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Stabilisation of marginal lateritic soil using high calcium fly ash-based geopolymer

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Marginal soils are traditionally stabilised with Portland Cement (PC) when used as a pavement material. The production of PC is however an energy-intensive process and emits a large amount of greenhouse gas into the atmosphere. Geopolymer is an environmentally friendly 'green' binder commonly used in building applications but rarely used in pavement applications. The application of geopolymer to marginal soil stabilisation is an innovative approach given the increasing scarcity of virgin quarry materials in many countries. This research investigates the effects of alkali activator and curing time on unconfined compressive strength (UCS) and microstructural characteristics of marginal lateritic soil (LS) stabilised with high calcium fly ash (FA)-based geopolymer, which is novel in the field of pavement geotechnics. The viability of using this stabilised material as a bound pavement material was also evaluated through laboratory evaluation tests. A liquid alkali activator was a mixture of sodium silicate (Na_2SiO_3) solution and sodium hydroxide (NaOH) solution at various Na_2SiO_3 :NaOH ratios. The results showed that the UCS increased with the curing time and the 7-day UCS for all Na_2SiO_3 :NaOH ratios tested meets the local national standard as pavement bound material for both light and heavy traffic roads. The maximum early strengths at 7 days of curing were found at Na_2SiO_3 :NaOH of 90:10, where calcium silicate hydrate (C-S-H), cementitious products from high calcium FA and Na_2SiO_3 , was found to play a significant role. The sodium aluminosilicate hydrate (N-A-S-H) products, being time-dependent, however came into play after a longer duration. The maximum 90-day UCS was found at a Na_2SiO_3 :NaOH ratio of 50:50. This study indicated that marginal LS could be stabilised by high calcium FA-based geopolymer and used as an environmentally friendly pavement material, which would furthermore decrease the need for high-carbon PC. The economical Na_2SiO_3 :NaOH ratio for both light and heavy traffic pavement materials was suggested to be 50:50.

Keywords: geopolymer; marginal lateritic soil; soil stabiliser; high calcium fly ash; strength; microstructure

1. Introduction

Highway pavement generally consists of base and subbase layers, which are constructed from suitable materials such as crushed rock and lateritic soil (LS). Due to high rainfall, temperature

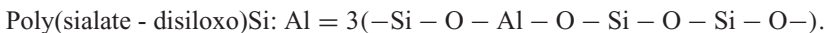
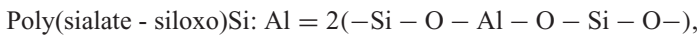
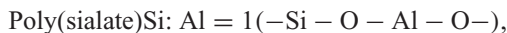
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and humidity with alternative wet and dry period, nearly 60% of the soils in Thailand are LS with colours ranging from red to yellowish red. The LS in East and Central of Thailand, which are the largest industrial zone of the country, does not typically meet the standard requirement as subbase/base materials. The LS in North, South and Northeast region of Thailand is classified suitable subbase materials. But some of these areas are located far away from quarry sources. When no such suitable materials are available and it is expensive to bring the materials from distant sources, an alternative way, widely practiced around the world, is to compact the *in situ* marginal soil mixed with Portland Cement (PC) (Chinkulkijniwat & Horpibulsuk, 2012; Jamsawang, Voottipruex, & Horpibulsuk, 2015). The production of PC is however an energy-intensive process and emits a very large amount of greenhouse gas, particularly carbon dioxide (CO₂) into the atmosphere (Davidovits, 1991, 1994a, 1994b, 1994c, 2002, 2013). The production of 1 tonne of PC clinker directly generates 0.55 tonnes of CO₂ and requires the combustion of carbon-fuel to yield an additional 0.40 tonnes of CO₂. Generally speaking, the production of 1 tonne of PC releases about 1 tonne of CO₂ (Davidovits, 2013).

In the light of these problems, the utilisation of low energy-intensive cementing agents in civil engineering applications has been increasingly researched in recent years. Low energy-intensive cementing agents include cement kiln dust (Ebrahimi, Edil, & Son, 2012), calcium carbide residue (Horpibulsuk, Phetchuay, Chinkulkijniwat, & Cholaphatsorn, 2013; Kampala & Horpibulsuk, 2013; Kampala, Horpibulsuk, Chinkulkijniwat, & Shen, 2013; Kampala, Horpibulsuk, Prongmanee, & Chinkulkijniwat, 2014), granulated blast furnace slag (Puppala, Wattanasanticharoen, & Punthutaecha, 2003) and geopolymer binder (Sukmak, De Silva, Horpibulsuk, & Chindaprasirt, 2014; Sukmak, Horpibulsuk, & Shen, 2013; Sulmak, Horpibulsuk, Shen, Chindaprasirt, & Suksiripattanapong, 2013b).

Geopolymer is an inorganic aluminosilicate material synthesised by alkaline activation of materials rich in alumina (Al₂O₃) and silica (SiO₂). It is formed through polycondensation of tetrahedral silica (SiO₄) and alumina (AlO₄), which are linked with other by sharing all the oxygen atoms (Davidovits, 1991; Gambrell, He, & Zhang, 2010). The chemical structure of geopolymer can generally be expressed as $M_n-(\text{Si}-\text{O}_2)_z[-\text{Al}-\text{O}]_n \cdot w\text{H}_2\text{O}$ where M is the alkaline element, $-$ indicates the presence of a bond, z is 1, 2 or 3, and n is the degree of polymerisation (Davidovits, 1991).

The mechanism of geopolymerisation involves the dissolution of Al and Si in the alkaline, then transportation of dissolved species, followed by a polycondensation forming a 3D network of aluminosilicate structures (Silva & Sagoe-Crenstil, 2008, 2009). Three typical structures of geopolymer are



Since fly ash (FA) offers the greatest opportunity given the plentiful worldwide stockpiles (Jaarsveld, Deventer, & Lorenzen, 1998), it is frequently used as a precursor for producing geopolymers. One billion tonnes of FA is produced annually worldwide in coal-fired power plants (Alvarez-Ayuso et al., 2008; Chindaprasirt, Chareerat, Hatanaka, & Cao, 2011; Chindaprasirt, Jaturapitakkul, Chalee, & Rattanasak, 2009; Nath & Kumar, 2013). Approximately 1.8 million tonnes of FA is used as a pozzolanic material in the concrete industry in Thailand (Chindaprasirt et al., 2009). FA can regularly replace cement content up to 50–70% in the high volume FA concrete (Rashad, 2014).

Geopolymer materials, exhibiting the following performance properties, can be made with both technological and commercial confidence (Duxson, Provis, Lukey, & van Deventer, 2007):

high compressive strength gain (Amnadnua, Tangchirapat, & Jaturapitakkul, 2013; Bagheri & Nazari, 2014; Chen & Chang, 2007; Chindaprasirt et al., 2011; Davidovits, 1994a; Komljenovic, Bascarevic, & Bradic, 2010; Lee & van Deventer, 2002; Nugteren, Butselaar-Orthlieb, Izquierdo, Witkamp, & Kreutzer, 2009; Suksiripattanapong, Horpibulsuk, Boongrasan, et al., 2015), rapid controllable setting and hardening (Lee & van Deventer, 2002), fire resistance (Cheng & Chiu, 2003; Lyon et al., 1997; Sakkas, Panias, Nomikos, & Sofianos, 2014; Sarker, Kelly, & Yao, 2014), high level of resistance to a range of different acids and salt solutions (Palomo, Blanco-Varela, et al., 1999), not subject to deleterious alkali–aggregate reactions (García-Lodeiro, Palomo, & Fernández-Jiménez, 2007), low shrinkage (Zhang, Guo, El-Korchi, Zhang, & Tao, 2013) and high surface definition that replicates mold patterns (Davidovits, 1991). Recently, Sukmak, Horpibulsuk, and Shen (2013) used locally available silty clay as an aggregate and high calcium FA as a precursor to develop masonry geopolymer units. The factors controlling the strength development (Sukmak, Horpibulsuk, Shen, et al., 2013) and sulphate resistance of soil stabilised with high calcium FA-based geopolymer have also been recently investigated (Sukmak et al., 2014).

Though there is readily available literature on the application of FA-based geopolymer, they have been predominantly used as building materials while the studies on the application of FA-based geopolymer to pavement materials are limited to date. Phetchuay et al. (2014) studied the viability of using calcium carbide residue as an alkali activator and FA as a precursor to stabilise problematic silty clay as a bound pavement material whose compressive strength meets the strength requirement, specified by the local national road authority of Thailand. Zhang et al. (2013) illustrated the feasibility of using geopolymer as an effective soil stabiliser for clayey soils based on an experimental study. Arulrajah et al. (2015) recently used spent coffee ground as an aggregate and FA-based geopolymer as a binder to develop a green engineering fill material.

This research aims to investigate the possibility of using high calcium FA-based geopolymer to stabilise a marginal LS to be a sustainable bound pavement material. Unconfined compressive strength (UCS) was used as an indicator for this investigation. The microstructural development of marginal LS–FA geopolymer was observed through scanning electron microscope (SEM) analysis for understanding the role of influential factors, controlling the strength development. The influential factors studied in this paper include $\text{Na}_2\text{SiO}_3:\text{NaOH}$ ratio and curing time at ambient room temperature. This study is significant from engineering, economical and environmental perspectives.

2. Materials and methods

2.1. Soil sample

The marginal LS was collected from a borrow pit in Rayong province, Thailand. The specific gravity is 2.58. The liquid limit, plastic limit and plastic index undertaken according to ASTM D4318 (2010) are 27.72%, 21.65% and 6.07%, respectively. Grain size distribution of this soil obtained from sieve analysis (ASTM D422-63, 2007) is shown in Figure 1. This soil is classified as silty clayey sand according to the Unified Soil Classification System and A-2-4(0) according to the AASHTO system (ASTM D3282-09, 2009). The mineral and chemical compositions of the marginal LS determined by X-ray fluorescence (XRF) analysis are summarised in Table 1. The compaction characteristics under modified Proctor energy (ASTM D1557-12, 2012), are optimum moisture content of 8.0%, and maximum dry unit weight (γ_{dmax}) of 20.85 kN/m³. California bearing ratio (CBR) value is 14.7% at 95% of maximum dry unit weight. Los Angeles (LA) abrasion described by ASTM C131 (2006) and C535 (2012) is 52.9%. With low CBR and high LA abrasion compared to the specification of the Department of Highways (DOH), Thailand

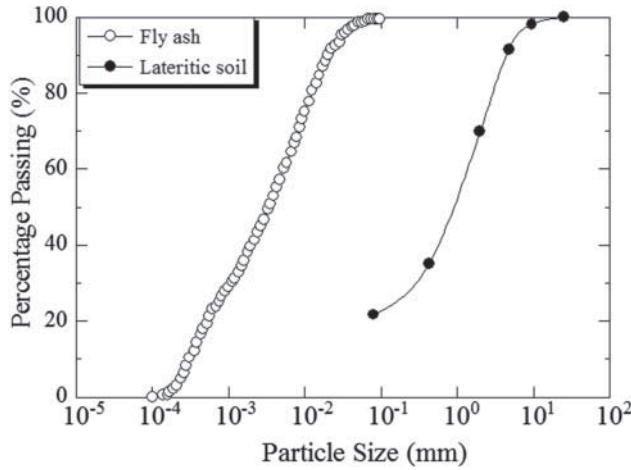


Figure 1. Particle size distribution of the LS and FA.

Table 1. Chemical compositions of FA and marginal LS.

Chemical composition (%)	FA	Marginal LS
SiO ₂	36.00	77.81
Al ₂ O ₃	16.80	4.42
Fe ₂ O ₃	17.64	10.93
CaO	26.73	1.13
SO ₃	N.D	1.36
K ₂ O	1.83	2.33
TiO ₂	0.48	1.33
MnO ₂	0.15	0.55
Br ₂ O	N.D	0.38

Note: N.D. = not detected.

(required CBR and LA abrasion are greater than 25% and less than 60% for subbase materials, located below the base course, respectively), this LS is classified as a marginal soil.

2.2. Fly ash

FA used in this study was obtained from Mae Moh power plant in Northern Thailand, which is the largest lignite power plant in Thailand. The chemical compositions of FA were determined using XRF technique and are shown in Table 1. The XRF spectrometer is an instrument used for routine, relatively non-destructive chemical analyses of rocks, minerals, sediments and fluids. It works on wavelength-dispersive spectroscopic principles. The major and trace elements in geological materials are analysed by the behaviour of atoms when they interact with X-radiation. The major components are 36.00% SiO₂, 26.73% CaO, 17.64% Fe₂O₃ and 16.80% Al₂O₃. According to ASTM C 618-12a (2012), it is categorised as class C high calcium FA (CaO > 10%). It has been shown that this FA is suitable as a precursor for making good geopolymer (Chindaprasirt, Chareerat, & Sirivivatnanon, 2007; Rattanasak, Pankhet, & Chindaprasirt, 2011). The high calcium content of FA leads to the formation of calcium silicate hydrate (C-S-H), which coexists with the geopolymerisation product (sodium alumino silicate hydrate, N-A-S-H) (Guo, Shi, &

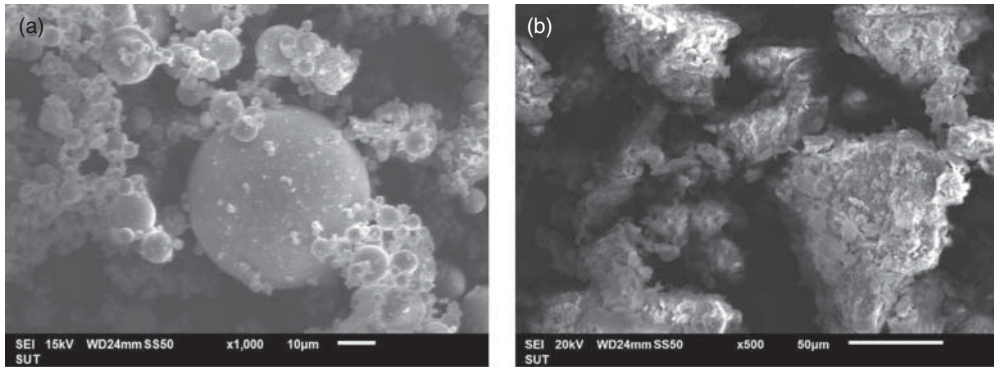


Figure 2. SEM images of (a) FA and (b) LS.

Dick, 2010; Somna, Jaturapitakkul, Kajitvichyanukul, & Chindaprasirt, 2011). The coexistence of C-S-H phase with N-A-S-H phase has been proved to improve the mechanical properties of final products (Temuujin & van Riessen, 2009). The particle size distribution and SEM image of FA are shown in Figures 1 and 2, respectively. The FA particles are generally fine and spherical while the LS particles are irregular in shape.

2.3. Liquid alkali activator

The liquid alkali activator was a mixture of sodium silicate (Na_2SiO_3) solution, composed of 15.50% Na_2O , 32.75% SiO_2 and 51.75% water by weight, and sodium hydroxide (NaOH) solution with 5 molars. The suitable concentration is generally between 4.5 and 18 molars (Andini et al., 2008; Chindaprasirt et al., 2009; Hanjitsuwan et al., 2014; Rattanasak & Chindaprasirt, 2009; Somna et al., 2011). The low NaOH concentration of 5 molars was considered in this study to avoid health harm of workers and to have cost-effectiveness.

2.4. LS-FA geopolymer

The NaOH and Na_2SiO_3 solutions were first mixed together and used as the liquid alkali activator. The LS and FA were air-dried and mixed thoroughly at soil to FA ratio of 70:30. The liquid alkali activator was mixed with a mixture of LS and FA for 10 min to develop LS-FA geopolymer at various Na_2SiO_3 : NaOH ratios of 100:0, 90:10, 80:20 and 50:50. This mixing procedure has been done by previous researchers (Horpibulsuk, Rachan, Chinkulkijniwat, Raksachon, & Suddepong, 2015; Sukmak, Horpibulsuk, & Shen, 2013; Suksiripattanapong, Horpibulsuk, Chanprasert, et al., 2015). The SiO_2 : Al_2O_3 ratios in this study range from 4.5 to 5.8 as summarised in Table 2. The mixtures with different ingredients were compacted in a standard mould of 101.6 mm in diameter and 116.4 mm in height (the ratio of height to diameter equals 1.15) under modified Proctor energy according to the specification of the DOH (ASTM D1557-12, 2012). All the compacted samples were then dismantled and wrapped with vinyl sheet to prevent the moisture loss. They were next cured at ambient temperature (27–30°C) until the various pre-planned curing times lapsed. Although the geopolymerisation reaction is significantly accelerated by the heat curing, the LS-FA geopolymer samples in this study were cured at ambient temperature to simulate the average field temperature. The samples were submerged under water for 2 h and were air-dried for 1 h prior to UCS test according to the specification of the (DH-S 204/2000) (DOH, 2000), Thailand. UCS tests on the soaked samples at the four different Na_2SiO_3 : NaOH ratios were undertaken after 7, 28, 60 and 90 days. The results were reported using mean UCS

Table 2. Initial molar ratios of LS-FA geopolymer.

Sample	Na ₂ O:SiO ₂	SiO ₂ :Al ₂ O ₃	H ₂ O:Na ₂ O	Na ₂ O:Al ₂ O ₃	SiO ₂ :Al ₂ O ₃ :Na ₂ O
1	0.174	5.800	11.250	1.008	5.798:1:1.008
2	0.179	5.535	11.818	0.993	5.535:1:0.993
3	0.183	5.258	12.375	0.963	5.258:1:0.963
4	0.188	4.500	13.985	0.845	4.501:1:0.845

values of at least three samples to assure test result consistency. In most cases, the results under the same testing condition were reproducible with low mean standard deviation, SD/\bar{x} ($< 10\%$, where \bar{x} is mean strength value).

Scanning electron microscopic (SEM) images were undertaken on the LS-FA geopolymer samples to analyse the microstructural changes with Na₂SiO₃:NaOH ratio and curing time. The small fragments from the centre of specimens were frozen at -195°C by immersion in liquid nitrogen for 5 min and coated with gold before SEM (JEOL JSM-6400 device) analysis (Du et al., 2014; Horpibulsuk, Rachan, Chinkulkijniwat, Raksachon, & Suddepong, 2010; Horpibulsuk, Rachan, & Raksachon, 2009; Sukmak, Horpibulsuk, & Shen, 2013; Sukmak, Horpibulsuk, Shen, et al., 2013).

3. Results

3.1. Compaction characteristics

Figure 3 shows the relationships between dry unit weight and liquid alkali activator content with various Na₂SiO₃:NaOH ratios of LS-FA geopolymer. The compaction curves of LS-FA geopolymer are different and depend on the Na₂SiO₃:NaOH ratio. For a particular Na₂SiO₃:NaOH ratio, the dry unit weight of LS-FA geopolymer increases with increasing liquid alkali activator content until $\gamma_{d,max}$ is attained at an optimum alkali activator content. Beyond this optimum value, the unit weight decreases as the alkali activator content increases. This characteristic is similar to a typical compaction behaviour of coarse-grained materials. The effect of Na₂SiO₃:NaOH ratio is also noticed in this figure in that $\gamma_{d,max}$ is 20.3 kN/m³ at Na₂SiO₃:NaOH ratio of 50:50, decreases to 19.2 when Na₂SiO₃:NaOH ratio increases to 80:20, increases to

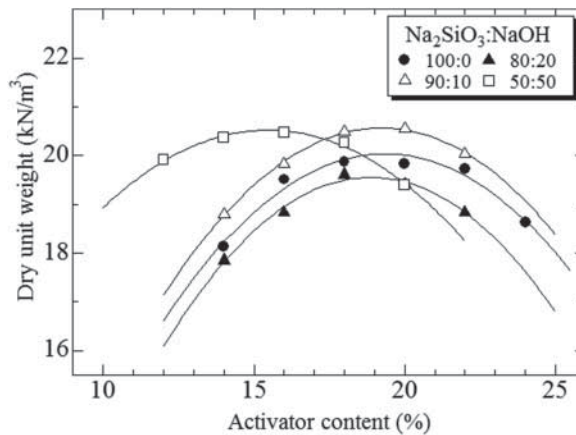


Figure 3. Compaction curves of LS-FA geopolymer at different ingredients.

Table 3. Optimum liquid alkaline activator and maximum dry unit weight.

Sample	Na ₂ SiO ₃ :NaOH	Optimum activator content (%)	Maximum dry unit weight, $\gamma_{d,max}$ (kN/m ³)	Activator:FA ratio (g/g)
1	100:0	19.60	20.21	0.653
2	90:10	19.13	20.56	0.638
3	80:20	18.38	19.56	0.613
4	50:50	15.68	20.45	0.523

Note: Activator:FA ratio is the ratio of optimum liquid alkaline activator that used in each mix (Na₂SiO₃:NaOH = 100:0, 90:10, 80:20 and 50:50) to FA by weight.

20.4 kN/m³ when Na₂SiO₃:NaOH ratio increases to 90:10 and then decreases to 20.0 kN/m³ at Na₂SiO₃:NaOH ratio of 100:0. The optimum Na₂SiO₃:NaOH ratio exhibiting the highest $\gamma_{d,max}$ was found at 90:10. Based on a linear regression analysis of the test result, the optimum liquid alkali activator for each Na₂SiO₃:NaOH ratio is summarised in Table 3.

3.2. Unconfined compressive strength

The UCS of geopolymers is attributed to the reaction between silica and alumina in the presence of alkali ions and in age of specimens (Somna et al., 2011). The UCS values of the LS-FA geopolymer for various Na₂SiO₃:NaOH ratios (100:0 to 50:50) and curing times (7–90 days) are presented in Figure 4. It is evident that the UCS values for all Na₂SiO₃:NaOH ratios increase as the curing time increases. At early stage of geopolymerisation, the maximum 7-day UCS is found at Na₂SiO₃:NaOH ratio of 90:10 (about 7100 kPa), which is greater than the strength requirement specified by the national road authority in Thailand (UCS > 1724 kPa for light traffic and UCS > 2413 kPa for high traffic) (DOH, 2000; Department of Rural Road [DRR], 2013). The light traffic roads infer to collector roads or rural roads, which are predominantly designed and constructed by the DRR. The designed equivalent single axle (ESA) load on the light traffic roads is not more than 1×10^6 . The heavy traffic roads refer to highways under the responsibility of the DOH. The designed ESA load on the heavy traffic roads is more than 1×10^6 . The

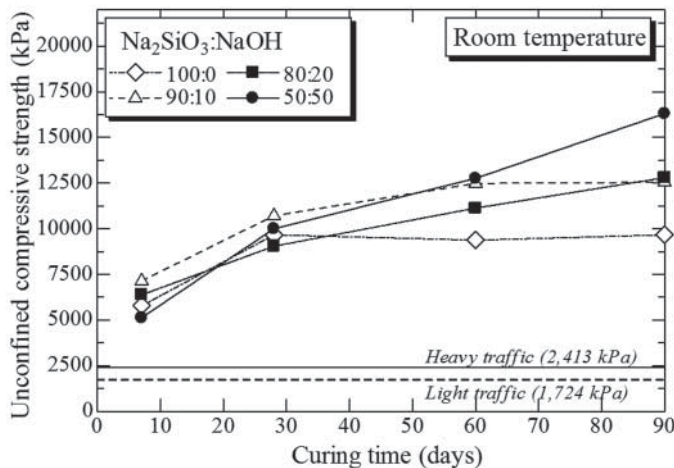


Figure 4. Effect of curing time on UCS of LS-FA geopolymer.

7-day UCS at Na₂SiO₃:NaOH ratio of 100:0 (no NaOH) is approximately 5800 kPa. This moderately high UCS at Na₂SiO₃:NaOH ratio of 100:0 is contributed from the C-S-H, which is the cementitious product from the reaction between silica from Na₂SiO₃ and calcium from FA. In the presence of Ca²⁺, Na₂SiO₃ forms soluble calcium silicate, which polymerises further to form gels that bind soil particles together and fills voids as the following equation (Brykov, Danilov, Korneev, & Larichkov, 2002): $\text{Ca}^{2+} + \text{Na}_2\text{SiO}_3 + m\text{H}_2\text{O} \rightarrow \text{CaO} \cdot 3\text{SiO}_2 \cdot m\text{H}_2\text{O} + 2\text{Na}^+$. The effect of C-S-H is minimal when the curing time is greater than 28 days as seen that the UCS of sample at Na₂SiO₃:NaOH ratio of 100:0 is essentially constant when the curing time is greater than 28 days.

The geopolymerisation reaction occurs when NaOH is mixed together with Na₂SiO₃, which causes the pH of the pore liquid to be higher than 10.5. The silica and alumina in amorphous phase of the high calcium FA are dissolved and the Na₂SiO₃ acts as a binder to develop N-A-S-H. As such, the reactions of high calcium FA, NaOH and Na₂SiO₃ result in the coexistence of C-S-H and sodium aluminosilicate geopolymer (N-A-S-H) products. Since the N-A-S-H products are time-dependent, the UCS of geopolymer samples with the presence of NaOH (Na₂SiO₃:NaOH ratios of 90:10, 80:20 and 50:50) increases with curing time even after 28 days of curing.

Due to the coexistence of C-S-H and N-A-S-H products, the geopolymer samples with Na₂SiO₃:NaOH ratios of 90:10 and 80:20 exhibit higher 7-day UCS than the geopolymer sample with Na₂SiO₃:NaOH ratios of 100:0 (its UCS is mainly contributed from C-S-H). The optimum coexistence of C-S-H and N-A-S-H products at 7 days of curing (providing the highest UCS) is found at Na₂SiO₃:NaOH ratio of 90:10. Since the geopolymerisation process at ambient temperature is time-consuming, the N-A-S-H products at the early state are minimal compared to the C-S-H products, which are from the faster reaction between Na₂SiO₃ and high calcium FA. Consequently, the 7-day UCS decreases with the reduction in Na₂SiO₃:NaOH ratio and the lowest UCS is found at Na₂SiO₃:NaOH ratio of 50:50 and is about 5100 kPa, which still meets strength requirement for heavy traffic bound/stabilised base.

At 28 days curing, the Na₂SiO₃:NaOH ratio of 90:10 still exhibits the highest UCS. However, the UCS development rate (slope of UCS versus time relationship) is greater for samples with lower Na₂SiO₃:NaOH ratio (higher NaOH content). This is attributed to the growth of N-A-S-H products over time. For curing times longer than 60 days, the UCS of geopolymer increases with decreasing Na₂SiO₃:NaOH ratio (increasing NaOH content); i.e. Na₂SiO₃:NaOH ratios of 50:50 and 100:0 exhibit the maximum and minimum UCS after 60 days of curing, respectively.

Based on the strength data, it is suggested that the Na₂SiO₃:NaOH ratio of 50:50 is the best ingredient whose UCS is greater than 2413 kPa (required for heavy traffic). The highest rate of UCS development of the geopolymer at this ingredient is also observed. This ingredient also provides the most economical because NaOH is much cheaper than Na₂SiO₃.

4. Microstructural analysis

Microstructural development of LS-FA geopolymer is explained via the SEM image, which is an advantageous tool for monitoring the growth of cementation matrix over time. Figure 5 shows the microstructure of the four Na₂SiO₃:NaOH ratios of 100:0, 90:10, 80:20 and 50:50 at 7 days of curing (early stage of geopolymerisation process) at ambient temperature. The cementitious (C-S-H and N-A-S-H) products on the high calcium FA surface are clearly observed at Na₂SiO₃:NaOH ratios of 90:10 and 80:20 when compared to those at Na₂SiO₃:NaOH ratios of 50:50 and 100:0, respectively. Many holes on the FA surface are clearly observed for

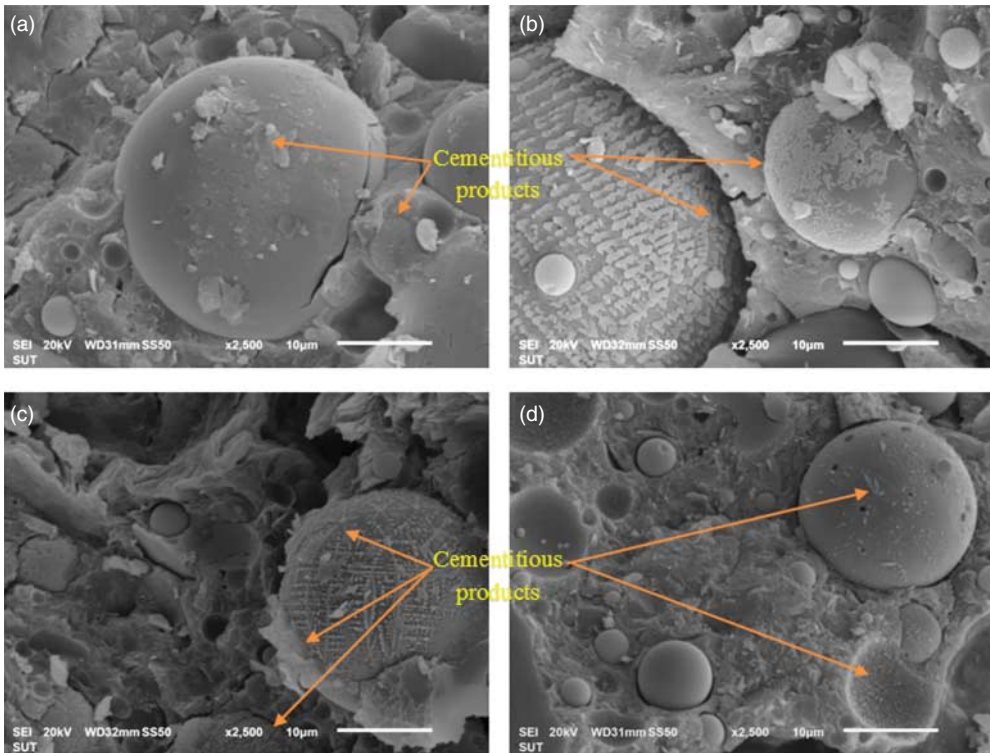


Figure 5. SEM images of LS-FA geopolymer cured at 7 days of curing at ambient temperature for various $\text{Na}_2\text{SiO}_3:\text{NaOH}$ ratios of (a) 100:0, (b) 90:0, (c) 80:20 and (d) 50:50.

$\text{Na}_2\text{SiO}_3:\text{NaOH}$ ratios of 50:50 due to strong alkaline reaction from NaOH while the least etched holes on FA surface are observed at $\text{Na}_2\text{SiO}_3:\text{NaOH}$ ratio of 100:0.

Figure 6 shows SEM images of the LS-FA geopolymer samples at $\text{Na}_2\text{SiO}_3:\text{NaOH}$ ratios of 90:10 and 50:50 cured at ambient temperature for 7 and 60 days of curing to illustrate the role of curing time. Comparing Figure 6(a) and 6(b) for samples with different $\text{Na}_2\text{SiO}_3:\text{NaOH}$ ratios of 90:10 and 50:50 at the same 7 days of curing, the etched holes on the FA surfaces are clearly observed for both $\text{Na}_2\text{SiO}_3:\text{NaOH}$ ratios but more cementitious products around FA particles and in the pores are detected at $\text{Na}_2\text{SiO}_3:\text{NaOH}$ ratio of 90:10. At longer curing time of 60 days, some holes on the surface of FA are partially filled with other smaller FA particles and the cementitious products form a dense matrix for both $\text{Na}_2\text{SiO}_3:\text{NaOH}$ ratios. In contrast to the SEM images at 7 days of curing, more cementitious products at 60 days of curing are detected at $\text{Na}_2\text{SiO}_3:\text{NaOH}$ ratio of 50:50 (Figure 6(c) and 6(d)). Consequently, the sample at $\text{Na}_2\text{SiO}_3:\text{NaOH}$ ratio of 90:10 exhibits the highest early UCS while the sample at $\text{Na}_2\text{SiO}_3:\text{NaOH}$ ratio of 50:50 exhibits the highest long-term UCS (*vide* Figure 4).

The effect of $\text{Na}_2\text{SiO}_3:\text{NaOH}$ ratio on the growth of geopolymerisation products is illustrated by comparing Figure 7(a)–(d), which show SEM images of the LS-FA geopolymer samples at various $\text{Na}_2\text{SiO}_3:\text{NaOH}$ ratios of 100:0, 90:10, 80:20 and 50:50 after 90 days of curing. For $\text{Na}_2\text{SiO}_3:\text{NaOH}$ ratio of 100:0 (no NaOH), the FA surface is approximately smooth and spherical with traces of C-S-H products. This indicates that the silica and alumina in FA was insignificantly leached out even after a very long curing time and the UCS of the samples is contributed from C-S-H (reaction of Na_2SiO_3 and CaO from FA) (Figure 7(a)). The NaOH content is not sufficient

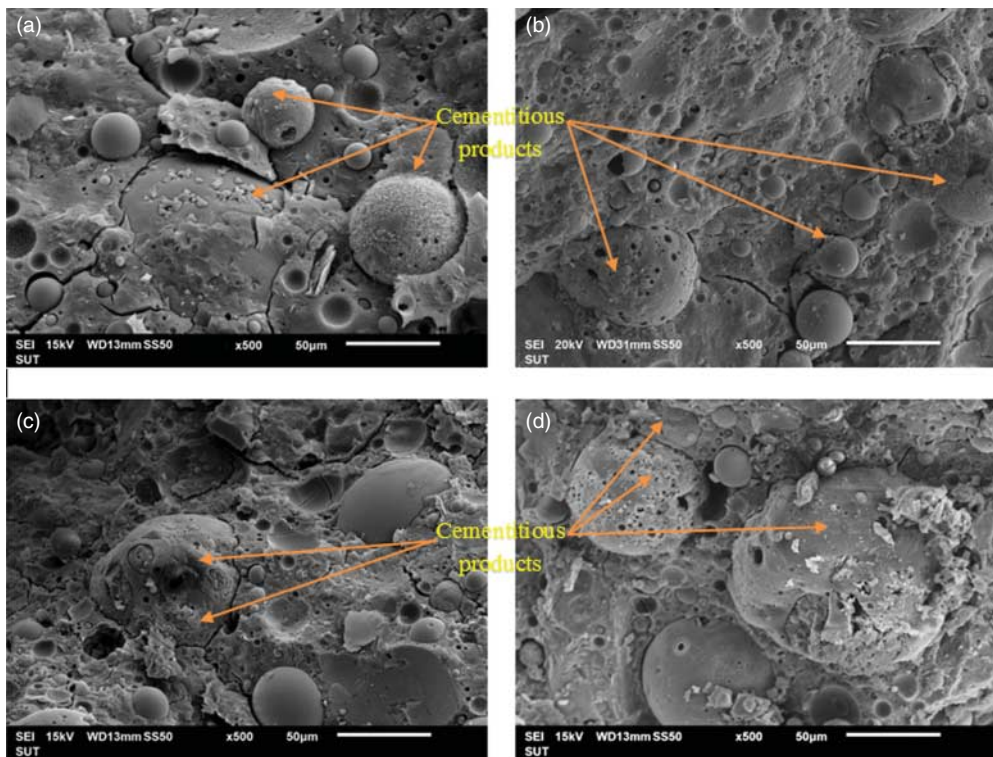


Figure 6. SEM images of LS-FA geopolymer cured at ambient temperature for $\text{Na}_2\text{SiO}_3:\text{NaOH}$ ratio of 90:10 and 50:50 for (a) 90:10, cured at 7 days; (b) 50:50, cured at 7 days; (c) 90:10, cured at 60 days and (d) 50:50, cured at 60 days.

for leaching silica and alumina from FA for the sample at $\text{Na}_2\text{SiO}_3:\text{NaOH}$ ratio of 90:10 as seen by the small amount of cementitious products on FA surface (Figure 7(b)) when compared to the samples at $\text{Na}_2\text{SiO}_3:\text{NaOH}$ ratios of 80:20 and 50:50 (Figure 7(c) and 7(d)). For both samples at $\text{Na}_2\text{SiO}_3:\text{NaOH}$ ratios of 80:20 and 50:50, the etched holes are mostly filled with other smaller size ash particles and the cementitious products fill up the pore space, resulting in a dense matrix. The cementitious products are more for the sample at $\text{Na}_2\text{SiO}_3:\text{NaOH}$ ratio of 50:50. As such, the maximum UCS is found at $\text{Na}_2\text{SiO}_3:\text{NaOH}$ ratio of 50:50 at 60 and 90 days of curing (*vide* Figure 4).

The present study on the improvement of marginal LS by FA-based geopolymer has significant impacts on sustainable pavement applications. The green geopolymer stabilised LS is proved as suitable where the 7-day UCS meets the specification for heavy traffic and the UCS increases with increasing curing time even after 28 days of curing due to the growth of geopolymerisation product (N-A-S-H) over time. The field construction can begin with roller-compacting underlying subgrade in accordance with the specifications of the road authority. The marginal LS was mixed with FA at construction site or in a ready mixer from a plant. Then, a mixture of LS and FA is activated by the liquid alkali activator at the optimum content. Next, the LS-FA geopolymer is compacted to attain at least 95% modified Proctor density. Finally, the field density and UCS of the cored pavement samples are measured for confirming the quality of construction. A life cycle analysis study is recommended for further study on the environmental aspect.

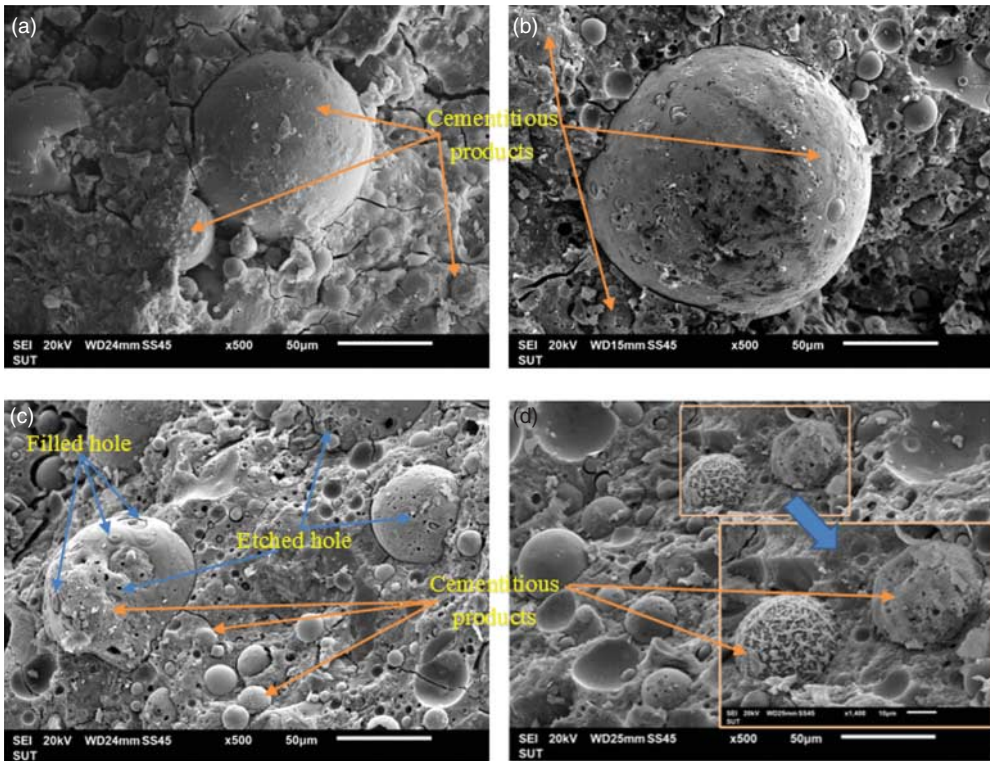


Figure 7. SEM images of LS-FA geopolymer cured at 90 days at ambient temperature for various ingredients of $\text{Na}_2\text{SiO}_3:\text{NaOH}$: (a) 100:0, (b) 90:10, (c) 80:20 and (d) 50:50.

5. Conclusions

This paper investigates UCS and microstructural characteristics of the marginal LS stabilised with high calcium FA-based geopolymer as low-carbon alternative green bound pavement material. It is evident from this study that the strength of LS-FA geopolymer meets the standard requirements for heavy and light traffic bound base materials specified by DOH and DRR, Thailand. The following conclusions are drawn:

- (1) The optimum liquid alkali activator content of the LS-FA geopolymer is dependent upon the $\text{Na}_2\text{SiO}_3:\text{NaOH}$ ratio. As the $\text{Na}_2\text{SiO}_3:\text{NaOH}$ ratio increases, the optimum liquid alkali activator content increases. The maximum dry unit weight decreases as the increase in optimum liquid alkali activator content.
- (2) The maximum 7-day soaked UCS of LS-FA geopolymer samples is found at $\text{Na}_2\text{SiO}_3:\text{NaOH}$ ratio of 90:10 and is 7143 kPa while the minimum UCS is found at $\text{Na}_2\text{SiO}_3:\text{NaOH}$ ratio of 50:50 and is 5126 kPa. The UCS values of the samples at all $\text{Na}_2\text{SiO}_3:\text{NaOH}$ ratios tested meet the strength requirement for both light and heavy traffic, specified by DRR and DOH, Thailand.
- (3) The coexistence of calcium silicate hydrate (C-S-H) and sodium aluminosilicate hydrate (N-A-S-H) products contributes to the UCS values of LS-FA geopolymer. The C-S-H is resulted from the reaction of CaO from FA and Na_2SiO_3 while N-A-S-H is the time-dependent geopolymer products.

- (4) The results of alkaline activated dissolution on the FA particles of LS–FA geopolymer at $\text{Na}_2\text{SiO}_3:\text{NaOH}$ ratio of less than 100:0 are clearly shown by several etched holes. For longer curing, the holes on FA particles are filled by smaller reactive FA particles and welded by the cementitious products, resulting in a condensed geopolymer matrix. Insignificant amount of etched holes on FA surface are found for the sample at $\text{Na}_2\text{SiO}_3:\text{NaOH}$ ratio of 100:0 for all curing times tested while the traces of C-S-H products on the FA surface are observed and imparts the UCS. The most cementitious products are found at $\text{Na}_2\text{SiO}_3:\text{NaOH}$ ratio of 90:10 for early stage (7 days) and 50:50 for long-term stage (> 60 days). As such, the early and long-term UCS are found at $\text{Na}_2\text{SiO}_3:\text{NaOH}$ ratios of 90:10 and 50:50, respectively.
- (5) FA-based geopolymer can be used as an alternative binder to PC for sustainable pavement applications. This study indicates that the marginal LS can be stabilised by the high calcium FA-based geopolymer to be a bound pavement material for both light and heavy traffic. This will lead to a usage reduction of PC and develop a possible environmentally sustainable material. The economical ingredient is suggested to be $\text{Na}_2\text{SiO}_3:\text{NaOH}$ of 50:50.

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Disclosure statement

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