the increment of SiO₂/Na₂O and Al₂O₃/Na₂O [5].

The effect of different ratios of alkali activator/ash and Na₂SiO₃/NaOH (KOH) on compressive strength of fly ash-based geopolymer has been studied by many researchers as mentioned earlier on. However, the study of mentioned ratios on geopolymer using Sarawak fly ash is still very limited. The appropriate mixing ratio to obtain the desired compressive strength and workability for industrial usage remains unclear. The effects of Si/Al, SiO₂/Na₂O and Al₂O₃/Na₂O have been reported elsewhere [3, 5, 7, 9, 20-24]. However, the study on variation of Na₂O and K₂O due to different ratios of alkali activator is very limited. The main objective of this research is to develop a comprehensive overview on compressive strength of geopolymer using Sarawak fly ash at different mixture ratios. It is aimed to provide a better understanding of Sarawak fly ash-based geopolymer for developing industrial applications in Sarawak. Essentially, this research studies the compressive strength of geopolymer in term of

oxide molar ratios in particular the effect of different Na₂O and K₂O due to different ratios of alkali activator.

2. Experimental Procedure

2.1. Materials

Sarawak fly ash obtained from Sejingkat Power Station was used in this research. **Table 1** shows the chemical compositions of the fly ash using WD-X-ray Fluorescence Spectrometer (WD-XRF). This fly ash can be classified as Class F type in accordance to the ASTM-C618 [25] standard.

The chemical compositions of fly ash sourced from other coal fired power stations in Malaysia reported by other researchers [26, 27] are also tabulated in **Table 1**. It is worth to mention that fly ash source from same power station may behave differently in chemical compositions when the collection time is different [2, 28-31]. However, the studies of fly ash sourced from Mukah Power Station and Jimah Power Station is very limited.

The results show that the chemical compositions of fly ash sourced from different power stations in Malaysia show dissimilarity. It could be due to the sources of combustion coal, coal type, geology of coal etc. [32]. All the fly ash is classified as Class F type except the fly ash sourced from Sultan Azlan Shah Power Station which is classified as Class C type. The studied fly ash shows moderate percentage of SiO₂ and Al₂O₃ content but low Fe₂O₃ and CaO content in comparison to the other fly ash sourced from different power stations. The MnO content in the studied fly ash is found to be extraordinary. Furthermore, it is similar to the MnO content in manganese slag as shown in **Table 1**. Juda-Rezler and Kowalczyk [33] reported that Mn content can be

bounded in pyrite and illite minerals in the original coal which should be removed during pre-combustion coal cleaning. The results have shown well agreement to Sia and Abdullah [34] reported that the Mn content in fly ash produced from Balingian coal in Sarawak is much higher and commonly higher than the original coal. It implies the low volatility of this content when it is subjected to combustion.

Washed sand with saturated surface dry condition was prepared prior to sample casting. Four series of alkali activators were studied in this research. Series 1 was a combination used of 8M NaOH and industrial grade Na_2SiO_3 . Series 2 was a combination used of 8M KOH and industrial grade Na_2SiO_3 . Different ratios of alkali activator/ash (0.3, 0.4, 0.5 and 0.6) and $\text{Na}_2\text{SiO}_3/\text{NaOH}$ or $\text{Na}_2\text{SiO}_3/\text{KOH}$ (0.5, 1, 1.5, 2, 2.5 and 3) were studied. Industrial grade Na_2SiO_3 (8.8%~9.5% Na_2O and 28%~30.6% SiO_2 by weight) was then completely replaced with the commercial grade Na_2SiO_3 (12% Na_2O and 30% SiO_2 by weight) in samples of alkali activator/ash=0.4; this was denoted to Series 3. This series provides in-depth study on the effect of different grades (i.e. different compositions of SiO_2 and Na_2O) of Na_2SiO_3 on compressive strength in particular to the oxide molar ratio. Finally, a combination used of $\text{Ca}(\text{OH})_2$ and commercial grade Na_2SiO_3 was used to produce $\text{Ca}(\text{OH})_2$ -based geopolymer (Series 4). KOH or NaOH was replaced by $\text{Ca}(\text{OH})_2$ in order to study the performance of strength and workability in comparison to the more commonly use of NaOH- and KOH-based geopolymer.

Table 1. Chemical Composition of Fly Ash

Elements (%)	Fly Ash				Manganese Slag [35]
Power Station	Sejingkat Power Station	Sultan Azlan Shah Power Station [26]	Sultan Abdul Aziz Shah Power Station [26]	Tanjung Bin Power Station [27]	-
Location	Kuching, Sarawak	Manjung, Perak	Kapar, Selangor	Pontian, Johor	-
SiO ₂	43.8	26.4	52.11	40.08	28.3
Al ₂ O ₃	18.1	9.25	23.59	18.81	10.5
Fe ₂ O ₃	7.7	30.13	7.39	17.7	0.3
CaO	3.9	21.6	2.61	14.32	11
MgO	0.5	-	-	1.52	14.9
MnO	22.8	0.27	0.49	-	26
K ₂ O	2	2.58	0.42	1.84	5.1
Na ₂ O	0.3	-	0.78	0.72	2.7
SO ₃	0.1	1.3	1.31	0.1	-
TiO ₂	0.6	3.07	0.88	4.44	-
P ₂ O ₅	0.1	0.67	0.8	0.37	-
BaO	-	-	-	0.85	-
LOI	0.5	-	-	-	-

Note: The chemical compositions of fly ash source from Mukah Power Station and Jimah Power Station are not available elsewhere

2.2. Sample Preparation and Tests

The mixture ratios of the geopolymer samples are tabulated in **Table 2**. Fly ash was initially mixed with sand using the Mortar mixer. The alkali activators were then added into the mixture for further mixing of 5 minutes. The mixture was casted into the cubic moulds with dimensions of 50mm × 50mm × 50mm. The samples were placed on the vibrating table to remove the air bubbles within the sample. After the vibration finished, the samples were sealed with plastic sheet to prevent the loss of moisture during the

heat curing in oven at 60°C for 24 hours. The samples were then demoulded for cube test or further curing at room temperature until the date test.

The workability of the mixture and the compressive strength of the samples were obtained using the flow table in accordance to the ASTM-C1437 [36] standard and compression test machine in accordance to the ASTM-C109/C109M [37] standard, respectively.

The designation of each sample is represented as ‘Series No. / Use of NaOH, KOH or Ca(OH)₂/ Na₂SiO₃/NaOH(KOH or Ca(OH)₂)/ Alkali activator/ash/ Water/binder’. For example, S1/Na/0.5/0.3/0 denotes the sample at Series 1, use of NaOH with Na₂SiO₃/NaOH=0.5, alkali activator/ash=0.3 and water/binder=0.

Table 2. The mixture ratios of the geopolymer samples

Series	Ash/sand ratio	Alkali activator type	Na ₂ SiO ₃ /NaOH (KOH or Ca(OH) ₂) ratio	Alkali activator/ash ratio	Water /binder
1	1:2	NaOH and industrial grade of Na ₂ SiO ₃		0.3,0.4,0.5,0.6	-
2	1:2	KOH and industrial grade of Na ₂ SiO ₃	0.5, 1, 1.5, 2, 2.5, 3	0.3,0.4,0.5,0.6	-
3	1:2	NaOH or KOH and commercial grade of Na ₂ SiO ₃		0.4	-
4	1:2	Ca(OH) ₂ and commercial grade of Na ₂ SiO ₃	0, 0.5, 1, 2, 3	0.3	0.4
			0.5	0.3,0.4,0.5,0.6	0.4
			0.5	0.3	0.4,0.5,0.6,0.7

3. Results and Discussion

3.1. Workability

From the alkali activator/ash point of view, the workability increases when the ratio is increased as shown in **Figs. 1a-1b**. The highest workability (i.e., approx. 250 mm) is

obtained at alkali activator/ash of 0.6. As the amount of the liquid content is greater than the solid content at higher ratio, the mixture tends to become more fluid thus enhancing the workability. It is also observed that the final volume of the mixture decreases when more liquid content is added to the mixture. It is most likely due to the better dissolution of fly ash when higher alkali activator/ash is used. When less liquid content is presented in the mixture at alkali activator/ash of 0.3, the workability is unmeasurable. It is because that the mixture collapses instead of flowing when it is subjected to flow table test. It is supposed that the alkali activators are insufficient to dissolve the fly ash particles. Most of the solid particles are still clearly seen throughout the mixture. In general, KOH-based geopolymer shows higher workability than NaOH-based geopolymer. It is most probably due to higher solubility of potassium than sodium.

The effect of $\text{Na}_2\text{SiO}_3/\text{NaOH(KOH)}$ on the workability is in the decreasing manner as represented in **Fig. 1c-1d**. The highest workability is obtained on the samples with $\text{Na}_2\text{SiO}_3/\text{NaOH(KOH)}$ ratio of 0.5 but the lowest at ratio of 3. It can be explained by the different percentage of Na_2SiO_3 and NaOH(KOH) in the mixtures. As Na_2SiO_3 is highly viscous, it increases the viscosity of the mixture when the ratio is increased thus reducing the workability. Inversely, the fluid-like nature of NaOH or KOH increases the workability.

As shown in **Figs. 1c-1d**, the workability of KOH-based geopolymer is generally higher than the NaOH-based geopolymer when commercial grade Na_2SiO_3 is used. It is found that the workability of NaOH-based geopolymer decreases but KOH-based geopolymer increases when commercial grade Na_2SiO_3 is used in comparison to industrial grade Na_2SiO_3 . It is noted that, according to our visual observations, the viscosity of commercial grade Na_2SiO_3 is slightly higher than the industrial grade

Na_2SiO_3 . The increase of concentration in silicate may increase the viscosity of solution [38] thus reducing the workability. However, it is supposed that the solubility of potassium has superior effect than the viscosity of silicate on workability when $\text{Na}_2\text{SiO}_3/\text{KOH}$ is low (i.e. higher amount of KOH than Na_2SiO_3). It explains why the workability of geopolymer using commercial grade Na_2SiO_3 is similar or lower than those using industrial grade Na_2SiO_3 at higher $\text{Na}_2\text{SiO}_3/\text{KOH}$.

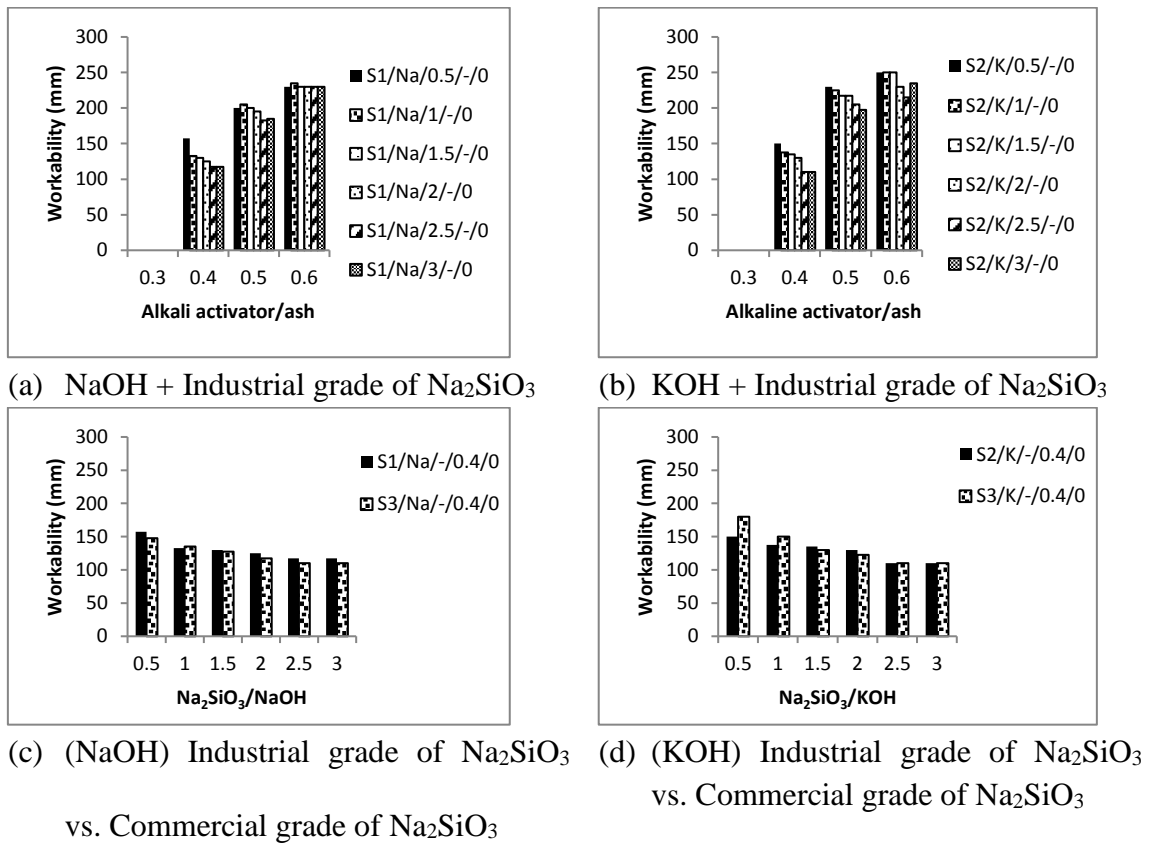


Fig. 1 Workability of the mixtures

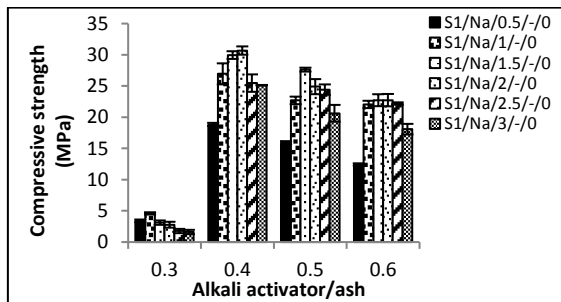
3.2. Compressive Strength

3.2.1. Effect of alkali activator/ ash on compressive strength

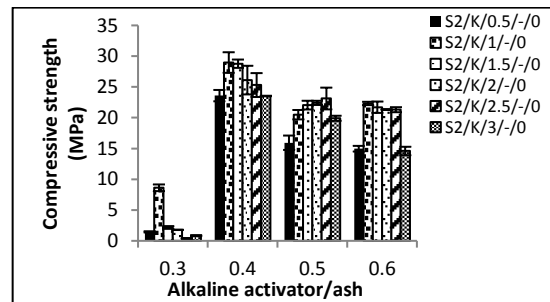
Fig. 2 shows the effect of alkali activator/ash on compressive strength of NaOH- or KOH-based geopolymer using industrial grade Na_2SiO_3 . When the alkali activator/ash

is very low (i.e., 0.3), the compressive strength is insignificant. It is supposed that the low amount of alkali activator at lower alkali activator/ash is insufficient to react with the fly ash as mentioned earlier. Therefore, the formation of rigid and coherent structure is unlikely consequently lowering the compressive strength. The compressive strength initially increases but decreases with the further increment of alkali activator/ash. The optimum compressive strength was observed at alkali activator/ash of 0.4 regardless of the type of alkali activators and curing conditions. It could be due to the higher extent of dissolution of fly ash when the alkali activator/ash is increased.

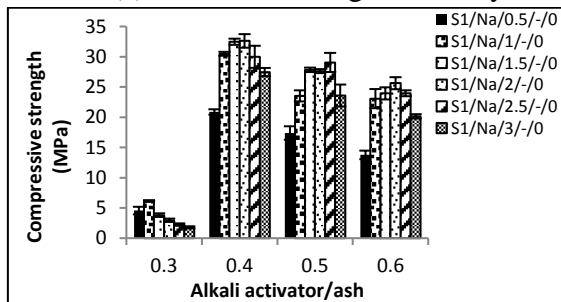
It was observed that fewer air bubbles are released from the sample surface at alkali activator/ash of 0.4 during the vibration. In comparison, greater amount of continuous air bubbles move towards the surface when the alkali activator/ash is increased. It is supposed that air bubbles which are not able to release from the sample may create pores thus producing more porous structure. The pores leave within the sample may weaken the geopolymer structure and compressive strength.



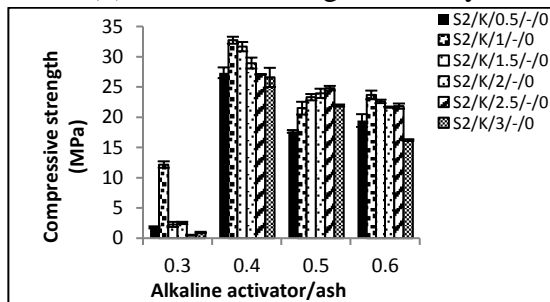
(a) Series 1: 60 degree – 1 day



(d) Series 2: 60 degree – 1 day



(b) Series 1: 60 degree – 7 days



(e) Series 2: 60 degree – 7 days

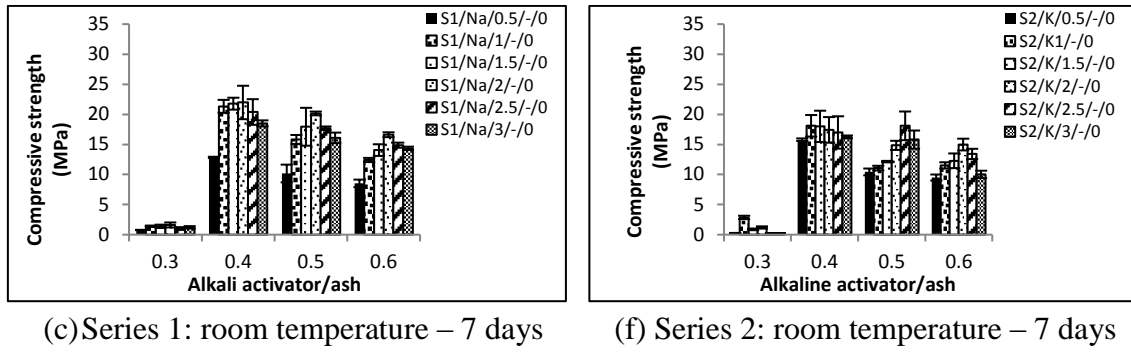


Fig 2. The effect of alkali activator/ash on compressive strength using industrial grade of Na_2SiO_3 with (a-c) Series 1: NaOH (d-f) Series 2: KOH

3.2.2. Effect of $\text{Na}_2\text{SiO}_3/\text{NaOH}$ or $\text{Na}_2\text{SiO}_3/\text{KOH}$ ratio on compressive strength

Fig. 3 shows that the compressive strength increases when $\text{Na}_2\text{SiO}_3/\text{NaOH}$ (KOH) is increased. Duxson, Provis [20] claim that the amount of aluminosilicate gel form is correlated with the compressive strength of geopolymer, in which higher formation of gel will lead to higher geopolymer strength. The highest compressive strength was obtained at $\text{Na}_2\text{SiO}_3/\text{NaOH}=2$ and $\text{Na}_2\text{SiO}_3/\text{KOH}=1$, both have alkali activator/ash of 0.4. Further increment results in strength loss. As the amount of Na_2SiO_3 within the sample rises, it provides more Si content to the system for geopolymerisation thus improving the strength gains [18]. However, excessive Na_2SiO_3 inhibits the geopolymerisation due to the formation of aluminosilicate gel precipitation [39-42]. It furthers apart the aluminosilicate source (i.e. fly ash) and the alkali activators. Therefore, it is supposed to obstruct the alkali hydroxide to leach out the Al and Si content from the reacting material and hinder the alkali hydroxide as catalyst in the system. Additionally, this excessive silicate from higher ratio of $\text{Na}_2\text{SiO}_3/\text{NaOH}$ (KOH) affects the water evaporation during the condensation reaction [43]. The excessive Na^+ may

form sodium carbonate when it contacts with CO₂ from the atmosphere subsequently reducing the strength development [44].

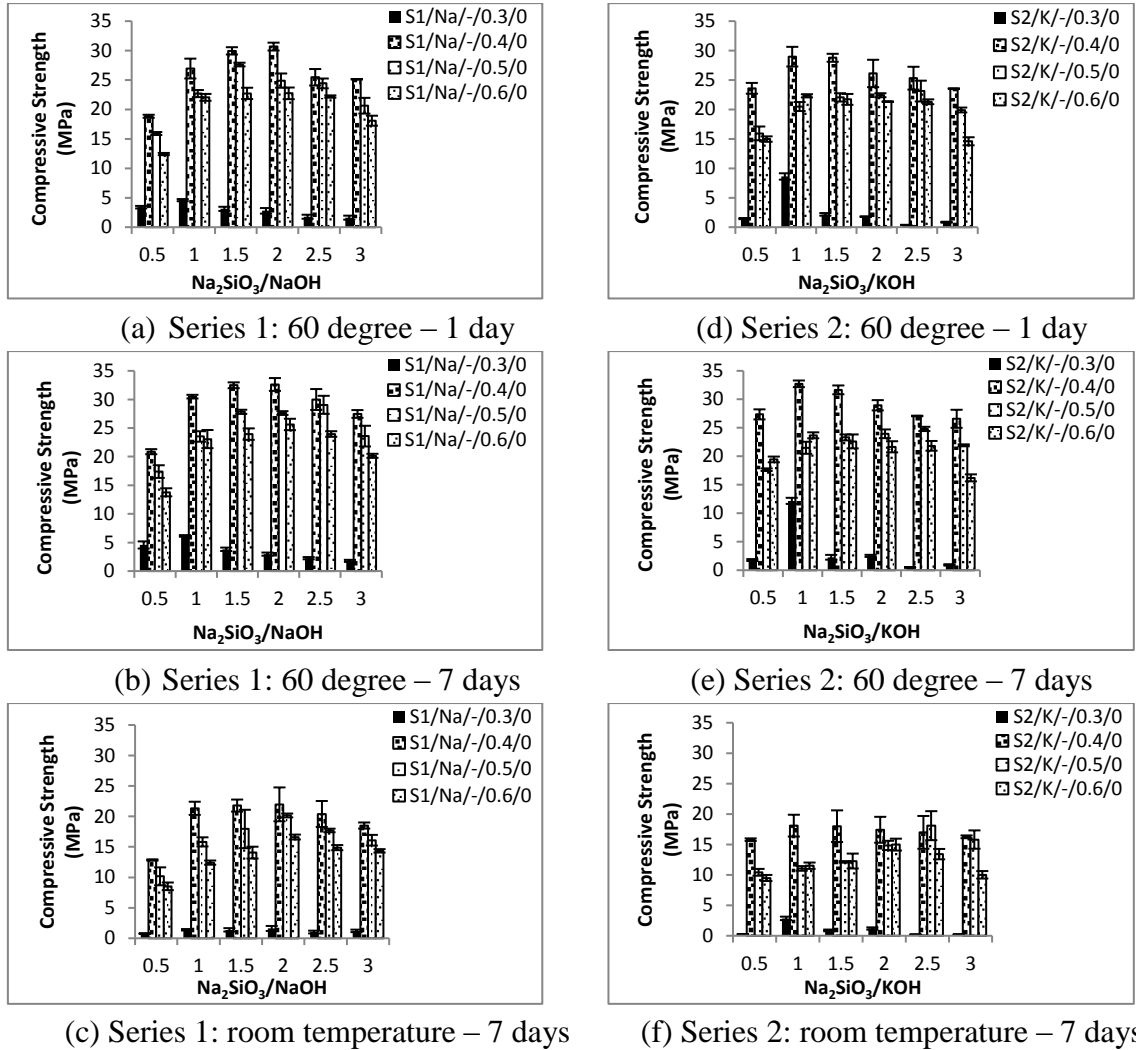


Fig 3. The effect of $\text{Na}_2\text{SiO}_3/\text{NaOH}$ or $\text{Na}_2\text{SiO}_3/\text{KOH}$ on compressive strength using industrial grade of Na_2SiO_3 with (a-c) Series 1: NaOH and (d-f) Series 2: KOH

3.2.3. Comparison of strength performance between NaOH- and KOH-based geopolymer

In this section, the effect of NaOH- and KOH-based geopolymers using industrial grade Na_2SiO_3 on the compressive strength is only considered. Those using commercial grade Na_2SiO_3 will be discussed here-in-after.

As shown in **Fig. 4**, the compressive strength of both NaOH- and KOH-based geopolymers cured at 60°C after 1 day and 7 days are similar. At $\text{Na}_2\text{SiO}_3/\text{NaOH(KOH)}=0.5$ and 1, KOH-based geopolymer shows higher compressive strength than NaOH-based geopolymer. It is because KOH-based geopolymer has lower porosity in its structure [3]. Additionally, KOH solution is capable to leach out more Al content than Si content as compared with NaOH solution [45]. The negative charge of Al^{3+} in IV fold coordination can be compensated by the positive charge of alkali ion such as K^+ or Na^+ [46]. Xu and Deventer [18] state the K^+ from KOH solution favours the formation of ionic pair (i.e. cation-anion) reaction with larger silicate oligomers. It demonstrates more existence of the geopolymer precursors (i.e. long chain silicate oligomers and Al-O-Si complexes) thus revealing stronger compressive strength.

When $\text{Na}_2\text{SiO}_3/\text{NaOH(KOH)}$ is greater than 1.5, NaOH-based geopolymer obtains higher compressive strength than KOH-based. It seems that the dissolution of KOH-based geopolymer tends to become lower and the geopolymerisation is affected by the increase of silicate content. Xu and Deventer [18] claim that higher extent of dissolution is expected in NaOH-based geopolymer than in KOH-based. The smaller ionic size of Na^+ than K^+ favours the ionic pair reaction with the smaller silicate oligomers thus enhancing the bond strength. Whereas, stronger ionic pair formation is anticipated when higher amount of sodium silicate is used.

At room temperature after 7 days, NaOH-based geopolymer obtains higher compressive strength of approx. 12% to 23% than KOH-based geopolymer. It shows that NaOH-based geopolymer exhibits better performance on compressive strength than KOH-based at room temperature.

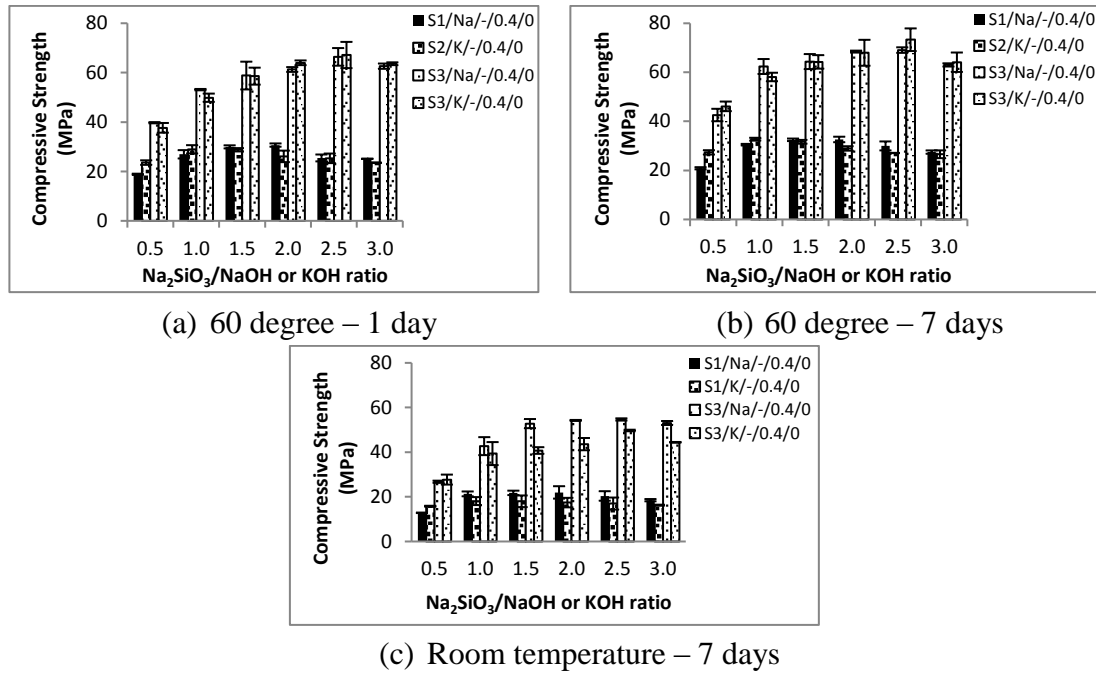


Fig 4. The effect of NaOH and KOH on the compressive strength

3.2.4. Compressive strength of geopolymer in term of oxide molar ratios

As shown in **Fig. 5**, the oxide molar ratios of geopolymer is governed by the ratios of $\text{Na}_2\text{SiO}_3/\text{NaOH}(\text{KOH})$ and alkali activator/ash. Both amorphous and crystalline phase of SiO_2 and Al_2O_3 are considered. The optimum $\text{SiO}_2/\text{Al}_2\text{O}_3$, CaO/SiO_2 , $\text{SiO}_2/\text{Na}_2\text{O}$ and $\text{Al}_2\text{O}_3/\text{Na}_2\text{O}$ ratios for the highest compressive strength on NaOH-based geopolymer in this research are 4.846, 0.081, 10.167 and 2.098, respectively. For same oxide molar ratio studies, it is 4.662, 0.084, 10.822 and 2.321 on KOH-based geopolymer, respectively. These confirm that the highest compressive strength is achievable at intermediate ratios. Higher ratios of the oxide molar do not necessarily lead to higher compressive strength. The optimum oxide molar ratios with high pH value allow the breakage of the glassy chain on fly ash surface through the alkaline activation. Thus, the internal Si and Al components can react with the alkali ion (e.g. Na^+) subsequently producing the amorphous reaction products through the geopolymerisation [5].

When alkali activator/ash is increased, $\text{SiO}_2/\text{Al}_2\text{O}_3$ increases but CaO/SiO_2 , $\text{SiO}_2/\text{Na}_2\text{O}(\text{K}_2\text{O})$ and $\text{Al}_2\text{O}_3/\text{Na}_2\text{O}(\text{K}_2\text{O})$ decrease regardless of types of geopolymer. The exception is observed when the alkali activator/ash is increased, $\text{SiO}_2/\text{K}_2\text{O}$ of NaOH-based geopolymer increases.

For both NaOH- and KOH-based geopolymer, $\text{CaO}/\text{Al}_2\text{O}_3$ is constant at 0.392 as shown in **Figs. 5a-5b**. It is because the alkali activators do not contribute to CaO and Al_2O_3 . These two oxides are provided by fly ash.

Figs. 5c-5d shows higher compressive strength is achievable when $\text{SiO}_2/\text{Al}_2\text{O}_3$ is increased. It is most likely due to the denser formation of Si-O-Si bond, which is shorter and stronger than Si-O-Al or Al-O-Al bonds [17, 20]. Strength loss by further increment of $\text{SiO}_2/\text{Al}_2\text{O}_3$ could be due to high alkali activator/ash which produces more porous structure. Large pores with some microcracks and inhomogeneity of microstructure [3], associate with the reduction of lability of the geopolymeric gel synthesis due to high Si/Al further reduces the dissolution rate of the aluminosilicate material and the structural reorganization and gel densification. When $\text{SiO}_2/\text{Al}_2\text{O}_3$ is low, sample appears to be loosely packed and large number of interconnected pores and voids between particles due to the unreacted material reduces the compressive strength [20].

The effect of CaO/SiO_2 on the compressive strength as represented in **Figs. 5e-5f**. It shows that the compressive strength decreases when CaO/SiO_2 is decreased regardless of the ratios of alkali activator/ash or $\text{Na}_2\text{SiO}_3/\text{NaOH}(\text{KOH})$. The formation of C-(N)-A-S-H gel due to small amount of CaO content in Class F type fly ash may contribute to some strength built up of geopolymer [47]. As shown in **Figs. 5c-5d** and **Figs. 5e-5f**, $\text{SiO}_2/\text{Al}_2\text{O}_3$ and CaO/SiO_2 are constant. It is because the used of NaOH or KOH in the mixture does not contribute to $\text{SiO}_2/\text{Al}_2\text{O}_3$ and CaO/SiO_2 .

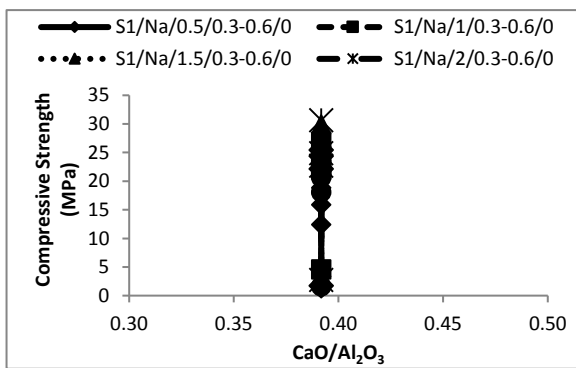
Figs. 5g-5h show similar pattern of results as **Figs. 5i-5j**. When $\text{Na}_2\text{SiO}_3/\text{NaOH}(\text{KOH})$ increases and constant alkali activator/ash ratio is only considered, the compressive strength of NaOH-based geopolymer increases with the increment of $\text{SiO}_2/\text{Na}_2\text{O}$ and $\text{Al}_2\text{O}_3/\text{Na}_2\text{O}$ (i.e. proportional relationship). Criado, Fernández-Jiménez [7] showed that higher degree of reaction product (i.e. sodium aluminosilicate gel) is achieved when the $\text{SiO}_2/\text{Na}_2\text{O}$ ratio is higher. More soluble silica due to higher ratio of $\text{SiO}_2/\text{Na}_2\text{O}$ will enhance the geopolymerisation thus increasing the compressive strength. However, the compressive strength of KOH-based geopolymer increases with the reduction of $\text{SiO}_2/\text{Na}_2\text{O}$ and $\text{Al}_2\text{O}_3/\text{Na}_2\text{O}$ (i.e. inversely proportional relationship). The lower reactivity and slower rate of reacting material dissolution may be the reason of causing the decline of compressive strength with respect to the increment of $\text{SiO}_2/\text{Na}_2\text{O}$ and $\text{Al}_2\text{O}_3/\text{Na}_2\text{O}$ ratios [7].

Higher $\text{Al}_2\text{O}_3/\text{Na}_2\text{O}$ in KOH-based geopolymer than in NaOH-based geopolymer could be attributed to the reduction of Na_2O in KOH-based geopolymer. Despite Na_2O content in fly ash, Na_2O in NaOH-based geopolymer is provided by both NaOH and Na_2SiO_3 ; however, Na_2O in KOH-based geopolymer is solely provided by Na_2SiO_3 . Having the constant alkali activator/ash, it is supposed that the reduction of Na_2O to the increment of $\text{Na}_2\text{SiO}_3/\text{NaOH}$ increases the compressive strength. Inversely, the increment of Na_2O when $\text{Na}_2\text{SiO}_3/\text{KOH}$ is increased lead to higher compressive strength.

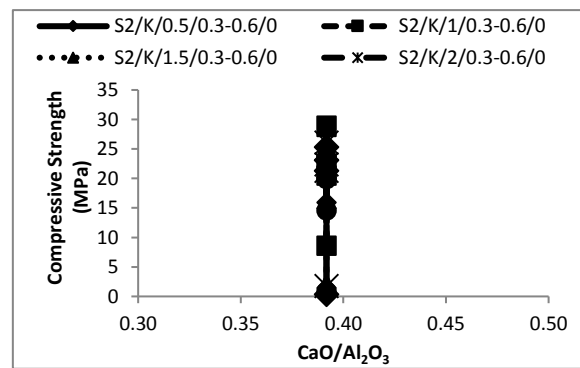
$\text{SiO}_2/\text{K}_2\text{O}$ in both types of geopolymer increases when $\text{Na}_2\text{SiO}_3/\text{NaOH}(\text{KOH})$ is increased as shown in **Figs. 5k-5l**. However, it increases on NaOH-based geopolymer increases but it decreases on KOH-based geopolymer when the alkali activator/ash is increased.

For $\text{Al}_2\text{O}_3/\text{K}_2\text{O}$, no effect has been shown in NaOH-based geopolymer as shown in **Fig. 5m**. It is because that Al_2O_3 is provided by fly ash, it is constant throughout the mixture ratios. Moreover, NaOH does not contribute to K_2O . The $\text{Al}_2\text{O}_3/\text{K}_2\text{O}$ increases when K_2O is reduced. It seems that the compressive strength of KOH-based geopolymer increases as K_2O reduces as shown in **Fig. 5n** shows.

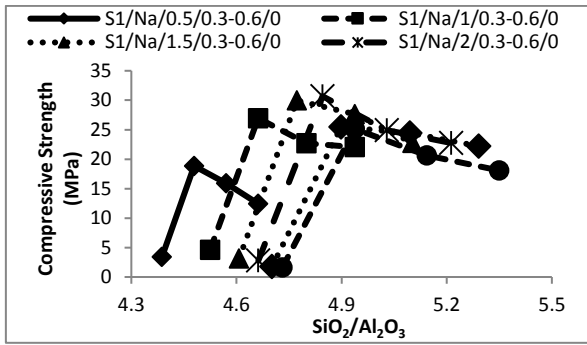
Both **Fig. 5l** and **Fig. 5n** show similar pattern of results as **Fig. 5g** and **Fig. 5i** respectively, although different types of alkali hydroxide are used. As mentioned earlier on, the variation of SiO_2 in these two types of geopolymer at same ratio of $\text{Na}_2\text{SiO}_3/\text{NaOH}(\text{KOH})$ is constant. The compressive strength of geopolymer is therefore supposed to be governed by Na_2O and K_2O in the mixture. At the highest compressive strength, Na_2O and K_2O of NaOH-based geopolymer is 0.68 and 0.17 whereas it is 0.27 and 0.61 in KOH-based geopolymer. It is supposed that the strength development on NaOH-based geopolymer is mainly attributed to Na_2O (major alkali oxide) rather than K_2O (secondary alkali oxide) in the mixture. Contrariwise, the strength development on KOH-based geopolymer is mainly governed by K_2O (major alkali oxide) rather than Na_2O (secondary alkali oxide) in the mixture. Furthermore, the reduction of major alkali oxide to the increment of $\text{Na}_2\text{SiO}_3/\text{NaOH}(\text{KOH})$ increases the compressive strength.



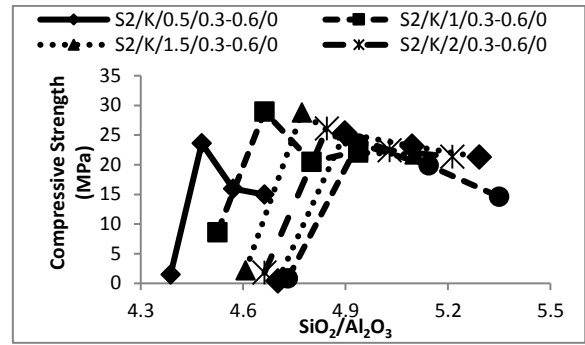
(a) Series 1: $\text{CaO}/\text{Al}_2\text{O}_3$



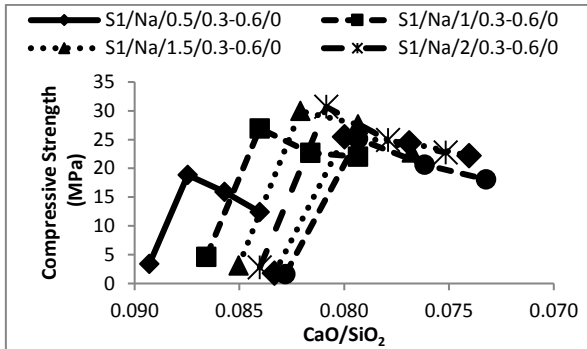
(b) Series 2: $\text{CaO}/\text{Al}_2\text{O}_3$



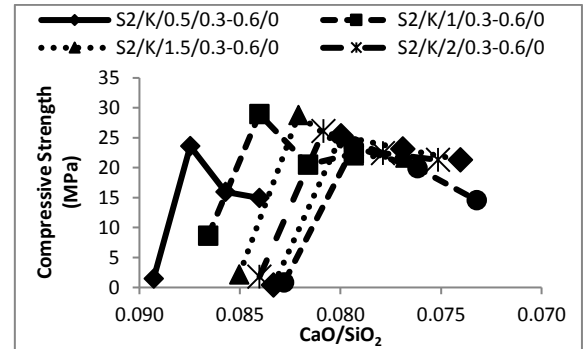
(c) Series 1: $\text{SiO}_2/\text{Al}_2\text{O}_3$



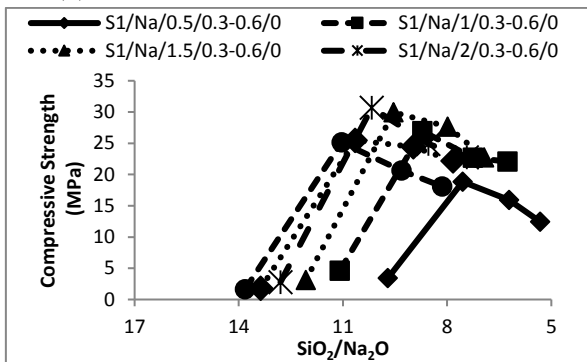
(d) Series 2: $\text{SiO}_2/\text{Al}_2\text{O}_3$



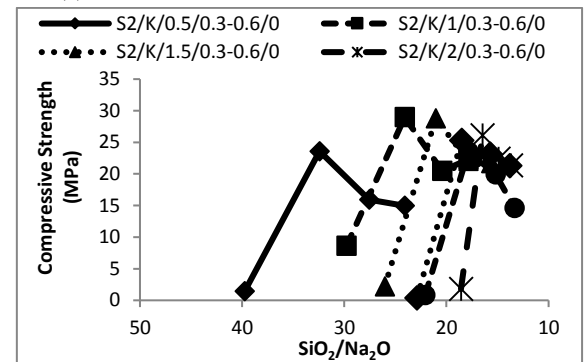
(e) Series 1: CaO/SiO_2



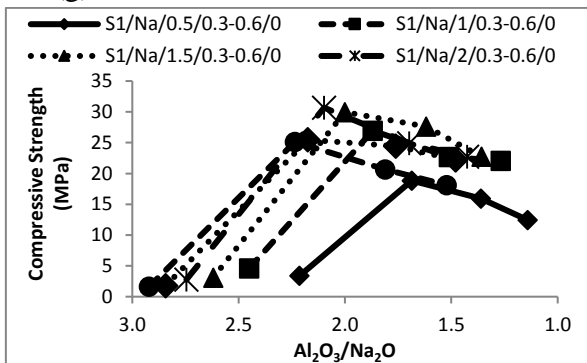
(f) Series 2: CaO/SiO_2



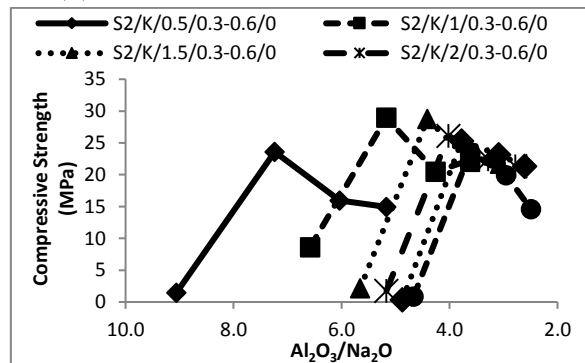
(g) Series 1: $\text{SiO}_2/\text{Na}_2\text{O}$



(h) Series 2: $\text{SiO}_2/\text{Na}_2\text{O}$



(i) Series 1: $\text{Al}_2\text{O}_3/\text{Na}_2\text{O}$



(j) Series 2: $\text{Al}_2\text{O}_3/\text{Na}_2\text{O}$

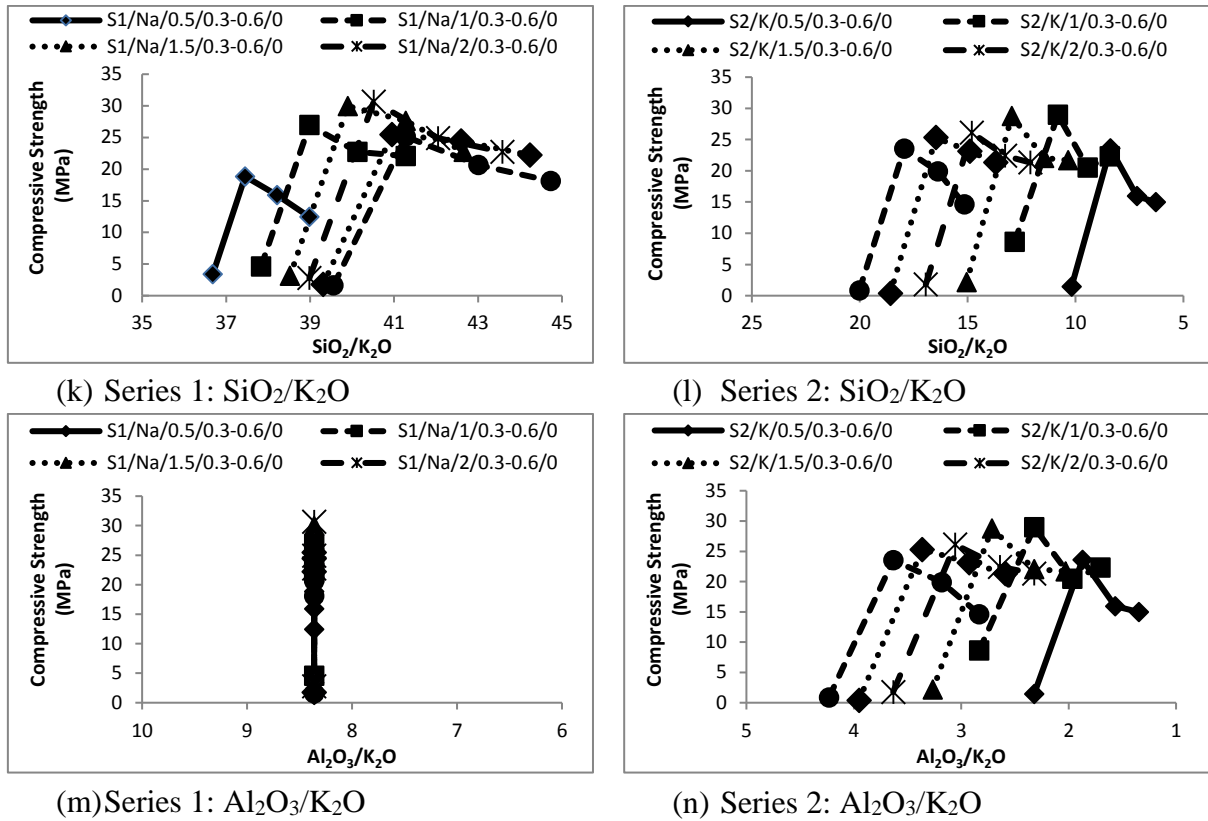


Fig 5. Effect of oxide molar ratios on the compressive strength of geopolymer using industrial Na_2SiO_3 (left column) Series 1: NaOH and (right column) Series 2: KOH

3.2.5. Industrial grade Na_2SiO_3 vs. Commercial grade Na_2SiO_3

Geopolymer using industrial grade Na_2SiO_3 at alkali activator/ash of 0.4, which exhibited the highest compressive strength, was then replaced with the commercial grade Na_2SiO_3 . The results of the geopolymer using commercial grade Na_2SiO_3 at various $\text{Na}_2\text{SiO}_3/\text{NaOH}(\text{KOH})$ were studied in comparison to the geopolymer using industrial grade Na_2SiO_3 . **Fig. 4** shows that geopolymer using commercial grade Na_2SiO_3 obtains significantly higher compressive strength than the samples using industrial grade Na_2SiO_3 . It is noted that the highest compressive strength of both NaOH- and KOH-based geopolymers using commercial grade Na_2SiO_3 were obtained at $\text{Na}_2\text{SiO}_3/\text{NaOH}(\text{KOH})=2.5$. This result is consistent with the finding as reported by

Hardjito and Rangan [14]. When commercial grade Na_2SiO_3 is used, the strength increment of NaOH-based geopolymer cured at 60°C after 1 day, 7 days and room temperature after 7 days is approximately 54%, 53% and 58% respectively. In similar curing conditions, the strength increment of KOH-based geopolymer is 52%, 52% and 57% respectively. The significant strength increment may be attributed to the different percentages of SiO_2 and Na_2O in Na_2SiO_3 , in which the commercial grade Na_2SiO_3 consists of higher percentage of SiO_2 and Na_2O than the industrial grade.

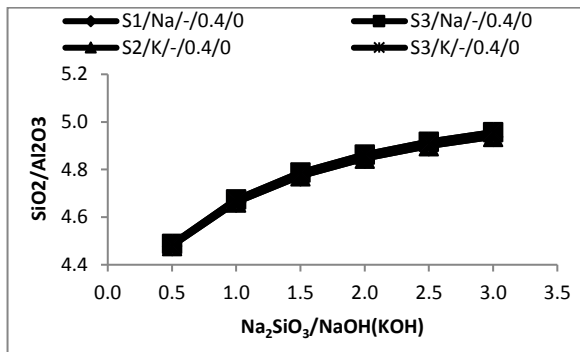
From the oxide molar ratio points of view, the effect of commercial grade Na_2SiO_3 on NaOH- and KOH-based geopolymers in comparison to industrial grade Na_2SiO_3 is illustrated in **Fig. 6**. The effect of commercial grade Na_2SiO_3 on $\text{SiO}_2/\text{Al}_2\text{O}_3$, CaO/SiO_2 , $\text{SiO}_2/\text{K}_2\text{O}$ and $\text{Al}_2\text{O}_3/\text{K}_2\text{O}$ of both NaOH- and KOH-based geopolymer is insignificant as shown in **Figs. 6a-d**. For $\text{SiO}_2/\text{Na}_2\text{O}$ and $\text{Al}_2\text{O}_3/\text{Na}_2\text{O}$, the results of geopolymer using commercial grade Na_2SiO_3 shows similar pattern to geopolymer of industrial grade Na_2SiO_3 . However, these two oxide molar ratios decrease when the commercial grade Na_2SiO_3 is used as illustrated in **Figs. 6e-f**. This is well reflected that although the tendency of $\text{SiO}_2/\text{Na}_2\text{O}$ and $\text{Al}_2\text{O}_3/\text{Na}_2\text{O}$ in both NaOH- and KOH-based geopolymer are different, the increment of $\text{SiO}_2/\text{Na}_2\text{O}$ and $\text{Al}_2\text{O}_3/\text{Na}_2\text{O}$ at constant $\text{Na}_2\text{SiO}_3/\text{NaOH}(\text{KOH})$ reduces the strength capability.

It is also noted that the main alkali oxide in KOH-based geopolymer using commercial grade Na_2SiO_3 is Na_2O (0.48) instead of K_2O (0.42). It is supposed that when Na_2O content is low, the strength development of KOH-based geopolymer is mainly governed by higher K_2O content in the sample. However, the strength development in this case is mainly attributed to Na_2O when K_2O in the sample is lower than Na_2O . As mentioned earlier on, the solubility of KOH-based geopolymer decreases

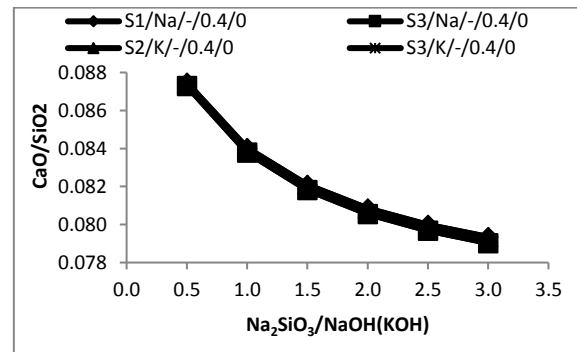
when the silicate ratio is increased. This may explain why KOH-based geopolymer obtains the highest compressive strength at lower $\text{Na}_2\text{SiO}_3/\text{KOH}$ when industrial grade Na_2SiO_3 is used.

The workability of geopolymer using commercial grade Na_2SiO_3 at the highest compressive strength is 110mm for both NaOH- and KOH-based geopolymer. Whereas, it is 125mm and 135mm on NaOH- and KOH-based geopolymer using industrial grade Na_2SiO_3 . Although the reduction of workability is exhibited, it does not lower the compressive strength. It shows that the increment of oxide molar ratios in particular the SiO_2 and Na_2O content is most likely lead to higher compressive strength.

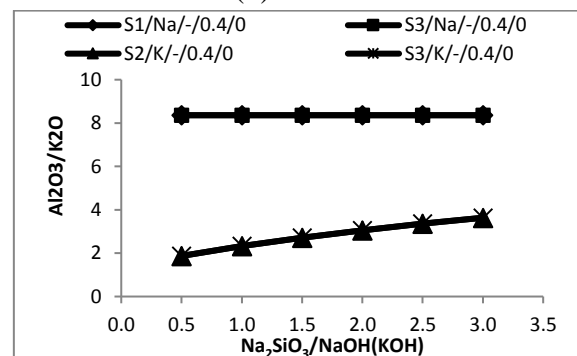
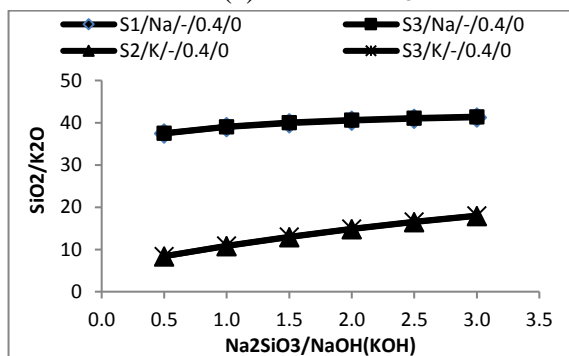
From the cost effective point of view, the industrial grade of Na_2SiO_3 is much cheaper than the commercial grade. Despite having better compressive strength on geopolymer using commercial grade of Na_2SiO_3 , geopolymer using industrial grade of Na_2SiO_3 is suitable for the application which requires lower compressive strength and higher workability.



(a) $\text{SiO}_2/\text{Al}_2\text{O}_3$



(b) CaO/SiO_2



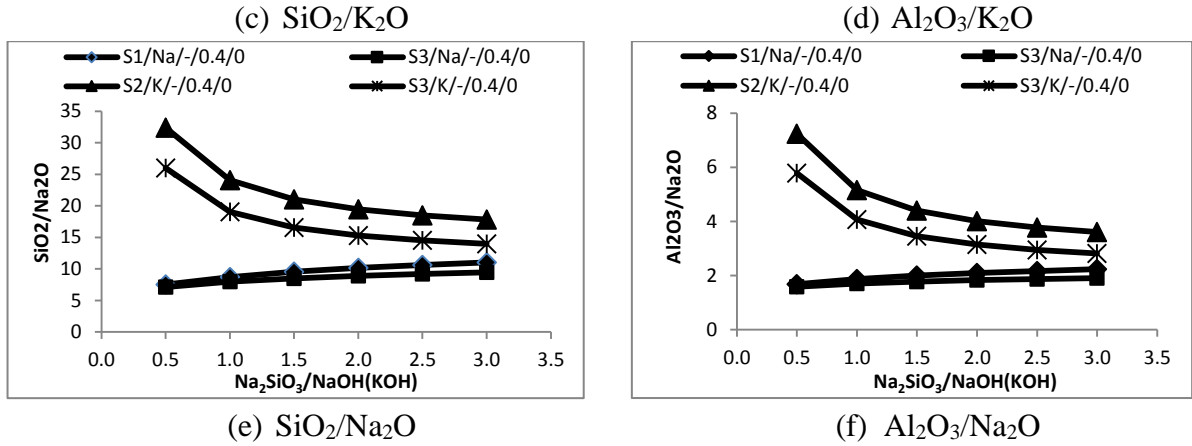


Fig 6. Variation of oxide molar ratios on NaOH- and KOH-based geopolymer when commercial grade Na_2SiO_3 is used in comparison to industrial grade Na_2SiO_3

3.2.6. Ca(OH)_2 -based geopolymer

The compressive strength of geopolymer using Ca(OH)_2 and commercial grade of Na_2SiO_3 as the alkali activator is shown in **Fig. 7**. The results show that the compressive strength of the sample after 1 day curing initially enhances with the alkali activator/ash increment but it decreases when the alkali activator/ash becomes greater than 0.4. For the samples cured for 7 days, the compressive strength gradually increases with the increment of alkali activator/ash. When the samples are exposed to the atmosphere, Ca(OH)_2 may react with CO_2 . The precipitator of this atmospheric carbonation, CaCO_3 , may precipitate in the pores of the sample thus reducing the total porosity and leading to higher compressive strength over the curing age.[48]

The effect of different ratios of $\text{Na}_2\text{SiO}_3/\text{Ca(OH)}_2$ on the compressive strength is shown in **Fig. 7b**. When $\text{Na}_2\text{SiO}_3/\text{Ca(OH)}_2=0$, the compressive strength of the sample is only 2 MPa. It can be explained by the poor self-cementing properties of Class F type fly ash due to lower CaO content as compared with Class C type fly ash [49]. As none alkali activator is added at this mixture ratio, the hardening of fly ash and strength

development are mainly attributed to the reaction between fly ash and water. Poorer self-cementing properties, therefore reduces the strength capability.

When $\text{Na}_2\text{SiO}_3/\text{Ca}(\text{OH})_2$ is greater than 0.5, the compressive strength of the samples decreases with the increment of $\text{Na}_2\text{SiO}_3/\text{Ca}(\text{OH})_2$. The highest compressive strength (i.e., 10 MPa) was obtained when $\text{Na}_2\text{SiO}_3/\text{Ca}(\text{OH})_2=0.5$. Fan, Yin [10] state that little amount of Na_2SiO_3 with $\text{Ca}(\text{OH})_2$ can accelerate the activation of fly ash. As the samples do not consist of alkali hydroxide, the activation and dissolution of aluminosilicate materials are thought to be minimal. In this case, the presence of calcium cation may compensate the negative charge of Al^{3+} in IV fold coordination or more importantly, is precipitated as C-S-H gel [50]. Therefore, the main reaction product is suggested to be C-S-H gel rather than the geopolymeric gel (i.e., alkali aluminosilicate gel). This explains the reduction of compressive strength by further increment of $\text{Na}_2\text{SiO}_3/\text{Ca}(\text{OH})_2$. Although the soluble silicate is increased in the mixture, deficiency of calcium cation reduces the formation of C-S-H gel. The results show in this research reveal that higher ratio of $\text{Na}_2\text{SiO}_3/\text{Ca}(\text{OH})_2$ would decrease the compressive strength.

When water/binder is increased, the compressive strength of the samples linearly decreases. It shows that the optimal water/binder for the highest compressive strength is 0.4. The reduction of compressive strength with the increment of water/binder may be attributed to the solubility of $\text{Ca}(\text{OH})_2$ in water and the evaporation of water when curing in oven. It is known that the solubility of $\text{Ca}(\text{OH})_2$ in water is very low.[51] When $\text{Ca}(\text{OH})_2$ is added into the water, the solution turns into milky-like and the precipitation of $\text{Ca}(\text{OH})_2$ is suspended in the solution. The OH^- ion of the $\text{Ca}(\text{OH})_2$ is therefore not available for the dissolution of fly ash. Unlike $\text{Ca}(\text{OH})_2$ being a weak base,

NaOH and KOH are categorised as strong base with high solubility. The later types can dissolve more silica and alumina from the fly ash. Additionally, alkali metal (e.g. Na and K) is more reactive than alkaline earth metal (e.g. Ca) [51]. Therefore, it explains why Ca(OH)₂-based geopolymer exhibited the lowest compressive strength as compared with NaOH- and KOH-based geopolymers. Moreover, the excessive water content in the sample may evaporate when it is subjected to oven dry. The pores left behind may weaken the matrix formed, consequently reducing the compressive strength.

The oxide molar ratio of Ca(OH)₂-based geopolymer is tabulated in comparison to NaOH- and KOH-based geopolymer as **Table 3** shows. The ratios of CaO/Al₂O₃, SiO₂/Al₂O₃ and CaO/SiO₂ are similar on these three types of geopolymer. The variation of SiO₂/Na₂O, SiO₂/K₂O, Al₂O₃/Na₂O and Al₂O₃/K₂O is significant. Ca(OH)₂-based geopolymer exhibits the highest ratios in these oxide molar ratios than the other two types of geopolymer. It is most likely due to the lowest Na₂O and K₂O present in Ca(OH)₂-based geopolymer in comparison to the latter types. Ca(OH)₂-based geopolymer shows the lowest compressive strength while the SiO₂/Na₂O and Al₂O₃/Na₂O are the highest. This has shown well agreement to the statement as postulated earlier on.

The workability of the Ca(OH)₂-based geopolymer is shown in **Table 4**. It decreases with the increment of alkali activator/ash and Na₂SiO₃/Ca(OH)₂. It is noted that Ca(OH)₂-based geopolymer sets and gets harden very quickly as compared with the NaOH- and KOH-based geopolymers. It is believed that Ca(OH)₂ accelerates the setting and hardening properties of geopolymer [10]. This hardening mechanism is most likely due to the formation of CaCO₃[46]. When the setting time is shortened, the dissolution of reacting material reduces. More unreacted particles present in the sample thus

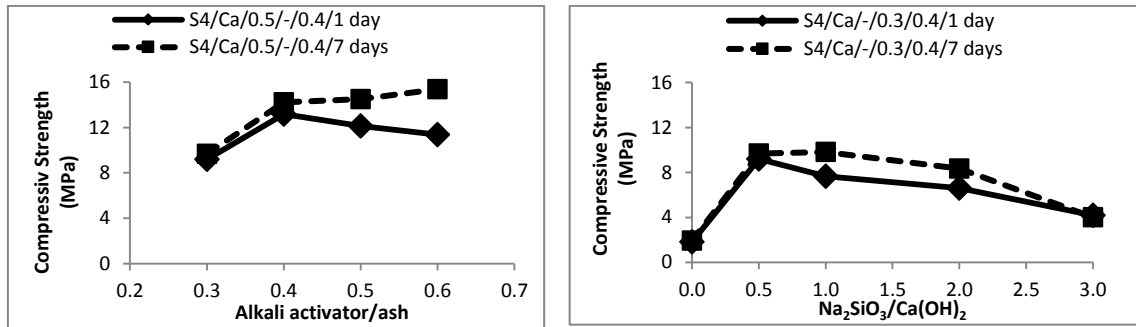
lowering the strength capability [52]. Having these properties, Ca(OH)₂-based geopolymer properties may be beneficial for the applications that require fast drying duration. Additionally, alkali hydroxide such as NaOH or KOH can be added into the mixture to achieve higher compressive strength. Therefore, geopolymer of high strength and fast drying performance can be achieved.

Table 3. The oxide molar ratios of Ca(OH)₂-based geopolymer in comparison to NaOH- and KOH-based geopolymer

Type	Sample designation	CaO/ Al ₂ O ₃	SiO ₂ / Al ₂ O ₃	CaO/ SiO ₂	SiO ₂ / Na ₂ O	SiO ₂ / K ₂ O	Al ₂ O ₃ / Na ₂ O	Al ₂ O ₃ / K ₂ O
CaOH-based	S4/Ca/0.5/0.4/0	0.392	4.347	0.090	36.803	36.346	8.466	8.361
NaOH-based	S3/Na/0.5/0.4/0	0.392	4.488	0.087	7.148	37.524	1.593	8.361
KOH-based	S3/K/0.5/0.4/0	0.392	4.488	0.087	25.990	8.396	5.791	1.871

Table 4. The workability of the samples at different ratios

No.	Na ₂ SiO ₃ / Ca(OH) ₂ ratio	Alkali activator/ ash ratio	Water/ binder ratio	Workability (mm)
a	0.5	0.3	0.4	150
	0.5	0.4	0.4	129
	0.5	0.5	0.4	125
	0.5	0.6	0.4	100
b	0	0	0.4	200
	0.5	0.3	0.4	150
	1	0.3	0.4	100
	2	0.3	0.4	100
	3	0.3	0.4	100
c	0.5	0.3	0.4	150
	0.5	0.3	0.5	180
	0.5	0.3	0.6	200
	0.5	0.3	0.7	245

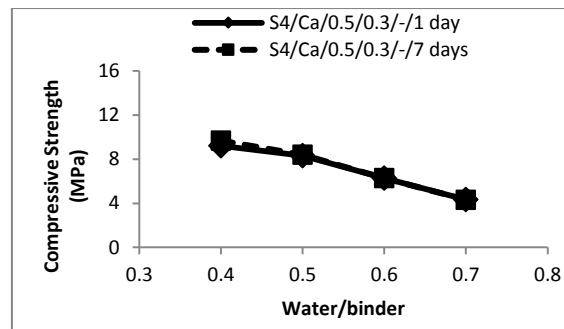


(a) Alkali activator/ash

[$\text{Na}_2\text{SiO}_3/\text{Ca}(\text{OH})_2 = 0.5$,
water/binder=0.4]

(b) $\text{Na}_2\text{SiO}_3/\text{Ca}(\text{OH})_2$

[Alkali activator/ash=0.3,
water/binder=0.4]



(c) Water/binder [$\text{Na}_2\text{SiO}_3/\text{Ca}(\text{OH})_2 = 0.5$, Alkali activator/ash=0.3]

Fig 7. Compressive strength of geopolymer using $\text{Ca}(\text{OH})_2$ at different ratios of (a) alkali activator/ash (b) $\text{Na}_2\text{SiO}_3/\text{Ca}(\text{OH})_2$ and (c) water/binder

4. Conclusion

A comprehensive overview on compressive strength of geopolymer using Sarawak fly ash with different alkali activator/ash and $\text{Na}_2\text{SiO}_3/\text{NaOH}$ (or KOH or $\text{Ca}(\text{OH})_2$) is studied in this research. Oxide molar ratios due to different ratios of alkali activator and mixture have been investigated. The results show that geopolymer made using Sarawak fly ash can possibly be used as construction materials. The conclusions are summarised as follows:

1. The workability is in the increasing manner when the alkali activator/ash is increased.

Inversely, it is in the decreasing manner when $\text{Na}_2\text{SiO}_3/\text{NaOH}$ and $\text{Na}_2\text{SiO}_3/\text{KOH}$ are

increased. The commercial grade Na_2SiO_3 shows significant effect on the workability of both NaOH- and KOH-based geopolymers.

2. High ratio of alkali activator/ash and $\text{Na}_2\text{SiO}_3/\text{NaOH}(\text{KOH})$ does not necessarily lead to high compressive strength. The optimal compressive strength was obtained when alkali activator/ash ratio was 0.4 regardless of the type of alkali activators (i.e., NaOH or KOH) and curing condition (i.e., 60°C or room temperature and 1 day or 7 days). With alkali activator/ash of 0.4, $\text{Na}_2\text{SiO}_3/\text{NaOH}=2$ and $\text{Na}_2\text{SiO}_3/\text{KOH}=1$ exhibited the highest compressive strength for geopolymer using Sarawak fly ash.
3. When $\text{Na}_2\text{SiO}_3/\text{NaOH}=0.5$ and 1, the compressive strength of KOH-based geopolymer was higher than NaOH-based but lower than NaOH-based when $\text{Na}_2\text{SiO}_3/\text{NaOH}>1.5$. NaOH-based geopolymer exhibited better compressive strength than KOH-based geopolymer when curing at room temperature.
4. The effect of oxide molar ratios on the compressive strength was studied. Higher ratios do not lead to higher compressive strength. The effect of $\text{CaO}/\text{Al}_2\text{O}_3$, $\text{SiO}_2/\text{Al}_2\text{O}_3$, CaO/SiO_2 on NaOH- and KOH-based geopolymer is similar. However, the tendency of $\text{SiO}_2/\text{Na}_2\text{O}$, $\text{Al}_2\text{O}_3/\text{Na}_2\text{O}$, $\text{SiO}_2/\text{K}_2\text{O}$ and $\text{Al}_2\text{O}_3/\text{K}_2\text{O}$ to NaOH- and KOH-based geopolymer shows dissimilarity.
5. The compressive strength of geopolymer using commercial grade Na_2SiO_3 was significantly higher than those using industrial grade Na_2SiO_3 regardless of the type of alkali hydroxide. The reduction of $\text{SiO}_2/\text{Na}_2\text{O}$ and $\text{Al}_2\text{O}_3/\text{Na}_2\text{O}$ in geopolymer using commercial grade Na_2SiO_3 in comparison to industrial grade Na_2SiO_3 increases the compressive strength. Higher ratio of SiO_2 and Na_2O in commercial grade Na_2SiO_3 is most likely attributed to the enhancement of geopolymerisation.

6. For geopolymer using industrial grade Na_2SiO_3 , the major alkali oxide in the sample is Na_2O rather than K_2O in NaOH-based geopolymer. Inversely, it is K_2O (major alkali oxide) rather than Na_2O in KOH-based geopolymer. Both NaOH- and KOH-based geopolymer show Na_2O as major alkali oxide when commercial grade Na_2SiO_3 is used.
7. $\text{Ca}(\text{OH})_2$ -based geopolymer demonstrated the lowest compressive strength than NaOH- and KOH-based geopolymers. The lowest solubility of $\text{Ca}(\text{OH})_2$ in comparison to the latter types reduces the dissolubility of silica and alumina from the fly ash. $\text{Ca}(\text{OH})_2$ -based geopolymer appears to set and get harden faster than NaOH- and KOH-based geopolymer.
8. Sarawak fly ash-based geopolymer can be a potential construction material for industrial application depending on the requirements of the compressive strength and workability. Geopolymer using industrial grade Na_2SiO_3 is beneficial for the application which requires low cost, low compressive strength but high workability. For geopolymer using commercial grade Na_2SiO_3 , it is suitable for the application that requires high compressive strength. $\text{Ca}(\text{OH})_2$ can be added into the geopolymer mixture to reduce the drying duration.

Acknowledgements

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References

- [1] Oka Y, Embi MR. Coal-Fired Boiler Plant History for Malaysian Projects. International Conference on Power Engineering. Hangzhou, China 2007. p. 197-203.
- [2] Muhandi, Marto A, Kassim KA, Makhtar AM, Lee FW, Yap SL. Engineering Characteristics of Tanjung Bin Coal Ash Electronic Journal of Geotechnical Engineering. 2010;15:1117-29.
- [3] Lizcano M, Kim HS, Basu S, Radovic M. Mechanical properties of sodium and potassium activated metakaolin-based geopolymers. J Mater Sci. 2012;47:2607–16.
- [4] Palomo A, Grutzeck MW, Blanco MT. Alkali-activated fly ashes: A cement for the future. Cem Con Res. 1999;29:1323–9.
- [5] Ryu GS, Lee YB, Koh KT, Chung YS. The mechanical properties of fly ash-based geopolymer concrete with alkaline activators. Constr Build Mater. 2013;47:409–18.
- [6] Nematollahi B, Sanjayan J. Effect of different superplasticizers and activator combinations on workability and strength of fly ash based geopolymer. Mater Design. 2014;57:667–72.
- [7] Criado M, Fernández-Jiménez A, Torre AGdl, Aranda MAG, Palomo A. An XRD study of the effect of the SiO₂/Na₂O ratio on the alkali activation of fly ash. Cem Con Res. 2007; 37 671–9.
- [8] Heah CY, Kamarudin H, Bakri AMMA, Bnhussain M, Luqman M, Nizar IK, et al. Study on solids-to-liquid and alkaline activator ratios on kaolin-based geopolymers. Constr Build Mater. 2012;35:912–22.
- [9] Komljenovi M, Bašćarevi Z, Bradić V. Mechanical and microstructural properties of alkali-activated fly ash geopolymers. J Hazard Mater. 2010;181:35–42.
- [10] Fan Y, Yin S, Wen Z, Zhong J. Activation of fly ash and its effects on cement properties. Cem Con Res. 1999;29:467–72.
- [11] Yang K-H, Cho A-R, Song J-K, Nam S-H. Hydration products and strength development of calcium hydroxide-based alkali-activated slag mortars. Constr Build Mater. 2012;29:410-9
- [12] Kong DLY, Sanjayan JG. Damage behavior of geopolymer composites exposed to elevated temperatures. Cem Con Compos. 2008;30:986–91.
- [13] Patankar SV, Ghugal YM, Jamkar SS. Effect of Concentration of Sodium Hydroxide and Degree of Heat Curing on Fly Ash-Based Geopolymer Mortar. Indian Journal of Materials Science. 2014.
- [14] Hardjito D, Rangan BV. Development and Properties of Low-Calcium Fly Ash-based Geopolymer Concrete. Perth, Australia Curtin University of Technology; 2005. p. 48.
- [15] Bakri AMMA-, Kareem OAKAA, Myint S. Optimization of Alkaline Activator/Fly Ash Ratio on the Compressive Strength of Fly Ash-Based Geopolymer. Malaysia: Universiti Malaysia Perlis (UniMAP); 2009.
- [16] Bakri AMMA, Kareem OAKAA, Myint S. Study on the Effect of Alkaline Activators Ratio in Preparation of Fly Ash-based Geopolymer. Malaysia: University Malaysia Perlis (UniMAP); 2009.
- [17] Jong BHWS, JR GEB. Polymerization of silicate and aluminate tetrahedra in glasses, melts, and aqueous solutions-I. Electronic structure of H₆Si₂O₇, H₆AlSiO₇, and H₆Al₂O₇-. Geochim Cosmochim Acta. 1980;44(3):491-511.
- [18] Xu H, Deventer JSJV. The geopolymerisation of alumino-silicate minerals. Int J Miner Process. 2000;59:247–66.
- [19] Duxson P, Mallicoat SW, Lukey GC, Kriven WM, Deventer JSJv. The effect of alkali and Si/Al ratio on the development of mechanical properties of metakaolin-based geopolymers. Colloids Surf, A. 2007;292:8–20.
- [20] Duxson P, Provis JL, Lukey GC, Mallicoat SW, Kriven WM, Deventer JSJv. Understanding the relationship between geopolymer composition, microstructure and mechanical properties. Colloids Surf, A. 2005;269:47-58.
- [21] Ozer I, SezenSoyer-Uzun. Relations between the structural characteristics and compressive strength in metakaolin based geopolymers with different molar Si/Al ratios. Ceram Int. 2015;41:10192–8.
- [22] Sindhunata, Deventer JSSv, Lukey GC, Xu H. Effect of Curing Temperature and Silicate Concentration on FLY-Ash-Based Geopolymerization. Ind Eng Chem Res. 2006;45:3559-68.
- [23] Rickard WDA, Temuujin J, Riessen Av. Thermal analysis of geopolymer pastes synthesised from five fly ashes of variable composition. J Non-Cryst Solids. 2012;358:1830–9
- [24] Buchwald A, Zellmann H-D, Kaps C. Condensation of aluminosilicate gels—model system for geopolymer binders. J Non-Cryst Solids. 2011;357:1376–82.
- [25] ASTM-C618. Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete. 2005.

- [26] Nizar IK, Bakri AMMA, Rafiza AR, H. Kamarudin, Alida A, Zarina Y. Study on Physical and Chemical Properties of Fly Ash from Different Area in Malaysia. *Advanced Materials Engineering and Technology II*. 2014;594-595 985-9.
- [27] Latifi N, Marto A, Rashid ASA, Yii JIJ. Strength and Physico-chemical Characteristics of Fly Ash–Bottom Ash Mixture. *Arab J Sci Eng* 2015;40:2447–55.
- [28] Shafiq N, Nuruddin MF, Kamaruddin I. Comparison of engineering and durability properties of fly ash blended cement concrete made in UK and Malaysia. *Advances in Applied Ceramics*. 2007;106:314-8.
- [29] Ismail KN, Hussin K, Idris MS. Physical, Chemical & Mineralogical Properties of Fly Ash. *Journal of Nuclear and Related Technology*. 2007;4:47-51.
- [30] Naganathan S, Mohamed AYO, Mustapha KN. Performance of bricks made using fly ash and bottom ash. *Constr Build Mater*. 2015;96:576–80.
- [31] Balakrishnan B, Awal ASMA, Shehu IA. Influence of High Volume Fly Ash in Controlling Heat of Hydration of Concrete. *International Journal of Engineering Research and Applications*. 2013;3(2):932-6.
- [32] Fernández-Jimeñez A, Palomo A. Characterisation of fly ashes. Potential reactivity as alkaline cements. *Fuel*. 2003;82:2259–65.
- [33] Juda-Rezler K, Kowalczyk D. Size Distribution and Trace Elements Contents of Coal Fly Ash from Pulverized from Boilers. *Pol J Environ Stud*. 2013;22:25-40.
- [34] Sia S-G, Abdullah WH. Enrichment of arsenic, lead, and antimony in Balingian coal from Sarawak, Malaysia: Modes of occurrence, origin, and partitioning behaviour during coal combustion. *International Journal of Coal Geology* 2012;101:1-15.
- [35] Rai A, Prabakar J, Raju CB, Morchalle RK. Metallurgical Slag as a Component in Blended Cement. *Constr Build Mater*. 2002;16:489–94.
- [36] ASTM-C1437. Standard Test Method for Flow of Hydraulic Cement Mortar. ASTM International 2013.
- [37] ASTM-C109/C109M. Standard Test Method for Compressive Strength of Hydraulic Cement Mortars (Using 2-in. or [50-mm] Cube Specimens). ASTM International; 2005.
- [38] Europe P. Sodium and Potassium Silicate 2004.
- [39] Liew YM, Kamarudin H, Bakri AMMA, Binhussain M, Luqman M, Nizar IK, et al. Influence of Solids-to-liquid and Activator Ratios on Calcined Kaolin Cement Powder. *Physics Procedia* 2011;22:312 – 7.
- [40] Heah CY, Kamarudin H, Bakri AMMA, Binhussain M, Luqman M, Nizar IK, et al. Study on solids-to-liquid and alkaline activator ratios on kaolin-based geopolymers. *Construction and Building Materials* 35 (2012) 912–922. 2012.
- [41] Villa C, Pecina ET, Torres R, Gómez L. Geopolymer synthesis using alkaline activation of natural zeolite. *Constr Build Mater*. 2010;24:2084–90.
- [42] Lee WKW, Deventer JSJv. The effects of inorganic salt contamination on the strength and durability of geopolymers. *Colloids Surf, A*. 2002;211:115-26.
- [43] Cheng TW, Chiu JP. Fire-resistant geopolymer produced by granulated blast furnace slag. *Miner Eng*. 2003;16:205–10.
- [44] Barbosa VFF, MacKenzie KJD, Thaumaturgo C. Synthesis and characterisation of materials based on inorganic polymers of alumina and silica: sodium polysialate polymers. *Int J Inorg Mater*. 2000;2:309–17.
- [45] Jaarsveld JGSv, Deventer JSJv, Lukey GC. The characterisation of source materials in fly ash-based geopolymers. *Mater Lett*. 2003;57:1272–80.
- [46] Davidovits J. *Geopolymer Chemistry and Application* 3rd ed. France: Institute Geopolymer 2008.
- [47] Tennakoon C, Nazari A, Sanjayan JG, Sagoe-Crentsil K. Distribution of oxides in fly ash controls strength evolution of geopolymers. *Constr Build Mater*. 2014;71:72–82.
- [48] Khater HM. Effect of Calcium on Geopolymerization of Aluminosilicate Wastes. *J Mater Civ Eng*. 2012;24:92-101.
- [49] Das SK, Yudhbir. Geotechnical Characterization of Some Indian Fly Ashes. *J Mater Civ Eng*. 2005;17:544-52.
- [50] Alonso S, Palomo A. Calorimetric study of alkaline activation of calcium hydroxide on metakaolin solid mixtures. *Cem Con Res*. 2001;31:25-30.
- [51] Chang R. *Chemistry*. 10 ed. New York: McGraw-Hill 2010.
- [52] Pacheco-Torgal F, Castro-Gomes JP, Jalalic S. Investigations on mix design of tungsten mine waste geopolymeric binder. *Constr Build Mater*. 2008;22:1939–49.