Final Report

Project : Strength Development of Soft Clay Stabilized with Bagasse Ash and Calcium Carbide Residue Based Alkali-activated materials

BY CHAYAKRIT PHETCHUAY

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Abstract

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Abstract: This research investigates strength development and the carbon footprint of Calcium Carbide Residue (CCR) and Bagasse ash (BA) geopolymer stabilized soft clay. Bangkok clay, a soft and highly compressible soft clay present in Bangkok, Thailand was investigated for stabilization with the CCR and BA geopolymers. BA is a pozzolanic material which is very rich in the oxides of silica and aluminum, and sometimes calcium. CCR is an industrial by-product obtained from acetylene gas production, high in $Ca(OH)_2$ and was used as a green additive to improve strength of the BA based geopolymer binder. The liquid alkaline activator used was a mixture of sodium silicate solution (Na_2SiO_3) and sodium hydroxide (NaOH). The influential factors studied for the geopolymerization process were Na_2SiO_3/NaOH ratio, NaOH concentration, L/BA ratio, initial water content, BA content, CCR content, curing temperature and curing time. The microstructural analyses of soft clay stabilized with CCR and BA based geopolymers is undertaken using Scanning Electron Microscopy (SEM) techniques to understand the role of influential factors controlling the strength development. Moreover, the carbon footprints of BA and CCR based geopolymers stabilized Bangkok Clay are calculated and compared with those of cement stabilized Bangkok clay at the same UCS values practically used in the soil improvement. The outcome of this research campaign the usage of CCR-BA geopolymer as a sustainable soil stabilizer alternative to high carbon Portland cement, which benefits in term of engineering, economic and environmental perspectives.

Keywords : Bangkok Clay, Calcium Carbide Residue, Bagasse Ash, Geopolymer

บทคัดย่อ

รหัสโครงการ: MRG6180169

ชื่อโครงการ: การพัฒนากำลังอัดของดินเหนียวอ่อนปรับปรุงด้วยวัสดุอัลคาไลน์จากเถ้าชานอ้อยและกากแคลเซียมคาร์ไบด์

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ระยะเวลาโครงการ: 2 ปี

บทคัดย่อ: งานวิจัยนี้ศึกษาการพัฒนากำลังอัดและการปลดปลดปล่อยก๊าซคาร์บอนของดินเหนียวอ่อนปรับปรุงด้วยจีโอโพลิเมอร์จากเถ้าชานอ้อย (BA) และกากแคลเซียมคาร์ไบด์ (CCR) ดินเหนียวกรุงเทพเป็นดินเหนียวอ่อนและมีการทรุดตัวสูงอยู่ในพื้นที่กรุงเทพฯ, ประเทศไทยจะถูกนำมาปรับปรุงด้วยกากแคลเซียมคาร์ไบด์และเถ้าชานอ้อยจีโอโพลิเมอร์ เถ้าชานอ้อยเป็นวัสดุปอซโซลานซึ่งมีค่าซิลิกา และอลูมินาปริมาณที่สูงและมีค่าปริมาณแคลเซียมเล็กน้อย กากแคลเซียมคาร์ไบด์เป็นวัสดุเหลือทิ้งจากอุตสาหกรรมผลิตก๊าซอเซทิลีนมีแคลเซียมไฮดรอดไซด์ปริมาณสูงเป็นองค์ประกอบหลักซึ่งถูกนำมาใช้เป็นสารผสมเพิ่มที่เป็นมิตรกับสิ่งแวดล้อมในการเพิ่มกำลังให้กับจีโอโพลิเมอร์จากเถ้าชานอ้อย สารอัลคาร์ไลน์ที่ใช้ได้จากส่วนผสมของโซเดียมซิลิเกต (Na_2SiO_3) และโซเดียมไฮดรอกไซด์ (NaOH) ตัวแปรที่ใช้ศึกษาปฏิกิริยาจีโอโพลิเมอร์คือ อัตราส่วน Na_2SiO_3/NaOH, ความเข้มข้นของโซเดียมไฮดรอกไซด์, อัตราส่วนสารอัลคาร์ไลน์ต่อเถ้าชานอ้อย, ปริมาณความชื้นเริ่มต้นของดิน, ปริมาณเถ้าชานอ้อย, ปริมาณกากแคลเซียมคาร์ไบด์, อุณหภูมิการบ่ม และอายุบ่ม การวิเคราะห์โครงสร้างทางจุลภาคของดินเหนียวอ่อนปรับปรุงด้วยกากแคลเซียมคาร์ไบด์และเถ้าชานอ้อนจีโอโพลิเมอร์จะถูกนำวิเคราะห์ด้วยภาพถ่ายกล้องจุลทัศน์แบบส่องกราด (SEM) เพื่อศึกษาอิทธิพลของตัวแปรต่างๆต่อค่ากำลังอัด นอกจากนั้นปริมาณการปลดปลดปล่อยก๊าซคาร์บอนของดินเหนียวกรุงเทพปรับปรุงด้วยจีโอโพลิเมอร์จากเถ้าชานอ้อยจะถูกคำนวณเทียบกับการปรับปรุงด้วยซีเมนต์ที่กำลังอัดเดียวกัน สิ่งที่ได้จากงานวิจัยนี้คือการใช้กากแคลเซียมคาร์ไบด์และเถ้าชานอ้อยจีโอโพลิเมอร์เป็นทางเลือกที่ยั่งยืนในการปรับปรุงดินแทนที่การใช้ซีเมนต์ซึ่งมีการปลดปล่อยคาร์บอนสูง ซึ่งเป็นประโยชน์ทางวิศวกรรม เศรษฐกิจ และสิ่งแวดล้อม

คำหลัก : ดินเหนียวกรุงเทพฯ, กากแคลเซียมคาร์ไบด์, เถ้าชานอ้อย, จีโอโพลิเมอร์

Chapter I

Executive summary

Introduction to research

Bangkok clay is one of the well-known soft clay deposits. It possesses high water content close to its liquid limit with large potential for settlement and low inherent shear strength. Several ground improvement techniques dealing with soft soil foundation have been developed over the past 30 years (Bergado et al., 2003; Bouazza et al., 2006; Shen et al., 2013a, b and c; Du et al., 2013 and 2014; Chai et al., 2014; Bo et al., 2015a and b; Wu et al., 2015). In situ deep mixing is an effective means, which has been developed over two decades primarily to effect columnar inclusions into the soft ground to transform soft ground to composite ground. The deep mixing technology was simultaneously developed in Sweden and Japan using quicklime as a hardening agent. Subsequently, ordinary Portland cement slurry was used as a cementing agent because it is readily available at reasonable cost. The influential factors, controlling the field strength of deep mixing columns such as penetration and withdrawal rates, water to cement ratio, and rate of blade rotation were extensively investigated by Horpibulsuk et al., (2004) (Ariake clay, Japan) and Horpibulsuk et al. (2011b and 2012c) (Bangkok clay, Thailand). However, the manufacturing of Portland cement is a resource exhausting and energy intensive process that releases large amount of the CO2 into the atmosphere, which cause the greenhouse gases (Davidovits 1991; Davidovits and Davidovics 2008). Therefore, the development of a new cementing agent and development of recycled construction materials derived from waste materials with low carbon dioxide release is considered an interesting issue. Commercial and industrial utilization of alkali-activated alumino-silicate cements, known as 'geopolymers' has been increasingly well-known over the past several decades as the search for high-performance and an environmentally maintainable alternative for ordinary Portland cement (J. Davidovits 1991; Phetchuay et al., 2016).

Geopolymers are a group of cementitious materials that has garnered increasing interest as an alternative stabilizing agent (Sukmak et al. 2013a; Suksiripattanapong et al. 2015a, 2015b; Horpibulsuk et al., 2015) to replace portland cement. The chemical process to produce geopolymers involves the co-polymerization of alumina and silica components whereby aluminosilicate-rich materials are dissolved by highly alkaline solutions such as sodium hydroxide (NaOH). Sodium silicate (Na2SiO3) can further increase the strength of the geopolymer (Palomo et al. 1999) because of the gel-like product derived from the aluminosilicate-sodium silicate reaction (Xie and Xi 2001). The silica-rich materials such as clay or kaolin (Buchwald and Kaps 2002), fly ash, and bottom ash (Davidovits et al., 1999) can be used as a precursor to react with the liquid alkaline activator. Fly Ash (FA) provides the greatest opportunity for commercial utilization of this technology due to the plentiful worldwide raw material supply, which is derived from coal-fired electricity generation (Mohapatra and Rao, 2001; Van Jaarsveld et al., 1998).

It has been reported that the mechanical properties of FA based geopolymer could be improved by high calcium additives due to the coexistence of geopolymerization products (Sodium Alumino Silicate Hydrate, N-A-S-H) and Calcium Silicate Hydrate (C-S-H) (Phoo-ngernkham et al., 2015; Phummiphan et al., 2015; Yip et al., 2005; Granizo et al., 2002; Yip et al., 2008). The Bagasse (BA) is the fibrous waste produced after the extraction of the sugar juice from cane mills. Bagasse ash is the residue obtained from the incineration of bagasse in sugar producing factories. This material usually poses a disposal problem in sugar factories particularly in tropical countries. In many tropical countries there are substantial quantities of Bagasse is rich in amorphous silica indicated that it has pozzolanic properties. Bagasse ash is a pozzolanic material which is very rich in the oxides of silica and aluminum, and sometimes calcium (Guilherme, Romildo, Eduardo, Luis, and Cristiano, 2004). Pozzolans usually require the presence of water in order for silica to combine 2 with calcium hydroxide to form stable calcium silicate, which has cementitious properties. Calcium Carbide Residue (CCR) is a waste material from acetylene gas factories, which has high calcium hydroxide [Ca(OH)2] content. It has been previously used itself as a green soil stabilizer (Horpibulsuk et al., 2012; Kampala et al. 2013 and 2014; Phetchuay et al., 2014; Vichan et al. 2013; Du et al., 2016 and Jiang et al., 2016) but not as an additive for geopolymer binder. The usage of high calcium CCR as a green additive in BA geopolymer stabilized clay is thus novel and significant in geotechnical and pavement applications.

This research attempts to examine the viability of using BA and CCR based Alkali-activated materials as a sustainable binder to improve strength of Bangkok clay. The Unconfined Compressive Strength (UCS) is used as a practical indicator to investigate the strength development. The influential factors studied include liquid alkaline activator, L content, L/BA ratio, BA content, water content, curing time, curing temperature and CCR content. The microstructural analyses of soft clay stabilized with BA and CCR based geopolymers is undertaken using Scanning Electron Microscopy (SEM) and X-ray Diffraction (XRD) techniques to understand the role of influential factors controlling the strength development. Moreover, the carbon footprints of BA and CCR based geopolymers stabilized CIS are calculated and compared with those of cement stabilized Bangkok clay at the same UCS values practically used in the soil improvement. The outcome of this research campaign the usage of BA-CCR geopolymer as a sustainable soil stabilizer alternative to high carbon Portland cement, which benefits in term of engineering, economic and environmental perspectives.

Literature review

1. Calcium carbide residue (CCR)

To improve economic and environmental impacts, some waste $Ca(OH)_2$-rich materials can be utilized together with waste pozzolanic materials, such as fly ash, biomass ash and rice husk ash to develop a cementitious material. Calcium carbide residue (CCR) is a by-product of the acetylene production process that contains mainly calcium hydroxide, $Ca(OH)_2$. Between 1995 and 1998, the demand for calcium carbide for the production of acetylene gas in Thailand was 74,000 t (Tanalapasakul, 1998). This demand is continuously increasing each year. Due to its highly basic pH, CCR has been little utilized and was typically gone to a disposal area in the form of slurry. After being sundried for a few days, the slurry form changes to a dry form.

Its production is described in the following equation:

$$CaC_2 + 2H_2O \longrightarrow C_2H_2 + Ca(OH)_2$$

From Eq., it can be seen that 64 g of calcium carbide (CaC_2) provides 26 g of acetylene gas (C_2H_2) and 74 g of CCR in the form of $Ca(OH)_2$.

Jaturapitakkul and Roongreung (2003) have introduced a cementitious material that is a mixture of CCR and rice husk ash. The cementing property was identified as a pozzolanic reaction between the two materials, and no Portland cement was included in the mixture. Consoli et al. (2001) have reported on the possibility of using CCR and fly ash to stabilize non-plasticity silty sand. For clayey soils, which have a high content of natural pozzolanic materials, stabilization by using CCR is very effective. Horpibulsuk et al. (2012a) and Kumpala and Horpibulsuk (2013) explained the possible mechanism controlling the engineering properties of CCR stabilized clay based on macro- and micro-scale observations. The optimum water content (OWC) of the stabilized clay exhibits the highest strength because it engenders the densest packing and highest cementitious products. Strength improvement for a particular curing time is classified into three zones: active, inert and deterioration (vide Fig. 2.1).

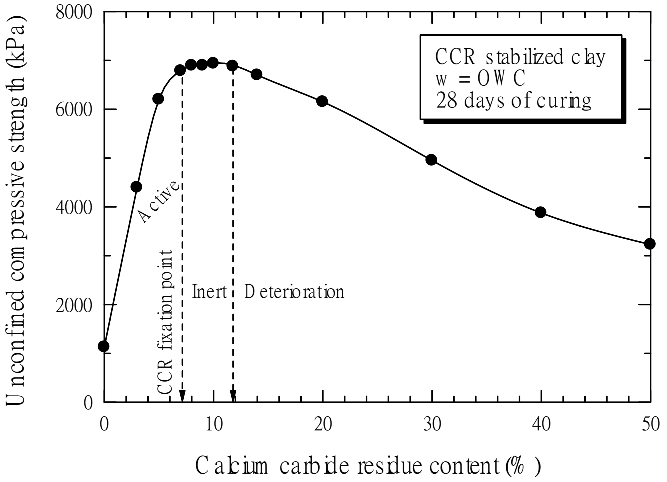


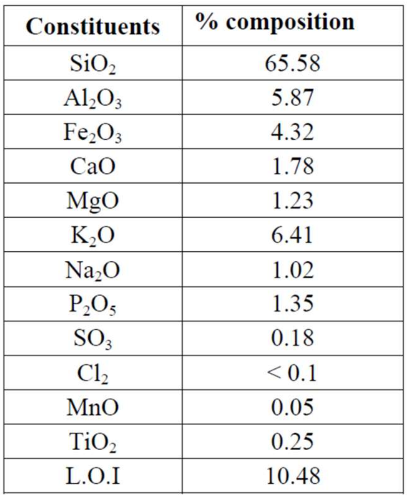
Figure 1 Improvement zones (Horpibulsuk et al., 2011c).

The data were obtained from an unconfined compression test under unsoaked condition on CCR-stabilized samples at optimum water content. In the active zone, strength increases remarkably with increased CCR content. All the input $Ca(OH)_2$ is consumed by the natural pozzolanic material in the soil to produce a pozzolanic reaction. This active zone can be determined from the CCR fixation point, which is obtained simply from the index test. CCR fixation is defined as the CCR content at which the plasticity index of the CCR-clay mixture changes insignificantly with the CCR input. Strength development in the inert zone tends to slow down; the incremental gradient becomes nearly zero and does not make any further significant improvement. A decrease in strength, which appears when the CCR content is in the deterioration zone, is caused by unsoundness due to free lime. This free lime [$Ca(OH)_2$] is clearly observed by the thermal gravity analysis (TGA) (Horpibulsuk et al., 2012a). Even with the high unsoaked strength in the active zone (Fig. 1), Kumpala et al. (2013a, 2013b) found that the wet-dry cycled strength of stabilized clay was considered insufficient according to recommendations by the ACI (1990) and the U.S. Army Corps of Engineers (2004). The input of FA (as a CCR replacement) may improve the strength of CCR stabilized clay when the CCR content is in excess of the active zone (i.e., in inert and deterioration zones) where natural pozzolanic material in the soil is not in sufficient quantities to react with the $Ca(OH)_2$. In the inert zone, the input FA enhances strength. The FA improves the densification and the pozzolanic reactive capacity. For the short-term, the strength increase is mainly caused by the packing effect because the pozzolanic reaction is a time-dependent process. The highest short-term strength is thus associated with the highest maximum dry unit weight. Over the time, a higher FA content is needed for the pozzolanic reaction; therefore, the optimal FA content increases. Improvement in the deterioration zone is not recommended in practice, even with the input of FA. Unsoundness due to the free lime content hinders the strength development by pozzolanic reactions. The soaked strength is generally lower than the unsoaked strength because the absorbed water increases repulsive forces. Even though the strengths of the stabilized clay are strongly dependent upon the CCR and FA contents, the ratio of soaked strength to unsoaked strength is almost equal. Most of the ratios vary between 0.45 and 0.65 with an average of 0.55. (Horpibulsuk et al., 2013)

2. Bagasse ash (BA)

Bagasse is the fibrous residue obtained from sugarcane after the extraction of juice at sugar mill factories and previously was burnt as a means of solid waste disposal. However, as the cost of fuel oil, natural gas and electricity has increased, bagasse has become to be regarded as a fuel rather than refuse in the sugar mills. The fibrous residue used for this purpose leaves behind about 8-10% of bagasse ash (Hailu, 2011). Bagasse ash has been reported to possess pozzolanic properties. It was reported that bagasse ash contains a large amount of silica and other relevant oxides which enhance good pozzolanic activity (Chusilp, 2009). The ash has been used alone or as admixture with lime and cement to stabilize laterite and black cotton soils (Amu et al, 2011; Osinubi and Thomas, 2007; Osinubi et.al, 2009 and Sabat, 2012). The chemical composition of BA is shown in table 1.

Table 1: Oxide composition of bagasse ash (Hailu, 2011)



Constituents	% composition
SiO_2	65.58
Al_2O_3	5.87
Fe_2O_3	4.32
CaO	1.78
MgO	1.23
K_2O	6.41
Na_2O	1.02
P_2O_5	1.35
SO_3	0.18
Cl_2	< 0.1
MnO	0.05
TiO_2	0.25
L.O.I	10.48

3. Geopolymer

The Cordi-Géopolymère private research laboratory in Saint-Quentin in 1972 discovered a fresh inorganic material called as ‘geopolymer'. Geopolymer can be formed at low temperature and small amount of time and based on the alkaline activation of easily obtainable natural and by-product silica and alumina materials happening as a network of the alumino-silicates (Davidovits 1988c). After shorter setting and hardening time, geopolymer with tightly packed poly-crystalline structure is formed showing better mechanical properties Geopolymer is extremely environmentally attractive for various reasons. Its performance as construction materials can be compared with Portland cement in lots of ways but the geopolymer needs no heat in its manufacturing process. This implies a substantial benefit with regards to reducing global CO_2 emissions. Furthermore, the utilization of industrial by-products meets the increasing trend towards waste re-utilization (Jiminez et al. 2004). Geopolymer is definitely an alumino-silicate material which includes excellent physical and chemical properties of numerous applications (Komnitsas and Zaharaki 2007).

4. Chemistry of geopolymer

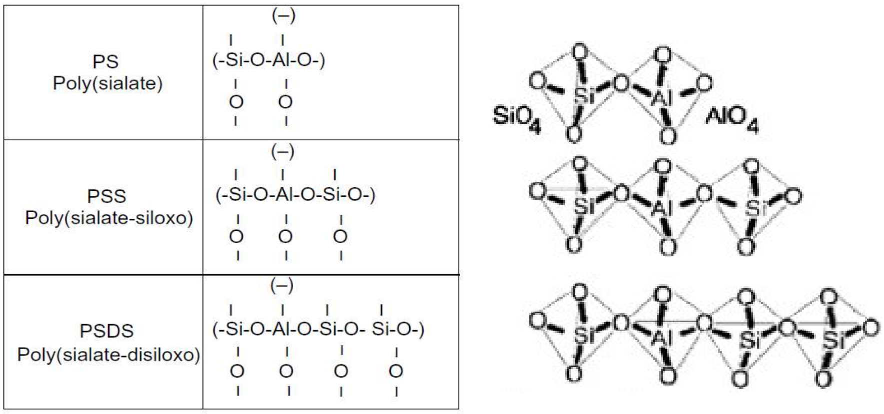
Three sources are used to form the geopolymer, i.e. raw materials, inactive filler and geopolymer liquor. Raw materials might be natural (alumino-silicate) minerals or industrial wastes e.g. fly ash, slag, and waste glass. Inactive filler, mainly kaolinite or meta-kaolinite, is employed for supplying Al^{3+} ions (Ikeda 1998). Geopolymer liquor is definitely an alkali hydroxide solution required for dissolving raw materials while sodium (or potassium) silicate solution acts as a binder, alkali activator and dispersant or plasticizer (Phair 2001). Geopolymer (poly (sialates)) contains silicate (SiO_4) and aluminate oxides (AlO_4) tetrahedral alternately linked where all oxygen atoms are exchanged (Davidovits 1976). Positive ions (Na^+, K^+ and Ca^{2+}) must certainly be contained in the framework voids to balance the negative charge of Al^{3+}.Poly (sialates) is chain polymers with Si^{4+} and Al^{3+} in 4-fold coordination with oxygen and their empirical formula could be expressed as:

$$M_n(–(SiO_2)_z–AlO_2)_n\ wH_2O$$

Where	z	is 1, 2, 3, or higher
	M	is a monovalent cation such as K^+ or Na^+
	n	is the degree of poly-condensation

The forms of polysialates distinguished are illustrated in Figure 2 (Davidovits 1988a). The complex geopolymer structure thus contains chains, sheet-like and three-dimensional networks composed of various unit kinds of connected SiO_4 and AlO_4 tetrahedral (Singh et al. 2005).

Geopolymerization can be an exothermic procedure that is conducted through oligomers dimer which provide the specific unit structures for the three dimensional macromolecular edifice. Among several hardening mechanisms could be the chemical reaction of alumino-silicate oxides with alkalis and alkali–polysilicates, leading to polymeric Si–O–Al bonds with a (Si_2O_5, Al_2O_2)n formula, which may be accomplished by calcining alumino-silicate hydroxides (Si_2O_5,$Al_2(OH)_4$) through the reaction (Davidovits 1988a).



PS Poly(sialate)	(–) (-Si-O-Al-O-) O O
PSS Poly(sialate-siloxo)	(–) (-Si-O-Al-O-Si-O-) O O O
PSDS Poly(sialate-disiloxo)	(–) (-Si-O-Al-O-Si-O- Si-O-) O O O O

Figure 2 The types of polysialates (Davidovits 1988a).

Primary steps of geopolymerization involve dissolution of solid alumino-silicate oxides in *M*OH solution (*M*: alkali metal), diffusion or transportation of dissolved Al and Si complexes from the particle surface to the inter-particle space, formation of a gel phase caused by the polymerization between added silicate solution and Al and Si complexes, and finally hardening of the gel phase (Van Jaarsveld 2000; Xu 2001) for the poly-condensation occurring during geopolymerization of minerals:

$$\text{Al–Si material}_{(s)} + M\text{OH}_{(aq)} + \text{Na}_2\text{SiO}_{3\,(s)\text{ or }(aq)} \quad (1)$$

$$\downarrow$$

$$\text{Al–Si material}_{(s)} + [M_z(\text{AlO}_2)_x(\text{SiO}_2)_y \cdot nM\text{OH} \cdot m\text{H}_2\text{O}]\ \text{gel} \quad (2)$$

$$\downarrow$$

$$\text{Al–Si material}_{(s)} + [M_a((\text{AlO}_2)_a(\text{SiO}_2)_b)\ nMOH \cdot m\text{H}_2\text{O}] \quad (3)$$

In reactions (1) and (2), the amount of Al–Si material used is dependent upon the particle size, the extent of dissolution of Al–Si materials, and the concentration of the alkaline solution. The forming of $[M_z(\text{AlO}_2)_x(\text{SiO}_2)_y nM\text{OH} m\text{H}_2\text{O}]$ gel is basically on the basis of the extent of dissolution of alumino-silicate materials, while geopolymer with amorphous structure is formed during the reaction (3). Enough time necessary for the alumino-silicate solution to create a continuous gel is dependent upon raw material processing conditions (Ivanova et al. 1994).

Dissolution of the starting materials could be the major step that has a twofold role, i.e. firstly, poly-sialate forming species are liberated from the starting materials (Duxson et al. 2007a; Grutzeck and Siemer 1997), and secondly, dissolution activates the top and binding reactions occur significantly supporting the ultimate strength of the structure. The extent of the dissolution part of geopolymerization is not fully clear whilst the extent to which other factors complement or no dissolution must be further investigated (Phair 2001).

Under alkaline conditions, alumino-silicates are changed into extremely reactive materials, and generally speaking it is thought that the dissolution process is initiated by the clear presence of hydroxyl ions. Higher levels of hydroxyl ions facilitate the dissociation of different silicate and aluminate species, promoting thus further polymerization (Davidovits 1988b; Phair et al. 2000). However, in case a quite high alkaline environment (>30 mol% overall Na_2O content) is employed, the connectivity of silicate anions might be reduced, causing poor polymerization (Singh et al. 2005).

The analysis of the dissolution on different alumino-silicate industrial minerals and by-products indicated that the extent of dissolution is higher when NaOH is employed in place of KOH (Panagiotopoulou et al. 2007) due to the smaller size of Na+ that may better stabilize the silicate monomers and dimmers contained in the solution. This thus enhances the minerals dissolution rate (Xu and Van Deventer 2000a).

Additionally, it absolutely was reported that Si and Al appear to possess a synchronized leaching behavior in both alkaline media.

Furthermore, there have been the studies of the dissolution on various kinds of fly ash in caustic soda solutions as much as 15 M at 25 and 80°C. It had been reported that high dissolution of Al_2O_3 is seen in 80°C, while the increased dissolution of SiO_2 occurs during leaching with increasing NaOH concentrations in 25°C.

5. Geopolymer Development

Geopolymer cements develop through a series of several distinct reaction processes from initial pozzolanic activation to final microstructure development. The benefits of using pozzolans as a matrix binder for agglomeration is that they tend to be economical, environmentally-friendly, more absorbent of liquids and produce a highly durable product (Jiminez et al. 2005). The major processes are dissolution of the aluminosilicate species within a highly basic, alkaline environment, polymerization of the dissolved minerals into short-lived structural gel, precipitation of formed hydration products similar to natural zeolites and final hardening of the matrix by excess water exclusion and the growth of crystalline structures (Petermann et al. 2010). Figure 3 illustrates the overall polymerization process in alkali-activated geopolymers.

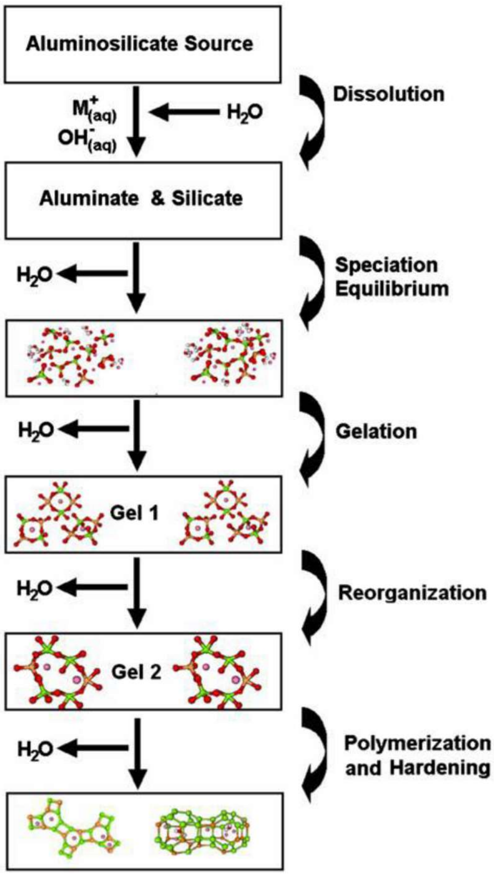


Figure 3 Geopolymer Development Model (Vijaya Rangan).

5.1 Dissolution

Dissolution occurs immediately upon contact between the alkaline solution and the pozzolanic material and allows for ionic interface between species and the breaking of covalent bonds between silicon, aluminum and oxygen atoms. Similarly to PCC, this process generates rapid and intense heat and is directly proportional to the pH level of the activating solution. The rate of dissolution is relevant to the amount and composition of the ashes and the pH of the activating solution (Jiminez et al. 2006: Xie and Xi. 2001:Petermann et al. 2010).

5.2 Polymerization

The polymerization process involves a substantially fast chemical reaction under alkaline condition on Si-Al minerals, resulting in a three-dimensional polymeric chain and ring structure consisting of Si-O-Al-O bonds. The formed gel product contains alkaline cations which compensate for the deficit charges associated with the aluminum-for-silicon substitution (Xie and Xi. 2001:Petermann et al. 2010). An intermediate, aluminum-rich phase is first formed which then gives way to a more stable, silicon-rich three-dimensional gel product of form Q^4(nAl), which is dependent upon curing conditions and activator type (Jiminez et al. 2006:Petermann et al. 2010).

5.3 Growth

During this process, the slow growth of crystalline structures become evident as the nuclei of the polymerized gel reaches critical size. The matrix crystallinity is relative to the rate by which precipitation occurs: fast reactions between alkali and ash do not allow time for growth of a well-structured crystalline environment (representative of typical zeolites). Therefore, most hardened geopolymer cements are referred to as zeolitic precursors rather than actual zeolites. The final product of geopolymerization is an amorphous, semi-crystalline cementitious material. (Petermann et al. 2010).

5.6 Raw materials

Theoretically, any material composed of silica and aluminium can be alkali- activated. So far the investigations performed have used the following raw materials:

(a) kaolinitic clays (Barbosa et al. 2000; Davidovits 1979; Davidovits and Sawyer 1985);

(b) metakaolin (Alonso and Palomo 2001a; Alonso and Palomo 2001b; Davidovits 1999);

(c) fly ashes (Fernandez-Jimenez and Palomo 2005; Palomo et al. 1999);

(d) blast furnace slag (Fernandez-Jimenez et al. 1999; Purdon 1940; Wang and Scrivener 1995);

(e) mixtures of fly ashes and slag (Puertas and Fernandez-Jimenez 2003; Puertas et al. 2000);

(f) mixtures of fly ashes and metakaolin (Swanepoel and Strydom   Appl Geochem 2002);

(g) mixtures of slag and metakaolin (Cheng and Chiu 2003);

(h) mixtures of slag and red mud (Zhihua et al. 2002; Zhihua et al. 2003);

(i) mixtures of fly ashes and non-calcined materials like kaolin and stilbite (Xu et al. 2002).

In 1974, Kaolinite and other clays were initially utilized in as fillers for the encapsulation of radioactive wastes right into a monolithic solid. Davidovits primarily used kaolinite and calcined kaolinite (metakaolin) as the supply of alumino-silicate oxides to be able to synthesize geopolymer (Davidovits 1984). A number of other researchers also have centered on the manufacture of geopolymer products and their industrial applications by utilizing either kaolinite or metakaolinite as the key reactant (Barbosa and MacKenzie 2003a; Barbosa and MacKenzie 2003b; Cioffi et al. 2003; Xu and Van Deventer 2002).

Kaolinite provides structure forming species to the entire geopolymerization process. Xu and Van Deventer (Xu and Van Deventer 2000b) stated that the addition of kaolinite is essential because the rate of Al dissolution from the raw materials is insufficient to generate a gel of the required composition. The lower reactivity of kaolinite requires sufficient time for interactions among the original materials or the source material and the gel phase to form. Little is known in regards to the behavior with this gel phase and the extent to which the character of the starting materials and the specific concentrations in solution are affecting its formation and setting (Xu and Van Deventer 2002). However, a massive amount added kaolinite might not take part in the synthesis reaction at all (Van Jaarsveld et al. 2002; Zaharaki et al. 2006).

Some authors (Xu and Van Deventer 2000b) studied sixteen different alumino-silicate minerals with the addition of kaolinite to be able to synthesize geopolymer and observed that for the majority of the alumino-silicate minerals the addition of kaolinite is required for the forming of gel. Only if kaolinite is utilized without the presence of other alumino-silicates, a poor structure is formed, which means synergy between different aluminosilicates is apparently quite important (Xu and Van Deventer 1999).

Furthermore, other authors (Palomo et al. 1999; Xu and Van Deventer 1999)studied the usage of natural minerals and wastes (in particular fly ash) in geopolymerization, as well as the immobilization of toxic metals was investigated extensively in recent years Also, some authors (Van Jaarsveld et al. 1998) have used black coal fly ash and construction wastes as the foundation for geopolymerization.

Some authors (Xu et al. 2002) used fly ash, kaolinite and albite (Na-rich end member of the Albite-Anorthite Series.) in several combinations for the synthesis of geopolymer. It is thought that the larger reactivity of fly ash and albite, the interaction between the original materials and the gel phase along with the reinforcing effect induced by the large unreacted albite particles are accountable for an ideal mechanical behavior (high compressive strength and low cracking probability).

Some authors (Davidovits 2005a) studied the 15 types of combustion fly ashes were tested for suitability in geopolymer cements. The samples were cured at room temperature and the compressive strength was measured after 28 days. A sizable variation in the behavior of the fly ashes was noticed which range from unworkable situations to strength of 95 MPa.

Some authors (Xu and Van Deventer 2000b) proved that calcined materials for instance slag, fly ash and metakaolinite which are generally amorphous, usually display a greater reactivity during geopolymerization in comparison to non-calcined materials. This is explained by the truth that calcination activates materials by changing their crystalline into amorphous structure with subsequent storage of the additional energy (Xu et al. 2002).

Moreover, the production of consistent geopolymer from heterogeneous industrial waste sources is really a challenging issue for the minerals industry, since raw material suitability cannot be fully guaranteed by elemental composition analysis (Fernandez-Jimenez and Palomo 2003). So far as fly ash based geopolymers are involved, the mechanical strength increases as a result of the formation of an Al-rich alumino-silicate gel during the initial stage of alkaline activation of ash particles, and may further increase as a result of the Si enrichment of the material (Fernandez-Jimenez et al. 2006). Therefore, it is important to control Al and Si dissolution from the raw materials, through pre-processing and/or utilization of combinations of raw materials with various reactivities (Duxson et al. 2007a).

5.7 Factors affecting of compressive strength

Measurements of compressive strength are employed by many researchers as an instrument to measure the success of geopolymerization due to the low cost and simplicity of compressive strength testing, along with of the truth that strength development is really a primary way of measuring the utility of the materials found in different applications of the construction industry (Provis et al. 2005).

The compressive strength of geopolymer is dependent upon many factors such as the gel phase strength, the ratio of the gel phase/undissolved Al–Si particles, the distribution and the hardness of the undissolved Al–Si particle sizes, the amorphous nature of geopolymer or the amount of crystallinity, and the surface reaction between the gel phase and the undissolved Al–Si particles (Van Jaarsveld et al. 2003; Xu 2001)

Furthermore, factors such as % CaO, % K_2O and the kinds of alkali have an important correlation with compressive strength. The significance of the molar Si/Al ratio during the alkaline dissolution of the individual minerals suggests that compressive strength is obtained by complex reactions between the mineral surface, kaolinite and the concentrated sodium silicate solution.

After geopolymerization, the undissolved particles remain bonded in the matrix, so the hardness of the minerals correlates positively with the last compressive strength (Xu and Van Deventer 1999; Xu and Van Deventer 2000b). During geopolymerization of natural minerals, it is known that after adding aggregate for instance granular sand to the geopolymer mixture, the compressive strength increases (Xu et al. 2002).

The quantity of metakaolinite added to the geopolymer matrix, along with the KOH concentration and the addition of sodium silicate, also play an important role on the ultimate compressive strength. some authors (Swanepoel et al. 1999) proved that the strength increases with increasing addition of metakaolinite. The main reason might be that the more metakaolinite added, the more Al gel forms in the system, causing a higher level of polymerization. Some authors (Wang et al. 2005) proved experimentally that the compressive strength, along with the apparent density and the content of the amorphous phase of metakaolinite-based geopolymer, increase with the increase of NaOH concentration within the range 4–12 mol/L. This is caused by the enhanced dissolution of the metakaolinite particulates and therefore the accelerated condensation of the monomer in the clear presence of higher NaOH concentration.

Some authors (Luz Granizo et al. 2007) supported the proven fact that the alkali activation of metakaolin using sodium silicate and NaOH containing solutions results in the production of material exhibiting higher mechanical strength compared to the activation with only NaOH. Furthermore, the flexural strength increases once the activator volume decreases or the concentration of Na increases.

Compressive strength of metakaolin based geopolymer increased linearly by approximately 400% from Si/ Al = 1.15 to Si/Al = 1.90, where it obtained its maximum value, before decreasing again at the greatest Si/Al ratio of 2.15 (Duxson et al. 2005) (Figure 4).

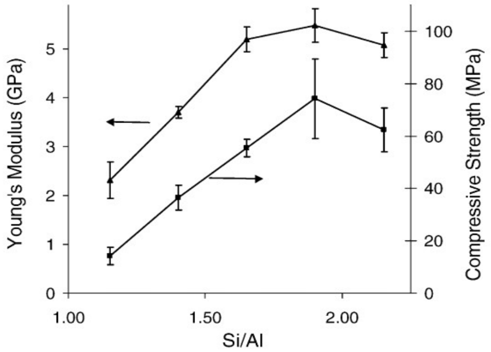


Figure 4 Young's moduli (▲) and ultimate compressive strengths (■) of geopolymers. (Duxson et al. 2005).

It is thought that the quantity of unreacted materials in specimens with higher silica content acts as defect site and includes a negative impact on strength. Higher strength was recorded once the ratios SiO_2/Al_2O_3 and Na_2O/Al_2O_3 were 3.0–3.8 and approximately 1, respectively (Duxson et al. 2005; Stevenson and Sagoe-Crentsil 2005). However, these initial ratios might be changed based on the total amount of the raw materials used as Al_2O_3 and SiO_2 source (Silva et al. 2007).

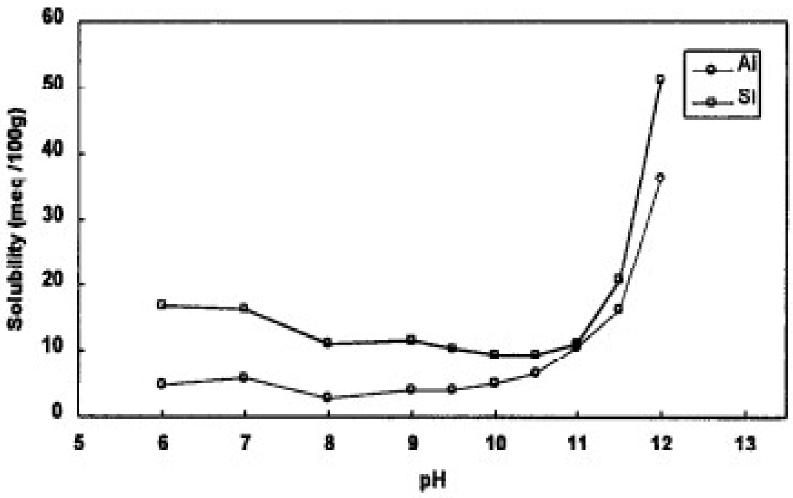


Figure 5 Dissolution of Al Si from metakaolin as a function of pH over a 5 h period (Phair and Van Deventer 2001).

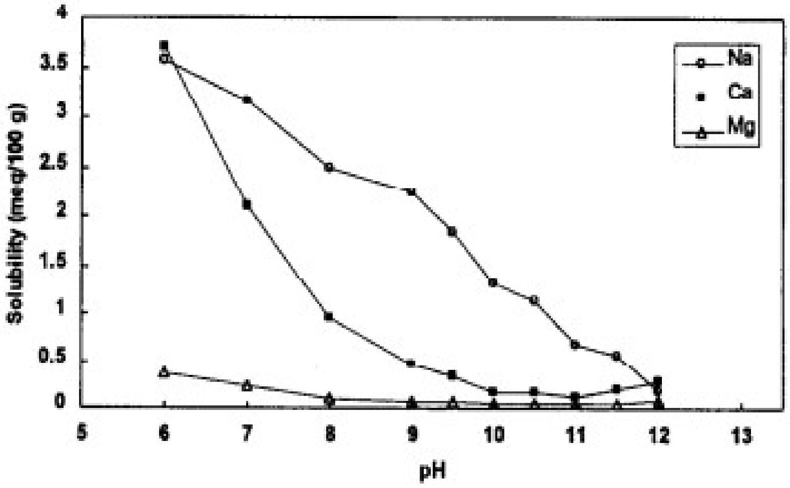


Figure 6 Dissolution of Na, Ca, and Mg metakaolin as a function of pH over a 5 h period. Ti and Fe concentration were negligible (Phair and Van Deventer 2001).

Based on some authors (Phair and Van Deventer 2001), probably the most significant factor that controls the compressive strength of fly ash-based geopolymer may be the pH of the original alkali metal silicate precursor. When working with cement as a setting additive in the geopolymer matrix, the compressive strength increases almost exponentially with increasing pH (Figure 5 and 6).

The larger alkali content was found to enhance solid dissolution but also to cause alumino-silicate gel precipitation at very early stages, causing lower compressive strength (Lee and Van Deventer 2002). Additionally, the calcium content in fly ash based geopolymer, along with the water/fly ash ratio, is apparently highly important (Van Jaarsveld et al. 2003).

Some authors (Palomo et al. 2007) proved that alkali activation of highly blended cements containing 30% Portland cement clinker and 70% fly ash results in acceptable mechanical strength, which will be strongly affected by the sort of the alkaline activator put into the system. Some authors (Kumar et al. 2005) indicated that mechanically activated fly ash based geopolymer exhibits higher compressive strength due to the formation of a tight microstructure. Mechanical activation of fly ash appears to favor geopolymerization, since the reaction requires less time and occurs at lower temperature.

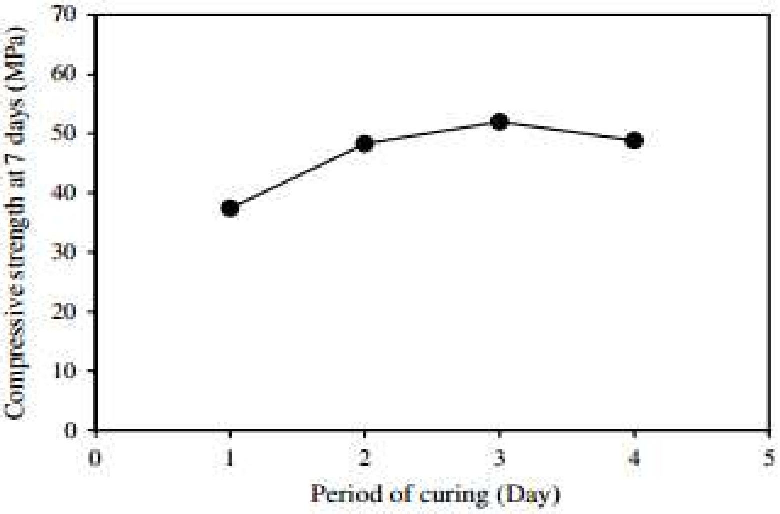


Figure 7 Duration of heat curing and strength cured at 60°C with delay time (Chindaprasirt et al. 2007).

The influence of curing temperature and time on the flexural properties of geopolymer centered on class C fly ash has been investigated by some authors . (Miller et al. 2005). It had been discovered that the curing regime includes a very significant effect on the physical and chemical properties of fly ash-based geopolymer. Indeed, the mere escalation in synthesis temperature is sufficient to boost the degree of long-range ordering in geopolymer binders (Duxson et al. 2007a).

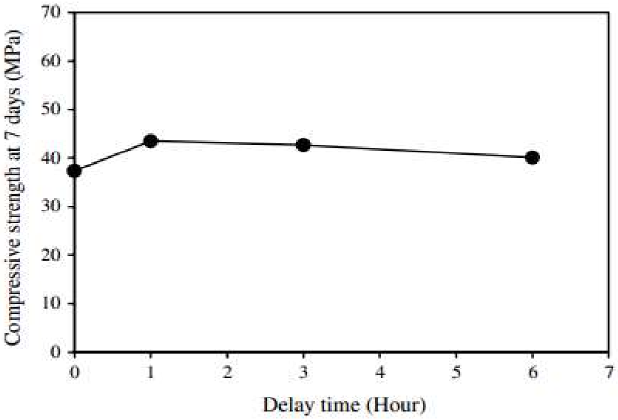


Figure 8 Strength and delay time of geopolymer mortar with 60°C heat curing for 24 h (Chindaprasirt et al. 2007).

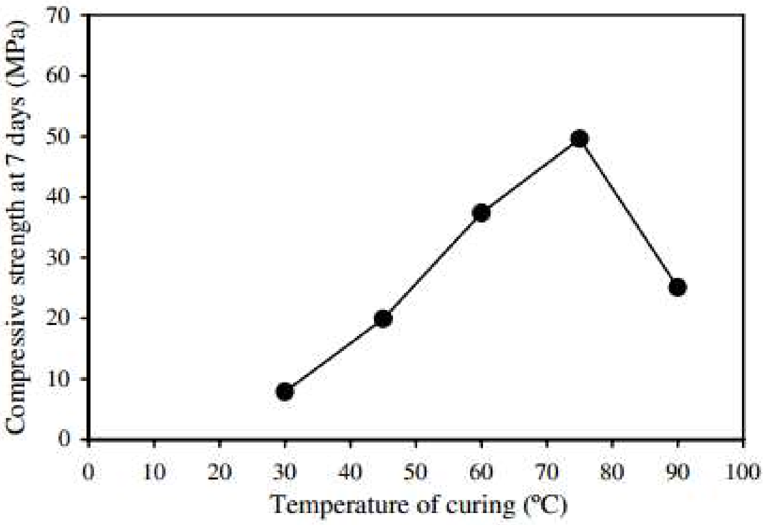


Figure 9 Strength and temperature of curing of geopolymer with no delay time before curing (Chindaprasirt et al. 2007).

Geopolymers include relatively massive amount water in large pores readily available for evaporation, which does not end up in capillary strain. This fact may account for the low temperature region of dimensional stability (Barbosa and MacKenzie 2003b). Once the freely evaporable water is taken from pores, the top part of the gel structure increases as water is liberated from the outer lining of the gel, and small pores leading to shrinkage are observed. In this instance, the gel contraction might be correlated with the decrease in surface area (Duxson et al. 2007b).

Moisture evaporation results in deterioration of the geopolymer product which cannot develop satisfactory strength. Furthermore, the addition of water improves the workability of the mortar (Chindaprasirt et al. 2007) (Figure 7, 8 and 9).

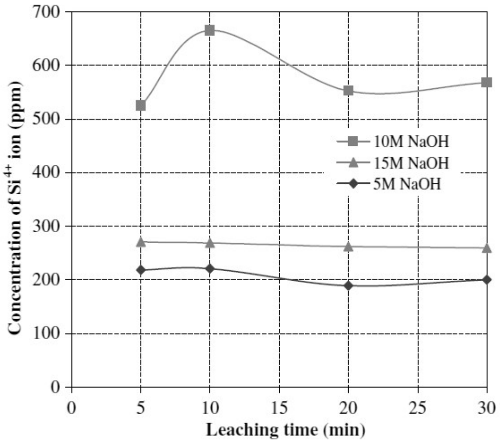


Figure 10 Si^{4+} ion concentration with fly ash/NaOH = 3:1 in 5, 10, and 15 M NaOH (Rattanasak and Chindaprasirt 2009).

Furthermore, some authors (Rattanasak and Chindaprasirt 2009) studied the influence of NaOH solution on the synthesis of fly ash geopolymer. To produce geopolymer paste, separate mixing and normal mixing were used. For separate mixing, NaOH solution was blended with fly ash for the initial 10 min; the subsequently sodium silicate solution was added to the mixture. For normal mixing, fly ash, sodium hydroxide and sodium silicate solution were incorporated and mixed at the same time. Geopolymer were cured at 65°C for 48 h. At 5 M NaOH, the dissolution was low because of the relatively low base condition. For 10 M NaOH, the base condition was higher and the dissolution was, therefore, increased. For the 15 M NaOH, the dissolution was again reduced owing primarily to a rise in coagulation of silica (Bergna and Roberts 2006) (Figure 10 and 11).

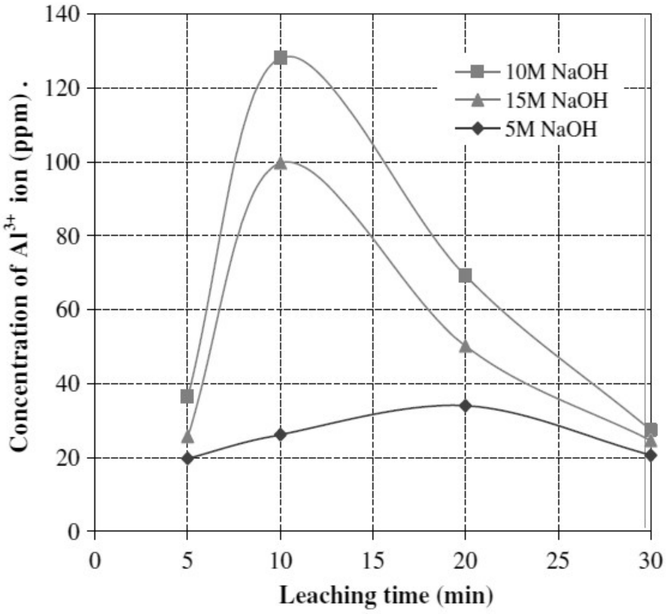


Figure 11 Al^{3+} ion concentration with fly ash/NaOH = 3:1 in 5, 10, and 15 M NaOH (Rattanasak and Chindaprasirt 2009).

The water within geopolymer and its subsequent removal by evaporation plays a significant role in obtaining a crack-free geopolymer, which means that rapid drying during curing ought to be avoided, while curing at less relative humidity (e.g. 30%) is advised (Perera et al. 2004). Also, it had been found that when the curing temperature is high (approximately 90°C), the geopolymer will substantially lose the moisture (Bakharev 2005b).

Other researches (Khalil and Merz 1994; Van Jaarsveld et al. 2002) proved that curing for longer amounts of time at elevated temperature generally seems to weaken the structure, suggesting that small levels of structural water must be retained to be able to eliminate cracking and maintain structural integrity. It appears that prolonged curing at elevated temperatures breaks down the cellular structure of the geopolymer synthesis mixture, leading to dehydration and excessive shrinkage, while long procuring at room temperature is good for strength development when utilizing fly ash as a raw material (Bakharev 2005b). Furthermore, J.G.S Van Jaarsveld et al.2002 (Table 1) stated that initial curing at higher temperatures (above 50–80°C) does not increase compressive strength substantially above that accomplished by curing at room temperature.

Generally speaking, it is needed to adequately cure to be able to achieve advanced mechanical and durability performance. Additionally, the setting time is practically important as it defines enough time necessary for transport, placing and compaction (Teixeira-Pinto et al. 2002). In order to raise the acceptance of geopolymerization by the industry, curing conditions ought to be just like those utilized in OPC production.

Table 2 The effect of curing conditions on the compressive strength of a matrix containing Macquarie fly ash with compositional variables: clay (kaolinite) content = 15% (mass) (J.G.S. Van Jaarsveld et al. 2002).

Time (h)	Temperature (°C)					
	30	50	70	30 B	50 B	70 B
6	6	-	14	19	-	28
12	15	26	34	7	22	21
24	20	12	33	19	24	29
48	19	-	28	21	-	15
Average (12/24 h samples)	17	19	34	13	23	25

[a] Samples were cured in an oven, open to the atmosphere except for samples denoted by “B” which were cured in sealed plastic bags under the same conditions. Compressive strength values in MPa.

Based on researches (Hardjito et al. 2004) collected the consequence of geopolymer concrete development. The binder in this concrete, the geopolymer paste, is formed by activating by-product materials, for example low-calcium (Class F) fly ash. he found that numerous variables for instance curing temperature, curing time, concentration of alkali solution, and delay time effected to compressive strength of geopolymer concrete as follows;

The curing temperature in the range of 30 to 90°C increases, the compressive strength of geopolymer concrete also increases. Higher curing temperature triggered larger compressive strength, although a rise in the curing temperature beyond 60°C did not raise the compressive strength substantially (Figure 13).

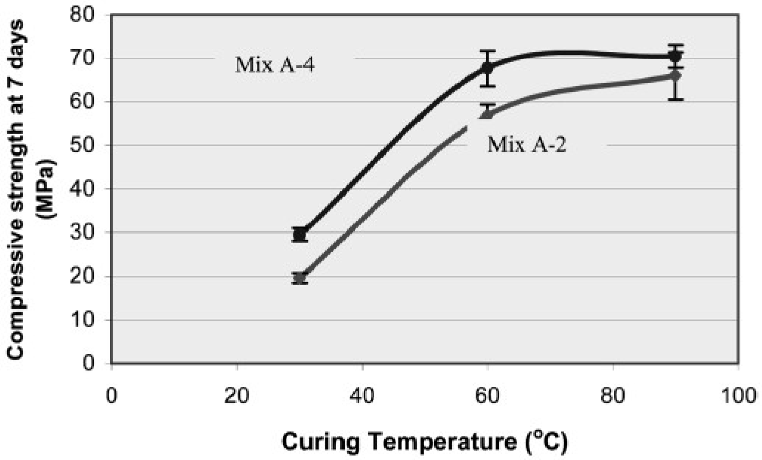


Figure 12 Effect of curing temperature on compressive strength (Hardjito et al. 2004).

The influence of curing time on the compressive strength indicate that a longer did not produce weaker material as claimed by researches (Van Jaarsveld et al. 2002). However, the escalation in strength for curing periods beyond 48 h is not significant (Figure 13).

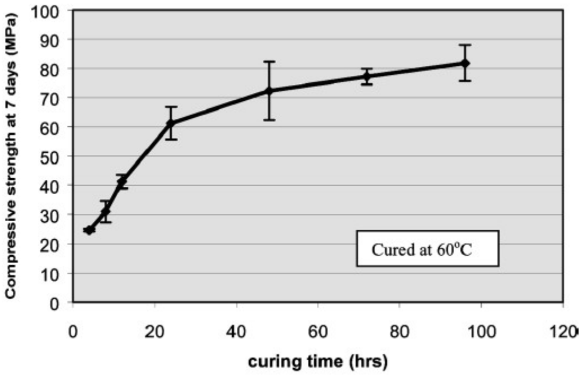


Figure 13 Influence of curing time on compressive strength (Hardjito et al. 2004).

The concentration of sodium hydroxide as measured by Molarity (second column). Mixture A-3 with higher concentration of NaOH yielded higher compressive strength than Mixture A-1. The same trend can also be observed for the Mixtures A-2 and A-4 (Table 3).

Table 3 Effect of parameter on compressive strength (Hardjito et al. 2004).

Mixture	Concentration of NaOH liquid in molarity (M)	Sodium silicate/NaoH liquid ratio by mass	7-day compressive strength after curing at 60°C for 24 h. (MPa)
A-1	8 M	0.4	17.3
A-2	8 M	2.5	56.8
A-3	14 M	0.4	47.9
A-4	14 M	2.517.3	67.6

The new concrete was permitted to stand at room temperature after mixing and just before being put into molds for a particular amount of time. The new geopolymer concrete is easily handled as much as 120 min without the sign of the setting and the degradation in the compressive strength (Figure 15).

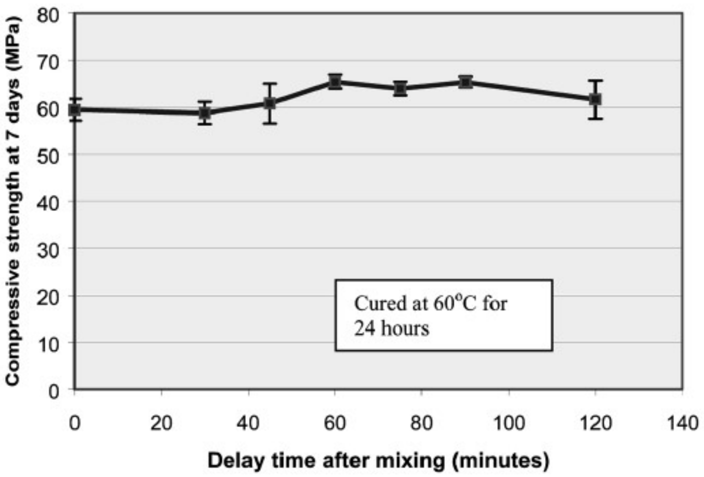


Figure 14 Influence of delay time on compressive strength (Hardjito et al. 2004).

The compressive strength does not vary with the age of concrete, when cured for 24 h. This observation is in contrast to the well-known behavior of OPC concrete, which undergoes a hydration process and hence gains strength over time (Figure 15).

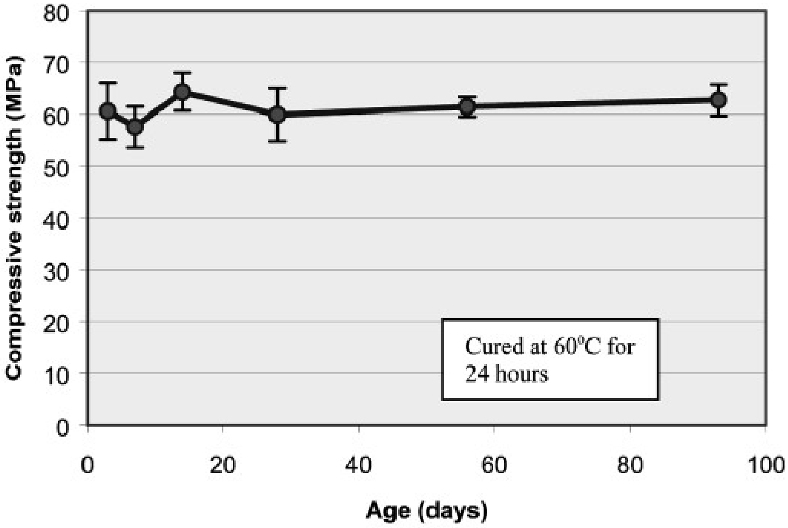


Figure 15 Compressive strength at different ages (Hardjito et al. 2004).

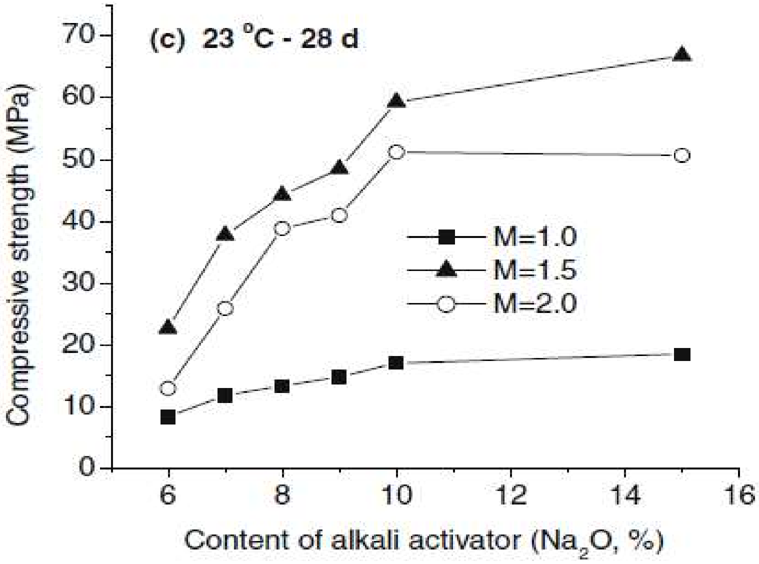


Figure 16 Effects of modulus (M) and content of the mixed alkali activator on the compressive strength of fly ash geopolymer cured at room temperature of 23°C for 28 days (Guo et al. 2010).

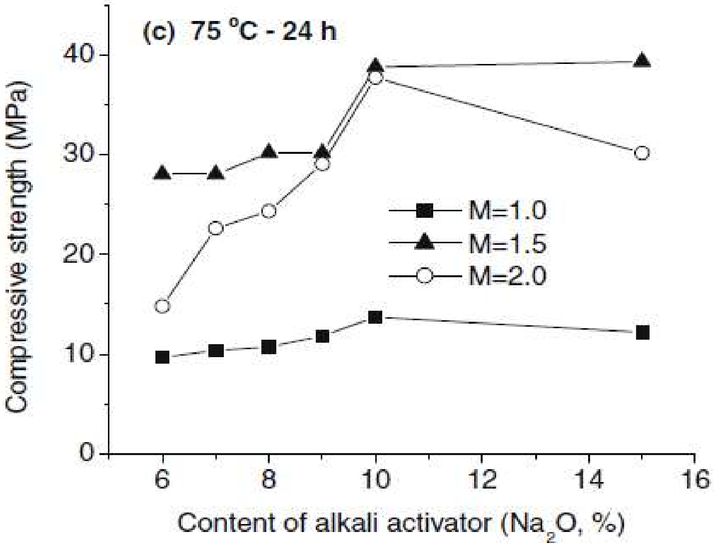


Figure 17 Effects of modulus (M) and content of the mixed alkali activator on the compressive strength of fly ash geopolymer cured at room temperature of 75°C for 4, 8, and 24 h (Guo et al. 2010).

Some authors (Guo et al. 2010) indicated that the high compressive strength was obtained once the class C fly ash (CFA) was activated by the mixed alkali activator (sodium hydroxide and sodium silicate solution) with the optimum modulus viz., molar ratio of SiO_2/Na_2O of 1.5. The appropriate content of the mixed activator was 50% as evaluated by the mass proportion of Na_2O to CFA. The compressive strength of those samples was 63.4 MPa when these were cured at 75°C for 8 h accompanied by curing at 23°C for 28 days (Figure 16 and 17).

5.8 Microstructural techniques

Several easy or advanced techniques can be utilized to acquire maximum information and elucidate geopolymerization mechanisms. The capability of Al–Si minerals to undergo geopolymerization might be predicted by specific surface area measurements, which offer an indication of how much surface area participates in heterogeneous reactions inside a solid–fluid system (Van Jaarsveld et al. 2002).

Optical microscopy provides a visible description of the microstructure because it is shown in scale the physical size and model of the different aspects of geopolymer. X-ray fluorescence (XRF) spectrometry works extremely well for elemental analysis of Al–Si minerals. X-ray diffraction (XRD) might be also a helpful tool although the quantity of information which may be obtained is restricted as a result of substantial amorphous nature of geopolymer. However it will provide information concerning the extent to which crystalline starting materials have reacted (Van Jaarsveld et al. 2002). Figure 18 presents the XRD pattern of geopolymer when fly ash is employed as raw materials and activated employing a NaOH (8M) solution and cured at 85°C (20 h) (Fernandez Jiminez et al. 2004).

Scanning electron microscopy (SEM) allows visual examination of a product from millimeters to micrometers to yield definitive topographical information along with good physical and mechanical description of the microstructure of crystalline and amorphous materials, which may not be detected by other techniques (Duxson et al. 2006; Lee 2002). Some authors (Jiminez et al. 2004) provided the geopolymer microstructures (Figure 19 - 22) are characterized by way of a dispersion of distinctive morphologies in a large of predominantly featureless hydration product (alumino-silicate gel). Occasionally, cracking in the item is observed. This might be because of the thermal treatment carried out within the activation process, mechanical damage during sample preparation or to drying shrinkage in the vacuum of the electron microscope. The relatively low magnification images (Figure 19 and 20) offer a summary of the distribution of numerous constituent phases with an increase of local detail being provided in Figure. 21 and 22.

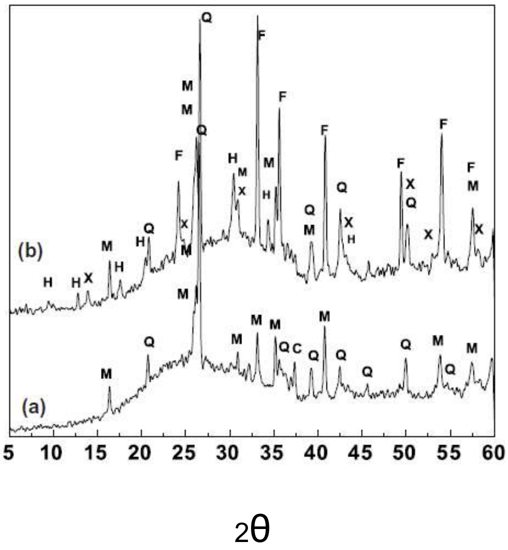


Figure 18 XRD spectra (a) un-reacted fly ash; (b) alkali-activated fly ash 20 h at 85°C Q=Quartz; M= Mullite; F=Hematite; C=CaO; H=Herschelite; X=Hydroxysodalite (Fernandez Jiminez et al. 2004).

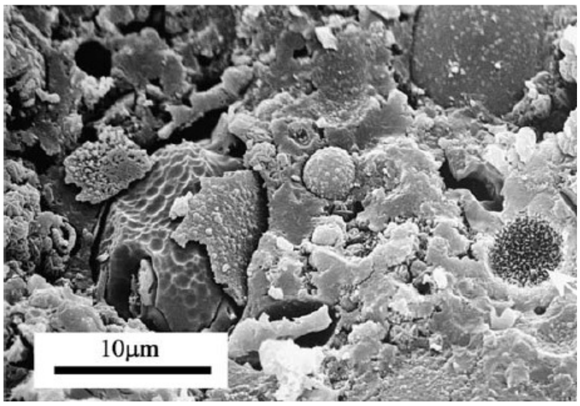


Figure 19 SEM micrograph of fracture surface of alkali-activated PFA geopolymer. Fe_2O_3 is arrowed (Jiminez et al. 2004).

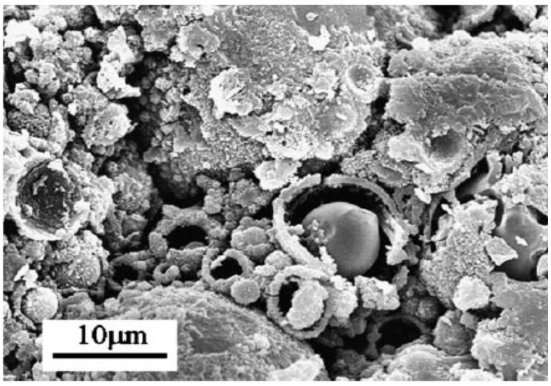


Figure 20 SEM micrograph of fracture surface of alkali-activated PFA geopolymer (Jiminez et al. 2004).

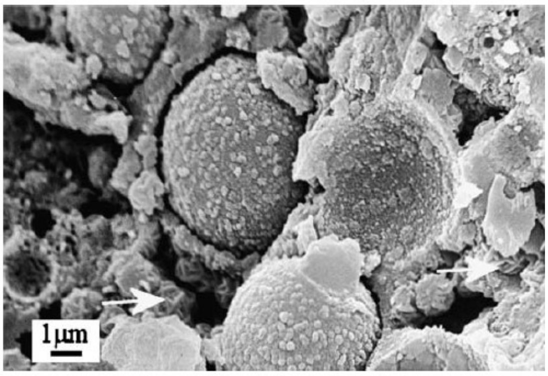


Figure 21 SEM micrograph of fracture surface of alkali-activated PFA geopolymer showing PFA particle with reaction shells and also unidentified spherical assemblages (arrowed) (Jiminez et al. 2004)

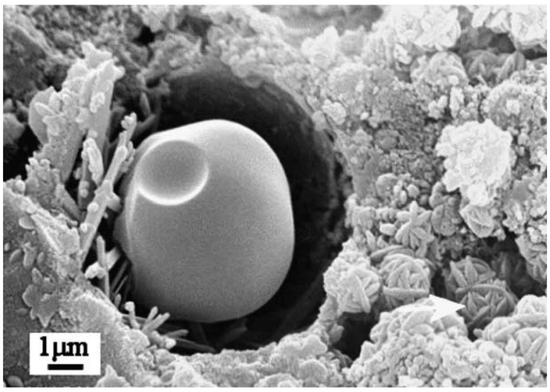


Figure 22 SEM micrograph of fracture surface of alkali-activated PFA geopolymer showing considerably eroded PFA particle and also unidentified spherical assemblages (arrowed) (Jiminez et al. 2004).

Objectives

The objectives of this research are as follows:

1. To study a possibility of using Bagasse ash (BA) Alkali-activation modified with Calcium carbide residue (CCR) to improve the strength of soft clay.
2. To calculate the carbon footprints of soft clay stabilized with Bagasse ash (BA) and Calcium carbide residue (CCR) geopolymer and compare with soft clay stabilized with cement
3. To investigate the microstructure analysis of soft clay stabilized with BA and CCR geopolymer.

Research methodology

In this research, the research methodology consists of 5 parts.

Part 1: Literature review.

Part 2: Surveying and collecting materials.

Part 3: Strength Development of Soft Clay Stabilized with Bagasse Ash and Calcium Carbide Residue Based Alkali-activated materials.

The influential factors include mixing ingredient (bagasse ash content, water content, liquid alkaline activation content, Na_2SiO_3/NaOH ratio, concentration of NaOH, CCR content) and curing time. The sample preparation started with mixing soft clay and BA for 5 min in a mixer to ensure homogeneity of the mixture. The mixer was stopped and the mixture was mixed with the liquid alkaline activator (L) and CCR for an additional 5 minutes. The uniform soft clay–BA–L-CCR mixtures were transferred to cylinder molds of 38 mm in diameter and 76 mm in height for UCS test. The BA-CCR geopolymer stabilized soft clay samples were dismantled, wrapped within vinyl sheet and then cured at room temperature for the required curing duration. The UCS tests were carried out on the samples after 7, 14 and 28 of curing in accordance with ASTM C69-09. For each curing time and ingredient, at least five samples were tested under the same conditions to assure test result consistency. In most cases, the results under the same testing condition were reproducible with low mean standard deviation, SD (SD/x b 10%, where x is mean strength value).

Part 4: The microstructure and carbon footprint of soft clay stabilized with BA and calcium carbide residue (CCR) Alkali-activated materials.

Part 5: Writing and submit a journal paper entitled “Strength Development of Soft Clay Stabilized with Bagasse Ash and Calcium Carbide Residue Based Alkali-activated materials”

Chapter II

Result

2. MATERIALS AND METHODS

2.1 Materials

2.1.1 Bangkok Clay (BC)

Bangkok Clay (BC) samples were collected from Bangkok area at a depth of 3-5 m. BC consists of 4% sand, 29% silt and 67% clay that results come from Figure 1. The specific gravity and organic content are 2.60 and 2.5%, respectively. Liquid Limit (LL) and Plastic Limit (PL) are approximately 64% and 26%, respectively. Based on the Unified Soil Classification System (USCS), the BA is classified as highly plastic (CH). The basic properties are shown in Table 1. The grain size distribution and chemical compositions of BC obtained from hydrometer analysis and X-ray Fluorescence (XRF) analysis are shown in Figure 1 and Table 2, respectively.

2.1.2 Bagasse Ash (BA)

BA was obtained from a local Thailand supplier. It grain size distribution is shown in Figure 1. Table 2 summarizes the chemical composition of BA using X-ray fluorescence (XRF). Total amount of the major components (SiO_2, Al_2O_3 and Fe_2O_3) of BA is 94.40% while the CaO content is 1.68%.

2.1.3 Calcium Carbide Residue (CCR)

CCR is a by-product from an acetylene gas (C_2H_2) production process. The main oxide of calcium carbide residue is calcium hydroxide ($Ca(OH)_2$) in a slurry form. CCR was dried by the sun and sent to landfills as waste. The CCR was oven-dried at 100 ^oC for 24 h and was then ground using a Los Angeles abrasion machine. The CCR was passed through a No. 40 sieve (425 μm). The specific gravity value is 2.32. Table 2 summarizes the chemical composition of CCR BA and BC, as obtained by conducting the X-ray fluorescence studies. The high $Ca(OH)_2$ and CaO contents of the CCR indicate that it can react with BA and produce a cementitious material (Palomo et al., 1999). The grain size distribution of the CCR compared with that of the BC is shown in Figure 1. The curves were obtained from laser particle size analysis, which is applicable for materials that react with water. The average grain size (D_{50}) of CCR is 0.01 mm, which is bigger than that of BC.

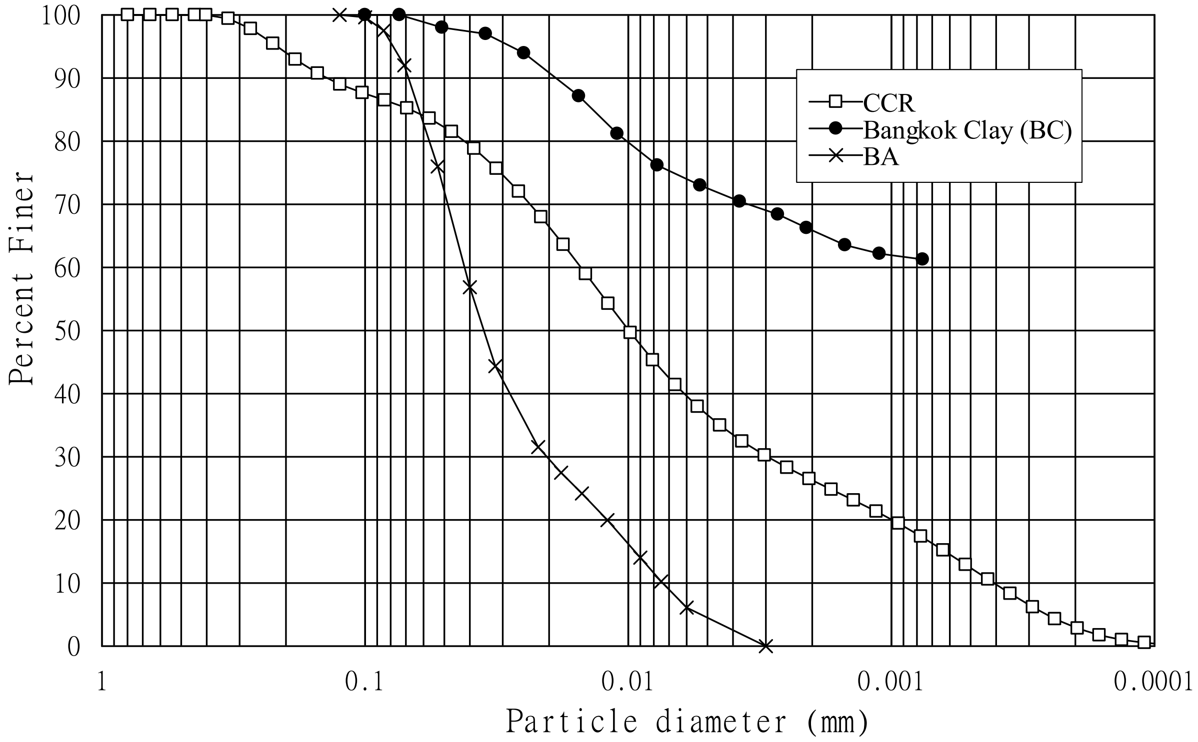


Fig. 1. Grain size distribution of clay and CCR.

Table 1 Basic properties of BC.

Properties	Characteristics
Liquid limit, LL (%)	65%
Plastic limit, PL (%)	32%
Plasticity index, PI (%)	33%
Grain size distribution	Clay 71% ; Silt 25% Sand 4%
Organic content	2.40%
Specific gravity, Gs	2.6
pH	7.2

2.1.4 Liquid alkaline activator (L)

The liquid alkaline activator (L) is a mixture of Na_2SiO_3, which consists of 9% Na_2O and 30% SiO_2 by weight, and NaOH at various concentrations.

Table 2 Chemical properties of Bangkok Clay, Bagasse ash and CCR.

Chemical composition (%)	BC	Bagasse Ash	CCR
Al_2O_3	12.760	15.380	6.941
SiO_2	66.953	66.800	19.423
SO_3	7.893	1.500	1.230
Cl	0.576	0.010	0.056
K_2O	1.387	5.500	0.721
CaO	5.642	4.000	69.660
TiO_2	1.179	0.050	0.675
Cr_2O_3	0.010	0.003	0.006
MnO_2	0.022	0.051	0.065
Fe_2O_3	3.523	3.600	1.041
CuO	0.026	0.005	0.030
ZnO	0.005	0.004	N.D.
PbO	0.010	0.004	0.013
SrO	0.013	0.020	0.044
Rb_2O	N.D.	0.004	0.017
ZrO_2	N.D.	0.014	0.007

N.D. = none detected

2.2 Sample Preparation and Testing

There are 6 series of unconfined compression test to investigate the role of influencing factors such as L content, BA content, L/BA, Na_2SiO_3/NaOH and CCR content. The testing program is summarized in Table 3

Table 3 Summary of the testing program.

		Series 1	Series 2	Series 3	Series 4	Series 5	Series 6
NaOH	(molar)	2.5,5, 7.5, 10, 12.5, 15	7.5	7.5	7.5	7.5	
Na_2sio_3:NaOH	(L)	70:30	80:20, 70:30 60:40, 50:50	70:30	70:30	70:30	-
Alkaline content	(L/BA)	1	0.5, 1.0, 1.5, 2.0	1	1	1	-
BA	(%)	30	30	20, 30, 40	30	30	-
CCR	(%)	-	-	-	0,3, 6, 9, 12, 15	0,12	-
Cement	(%)	-	-	-	-	-	3, 6, 9 12, 15, 20,30
Water content of LL	(%)	1.0, 1.5, 2.0	1.0, 1.5, 2.0	1	1	1	1
Curing temp.	(°C)	38	38	38	38	25	25
Curing time	(days)	7, 14, 28	7, 14, 28	7	7, 14, 28	7	7

2.2.1 BA geopolymer stabilized BC

The BA geopolymer binder was a combination of BA and liquid alkaline activator (Na_2SiO_3 and NaOH). The influencing factors were varied depending upon the test series. The BA contents were 20, 30 and 40% by weight of dry soil. The Na_2SiO_3/NaOH ratios were 80:20, 70:30, 60:40 and 50:50. The NaOH concentrations were 2.5, 5, 7.5, 10, 12.5 and 15 molars. The L/BA ratios were 1.0, 1.5 and 2.0. The initial water content (*w*) of BC varied from 1 to 2 times LL to simulate the variation of in-situ water content. The curing temperatures were 25 and 38 ^{o}C.

The sample preparation started with mixing BC and BA for 5 minutes in a mixer to ensure homogeneity of the mixture. The mixer was stopped and the mixture was mixed with the liquid alkaline activator (L) for an additional 5 minutes. The uniform BC-BA-L mixtures were transferred to cylinder molds of 38 mm in diameter and 76 mm in height for UCS test. The BA geopolymer stabilized BC samples were dismantled, wrapped within vinyl sheet and then cured at target temperatures of 25 and 38 ^{O}C for the required curing duration. The 38 ^{O}C temperature was used to simulate an average heat temperature in countries with a tropical climate, including Australia and Thailand (Phetchuay et al., 2014). The UCS tests were carried out on the samples after 7, 14 and 28 days of curing in accordance with ASTM C69-09. For each curing time and ingredient, at least five samples were tested under the same conditions to assure test result consistency. In most cases, the results under the same testing condition were reproducible with low mean standard deviation, SD (SD/$\overline{x}$ < 10%, where $\overline{x}$ is mean strength value).

2.2.2 CCR-BA geopolymer stabilized BC

The BA content was fixed at 30% by weight of dry soil and the Na_2SiO_3/NaOH ratio, NaOH concentration, L/BA ratio and water content were fixed at the optimal ingredient obtained from the test result of BA geopolymer stabilized BC. The CCR contents were however varied to investigate the influence of CCR on UCS development. The CCR contents were 3, 6, 9, 12 and 15%. The uniform BC-CCR-BA-L mixtures were transferred to cylinder molds of 38 mm in diameter and 76 mm in height for UCS test. The samples were also wrapped within vinyl sheets as the BA geopolymer stabilized BC and subsequently cured at 38 ^{O}C. UCS values of BA-CCR geopolymer stabilized BC were measured after 7, 14 and 28 days of curing.

2.2.2 Cement stabilized BC

The cement contents tested were 3, 6, 9, 12,15, 20, 25 and 30% by weight of dry soil. The initial water content of BC was fixed at LL. First, check the initial water content. second, add water from back calculation and mixing in a mixer then keep soil in close bag for a night. Third, check water content and mixing BC and BA for 5 minutes in a mixer to ensure homogeneity of the mixture. The BC-cement mixtures were transferred to cylinder molds of 38 mm in diameter and 76 mm in height and then cured at 25 ^{O}C. UCSs of cement stabilized samples were measured after 7 days of curing. The UCS results were compared with those of BA based geopolymer stabilized BC.

3. RESULTS AND DISCUSSION

3.1 Strength of BA geopolymer stabilized BC

Figure 2 presents the effect of NaOH concentration on UCS development, which shows the relationship between 7-day UCS versus NaOH concentration at Na_2SiO_3/NaOH = 70:30, BA = 30%, L/BA = 1, *w* = LL and 38 ^{o}C. The UCS increases with increasing NaOH concentration due to more leaching of silica and alumina ions from BA for the geopolymerization reaction. The increase of UCS with NaOH concentration in geopolymeric system has been previously reported by several researchers (Allahverdi and Khani, 2009; Hardjito et al., 2004; Yunfen et al., 2009; Guo et al., 2010). Figure 2 shows that the NaOH concentration of 7.5 molar is regarded as alkaline fixation point for *w* = LL, beyond which the rate of UCS development declines.

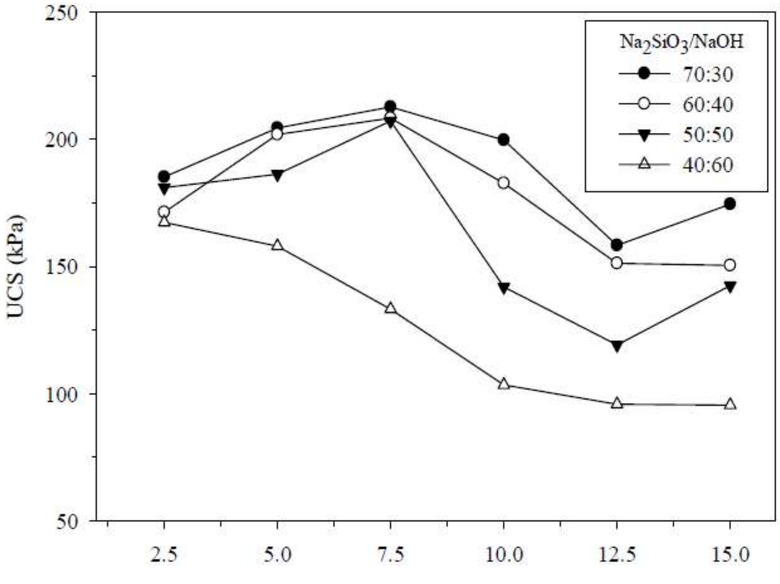


Fig. 2. Effect of solution of NaOH on compressive strength.

The effect of BA content on 7-day UCS of the BA geopolymer stabilized BC is illustrated in Figure 3, which shows the UCS versus BA content of samples with Na_2SiO_3/NaOH = 70:30 and *w* = LL for various NaOH concentrations. The SiO_2 and Al_2O_3 in BA are in the amorphous phase and can effectively react with NaOH and Na_2SiO_3. For a particular NaOH concentration, the higher BA content results in higher consumed silica and alumina oxides. Hence, the UCS of the BA geopolymer stabilized BC increases as the BA content increases with the highest UCS found at the maximum input BA content of 30%. Similar to the results presented earlier in Figure 2, a higher NaOH concentration yields a stronger geo-polymerization reaction and subsequently higher strength. It is evident from Figures 2 and 3 that the increase in both BA content and NaOH concentration provides a positive impact on UCS values for all ingredients.

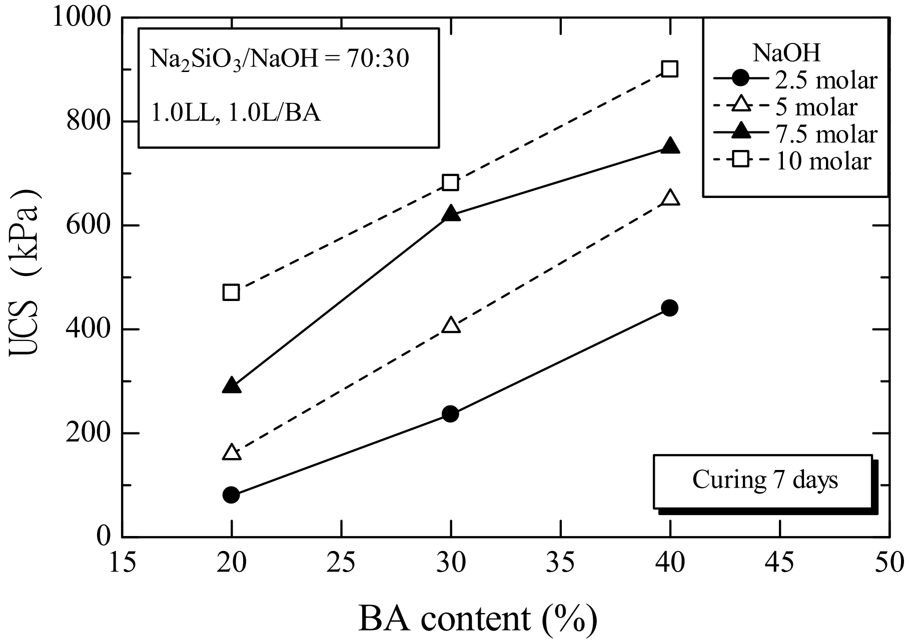


Fig. 3. Effect of BA content on compressive strength.

The effect of initial water contents, curing times, Na_2SiO_3/NaOH ratios and L/BA ratios on UCS development of BA geopolymer stabilized BC is summarized in Table 4. For a particular curing time, Na_2SiO_3/NaOH ratio and L/BA ratio, a higher *w* results in a lower UCS. The higher water content causes a larger spacing between clay particles (Horpibulsuk et al. 2011) and dilutes the concentration solution of NaOH (Suksiripattanapong et al., 2015); hence, the maximum UCS of BA geopolymer stabilized BC is found at *w* = LL. The maximum UCS of BA geopolymer stabilized BC is found at *w* = LL, Na_2SiO_3/NaOH = 70:30, L/BA = 1.0 and 28 days of curing. Figure 4 shows the effect of Na_2SiO_3/NaOH and L/BA ratios on the UCS of the BA geopolymer stabilized BC at *w* = LL. For a particular L/BA, the UCS increases with increasing Na_2SiO_3/NaOH until an optimal value and then decreases. The optimal Na_2SiO_3/NaOH tends to increase with increasing L/BA ratio. For example, at L/BA = 1, the optimal Na_2SiO_3/NaOH is 70:30 whereas at L/BA = 2, the optimal Na_2SiO_3/NaOH is 70:30. Evidently, a higher BA content (lower L/BA) requires a larger NaOH content for leaching SiO_2 and Al_2O_3 from BA for the geo-polymerization reaction.

Table 4 UCS test result at 7.5 molar NaOH and 30% BA (kPa), curing 38 ℃

Description	**Na_2SiO_3:NaOH**	**7 Days**			**14 Days**			**28 Days**		
		L/FA			**L/FA**			**L/FA**		
		1.0	**1.5**	**2.0**	**1.0**	**1.5**	**2.0**	**1.0**	**1.5**	**2.0**
1.0LL	80:20	439	248	225	2150	1120	985	6500	3152	2700
	70:30	694	326	277	2497	1263	1050	7185	3650	3054
	60:40	597	298	239	2354	1195	990	8647	3785	3100
	50:50	416	230	137	2231	1020	754	5306	2506	2100

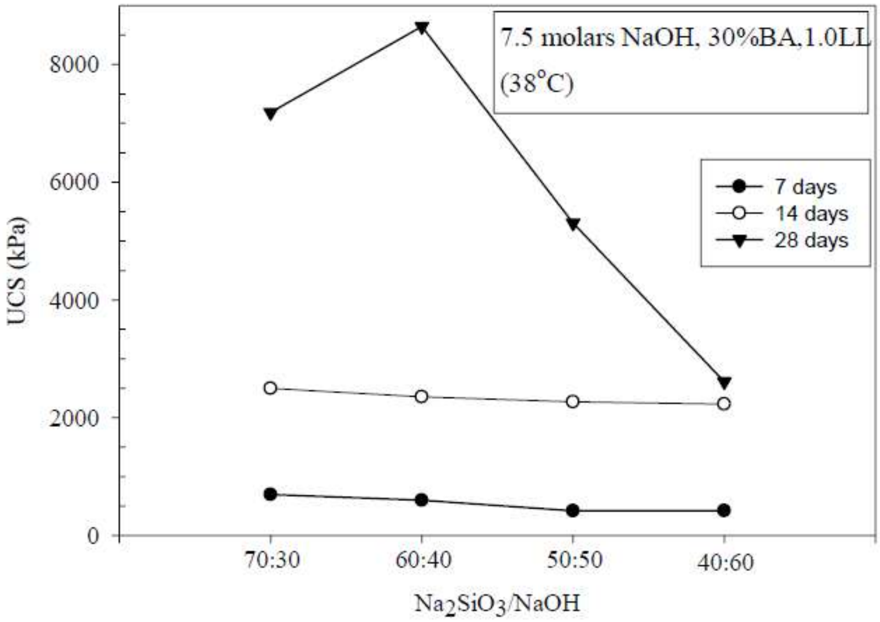


Fig. 4. Effect of liquid alkaline activator.

The UCS versus L/BA relationship of 38 ^{o}C cured samples at various water contents and curing times for a particular 7.5 molar NaOH and Na_2SiO_3/NaOH of 70:30

is shown in Figure 5 to illustrate the effect of water content on optimal L/BA. The UCS for all L/BA and water contents tested increases with curing time for all water contents tested. Typically, the UCS increases with L/BA until the optimal L/BA due to the increase in binder content. Beyond the optimal L/BA, the UCS decreases because the excessive L/BA ratio causes the precipitation at very early stage before poly-condensation process in geopolymerization (Sukmak et al., 2013a and b). At *w* = LL, the UCS decreases significantly when L/BA is greater than the optimal value of 1.0. Whereas at higher water content (*w* > LL), the UCS gradually increases with increasing L/BA without the distinct peak even after the optimal L/BA. The clay with higher water content needs more alkalinity to produce optimal pH environment to dissolve silicon and aluminum in the amorphous phase of BA; hence, the optimal L/BA tends to increase with water content.

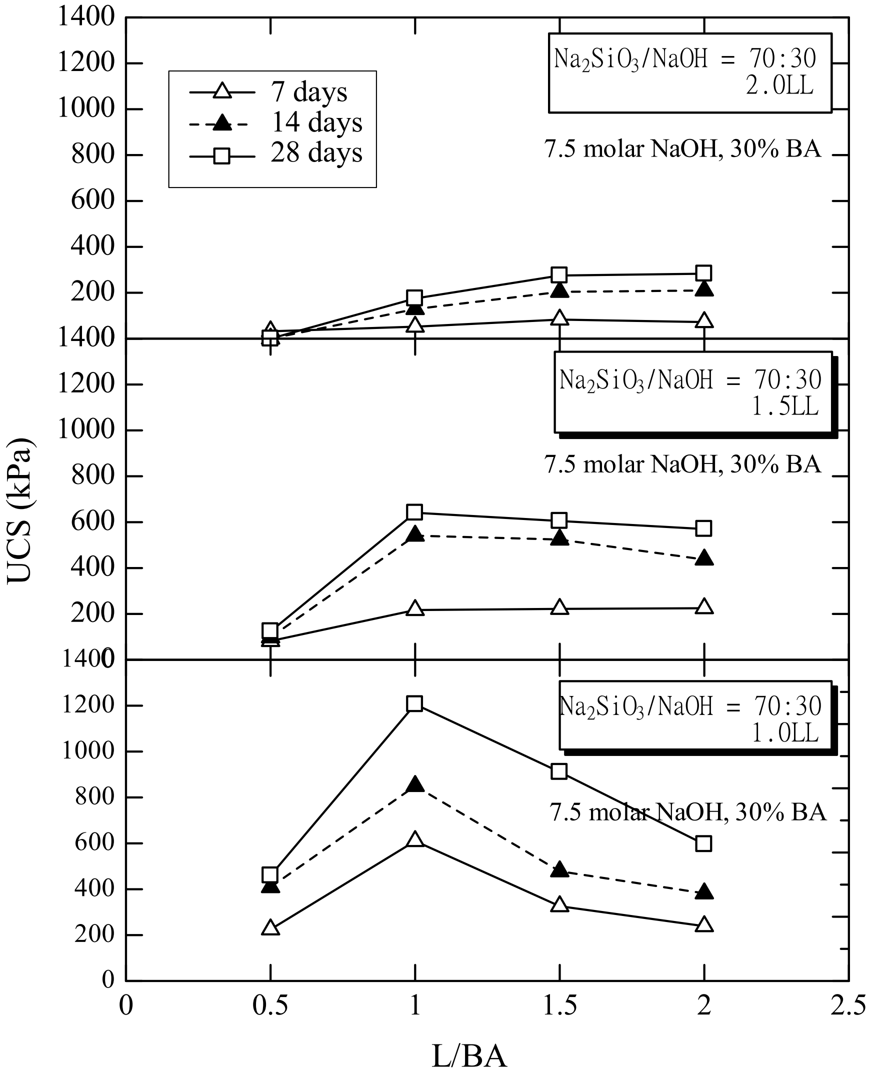


Fig. 5. Effect of liquid alkaline activator / BA at different LL.

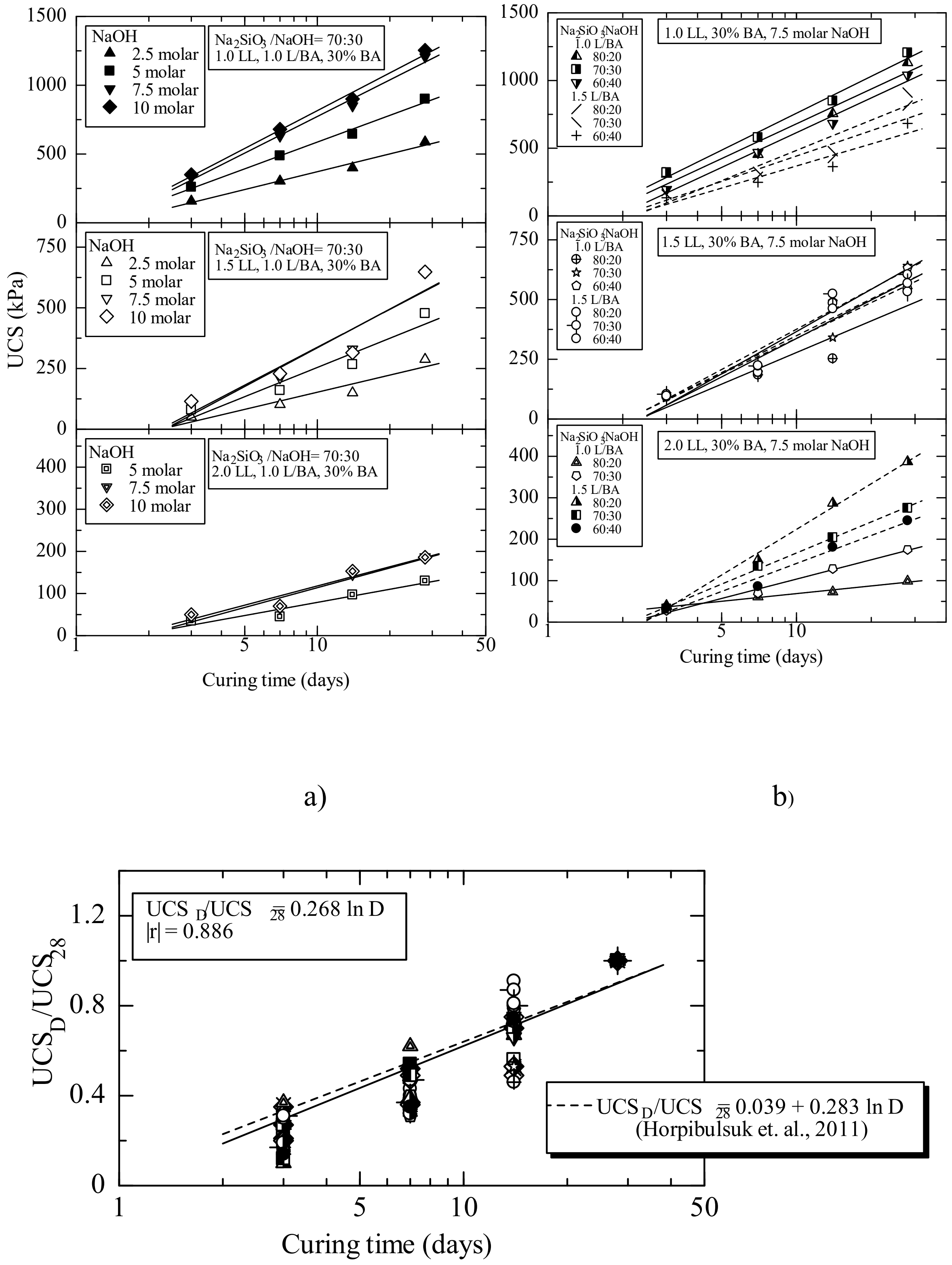


Fig. 6. Strength development with time for different NaOH, LL, ratio of Na_2SiO_3/NaOH, L/BA and their generalization.

The typical UCS development with curing time for the BA geopolymer stabilized BC with various initial water contents, NaOH concentrations, Na_2SiO_3/NaOH ratios and L/BA ratios at 30% BA is shown in Figure 6. The strength development with curing time (days) in natural logarithmic scale can be expressed as a linear variation. The 28-day UCS was taken for the examination of the normalized characteristic, as previously done by Horpibulsuk et al. (2003, 2009, 2011a, 2011b, 2012b). Although the UCS values are different for different NaOH concentrations, Na_2SiO_3/NaOH ratios, L/BA ratios and water contents, the normalized strength, UCS_D/UCS_{28}, is essentially the same, where UCS_D is the UCS at any curing time and UCS_{28} is the 28-day UCS. The normalized strength of the geopolymer stabilized BC is also compared with that of the cement stabilized clays (data from Horpibulsuk et al., 2011a) in Figure 6. It is evident that the normalized behavior of BA geopolymer is similar to that of cement stabilized clays and the rate of UCS development of BA geopolymer stabilized clay is comparable with that of cement stabilized clay. The normalized UCS_D/UCS_{28} is presented in the form:

$$UCS_D/UCS_{28} = 0.268 \qquad \text{for } 3 < \text{curing time} < 28 \text{ days} \qquad (1)$$

with a high degree of correlation of 0.886. The proposed equation is useful to predict the target UCS values for 30% BA at any curing time when 28-day UCS is known.

3.2 Strength of BA-CCR geopolymer stabilized BC

The effect of CCR content on UCS of BA-CCR geopolymer stabilized BC at various curing times is shown in Figure 7. The UCS development is classified into three zone (inactive, active and quasi-inert zones). For CCR content < 7%, the UCS values for all curing times decrease with increasing CCR content while for CCR content > 12%, the UCS values slightly increase with increasing CCR content. The CCR contents between 7 and 12% are regarded as active zone, which significantly improves the UCS of the BA-CCR geopolymer stabilized BC; i.e., the UCS increases approximately 1.5 times of the original value after adding 15% CCR. The addition of a sufficient quantity of Ca^{2+} to BA based geopolymers in the form of CCR can lead to the existence of phase separated Al-substitute calcium silicate hydrate (C-(A)-S-H) and geopolymer (N-A-S-H) gel (Yip et al., 2005 and 2008; Granizo et al., 2002; and Xu and Van Deventer, 2005). Ca^{2+} is also capable of acting as charge-balancing cation within the geopolymeric binding structure (Li et al., 2010) and provides extra nucleation sites for precipitation of dissolved species and cause rapid hardening (Van Deventer et al., 2007; Lee and Van Deventer, 2002).

However, the role of Ca^{2+} is more prevalent at relatively low alkalinity condition system and the dissolution of $Ca(OH)_2$ is hindered when the OH- concentration is high. As such, the insignificant strength gain is noted when CCR content is excessive of 12%.

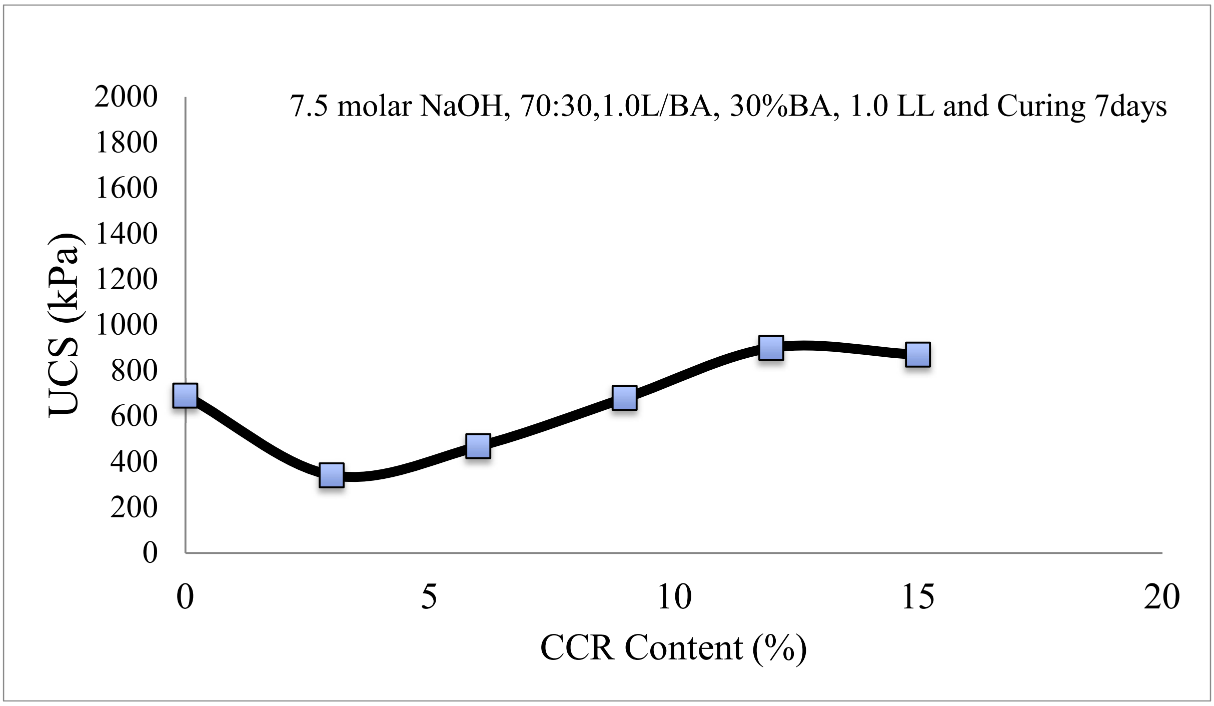


Fig. 7. Effect of CCR content on compressive strength.

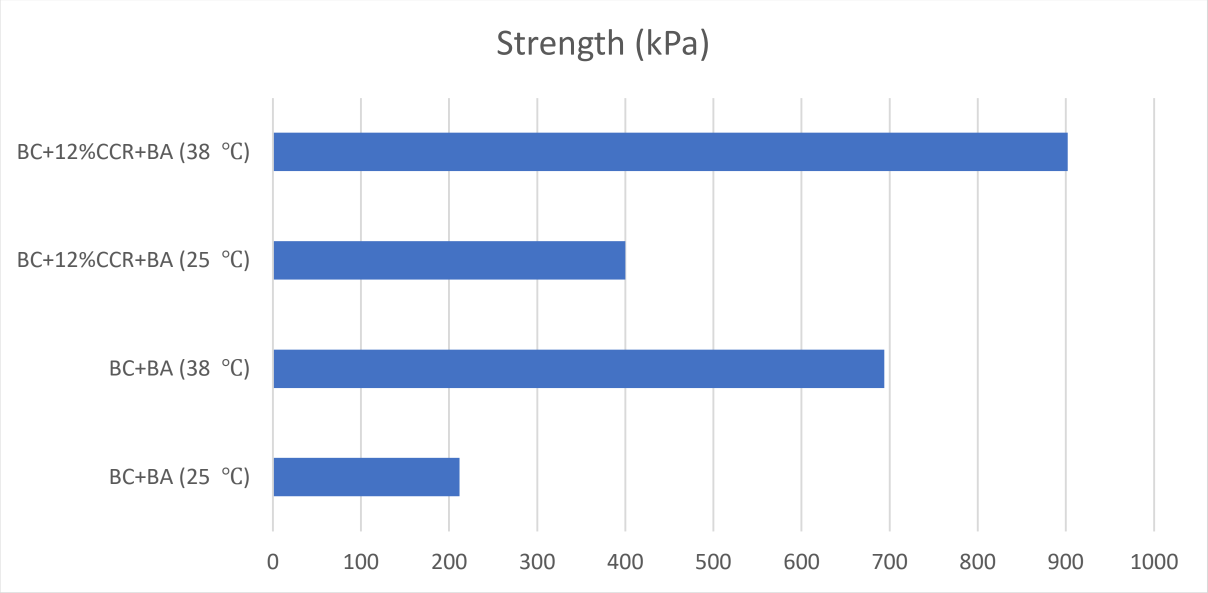
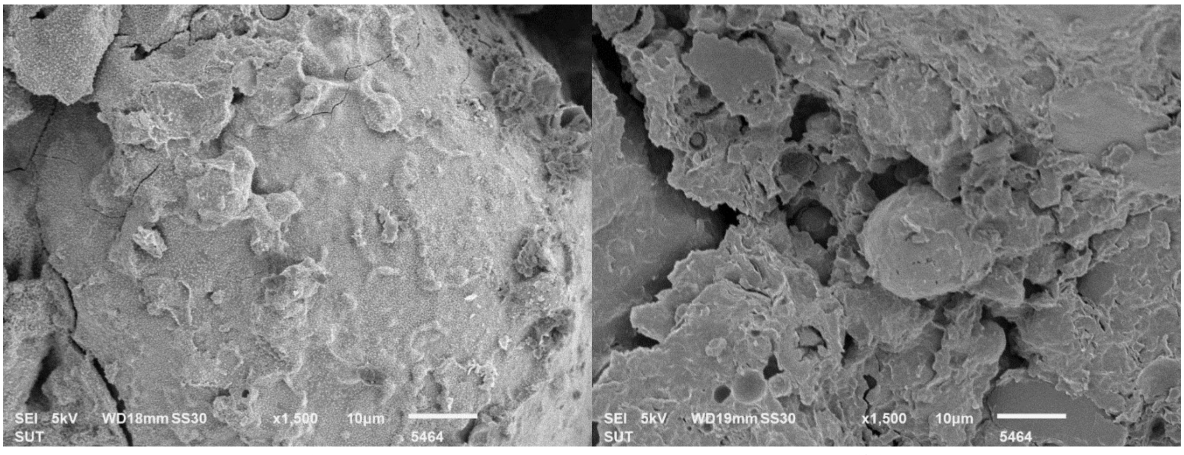


Fig. 8. The effect of temperature on strength at LL

The effectiveness of input CCR at room temperature (25 °C) is also illustrated by the comparison of UCS development between the BA-CCR geopolymer stabilized BC and BA-CCR geopolymer at two different curing temperatures (25 and 38 °C) but at the same NaOH concentration (7.5 molar), L/BA ratio (1.0), Na_2SiO_3/NaOH ratio (70:30) and water content (*w* = LL) in Figure 8. For both BA geopolymer and BA-CCR geopolymer, the UCS increases significantly as the temperature increases because increased temperatures enhance the geo-polymerization reaction (Suksiripattanapong et al., 2015). The UCS of CCR-BA geopolymer stabilized BC is higher than that of the BA geopolymer stabilized BC for both temperatures tested. It is of interest to mention that the UCS of CCR-BA geopolymer stabilized BC at 25 °C is comparable with that of BA geopolymer stabilized BC at 38°C, showing the effectiveness of input CCR on UCS development at room temperature.

3.3 Microstructural analysis

To confirm the results of the analysis on the development of strength, this article has taken samples to test SEM and finds the interested issues. The completely geo-polymerization was showed at the suitable ratio of alkaline activator. Figure 9 (a) shows the chemical attack at some points on the surface of the BA and soil particles, which have a lot of small spine, exposing smaller particles, whether hollow or partially filled with other yet smaller spine from geo-polymerization. In the case of Figure 9 (b) are formed as the main reaction Geopolymer which can produce high early strength.



(a) (b)

Fig. 9. SEM images of clay CCR-BA geopolymer at Na_2SiO_3:NaOH = 70:30, BA = 30%, 38℃ curing after 28 days of curing.

3.4 Carbon footprint evaluation

The relationship between UCS and cement content at *w* = LL is shown in Figure 10. The UCS increases significantly with cement content when cement content is between 3 and 30%. The carbon footprint, defined as CO_2-e emitted (kg CO_2-e/ton), of BA geopolymer and BA-CCR geopolymer stabilized BC is calculated and compared with that of cement stabilized BC at the same UCS in Figure 11. The CO_2 emission calculation considered the mining, processing and manufacturing of raw materials. Table 5 shows the mix design of cement stabilized BC, BA geopolymer stabilized BC and BA-CCR geopolymer stabilized BC at low to high UCS values of 400, 600 and 800 kPa. The emission factors of materials are presented in Table 6. NaOH and BA have the highest and lowest emission factor, respectively. The emission factor of CCR is assumed to be equal to that of BA (0.007 kg CO_2-e/ton), which has the similar energy consumption, related to milling and grinding, drying, and transport. Figure 10 shows that the emission CO_2-e values of geopolymer binders (BA, Na_2SiO_3 and NaOH) are 176 and 210 kg CO_2-e/ton for UCS values of 400 kPa and 600 kPa, respectively while they are 215 and 258 kg CO_2-e/ton for cement stabilized BC. It is evident that the emission CO_2-e of BA geopolymer stabilized BC is 22% and 23% lower than that of cement stabilized BC at UCS of 400 kPa and 600 kPa, respectively. Whereas the CO_2-e of BA-CCR geopolymer stabilized BC was approximately 43% lower than that of cement stabilized BC at the same UCS of 800 kPa. In other words, the reduction in carbon footprints is evident as UCS increases. Previous research on geopolymer concrete with high compressive strength by McLellan et al. (2011) demonstrated that typical Australian geopolymer concrete has 44-64% reduction in greenhouse gas emissions when compared to OPC concrete. The research depicts the advantage of BA-CCR geopolymer over Portland cement for sustainable soil improvement in term of engineering, economic and environmental perspectives.

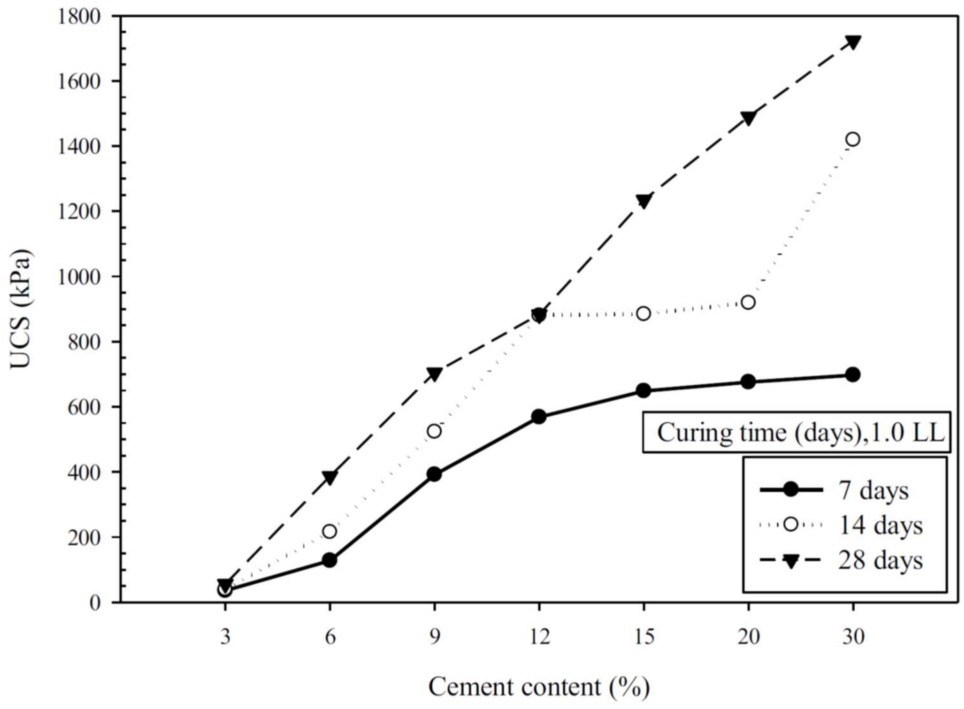


Fig. 10. The relationship between strength and cement content at liquid limit**.**

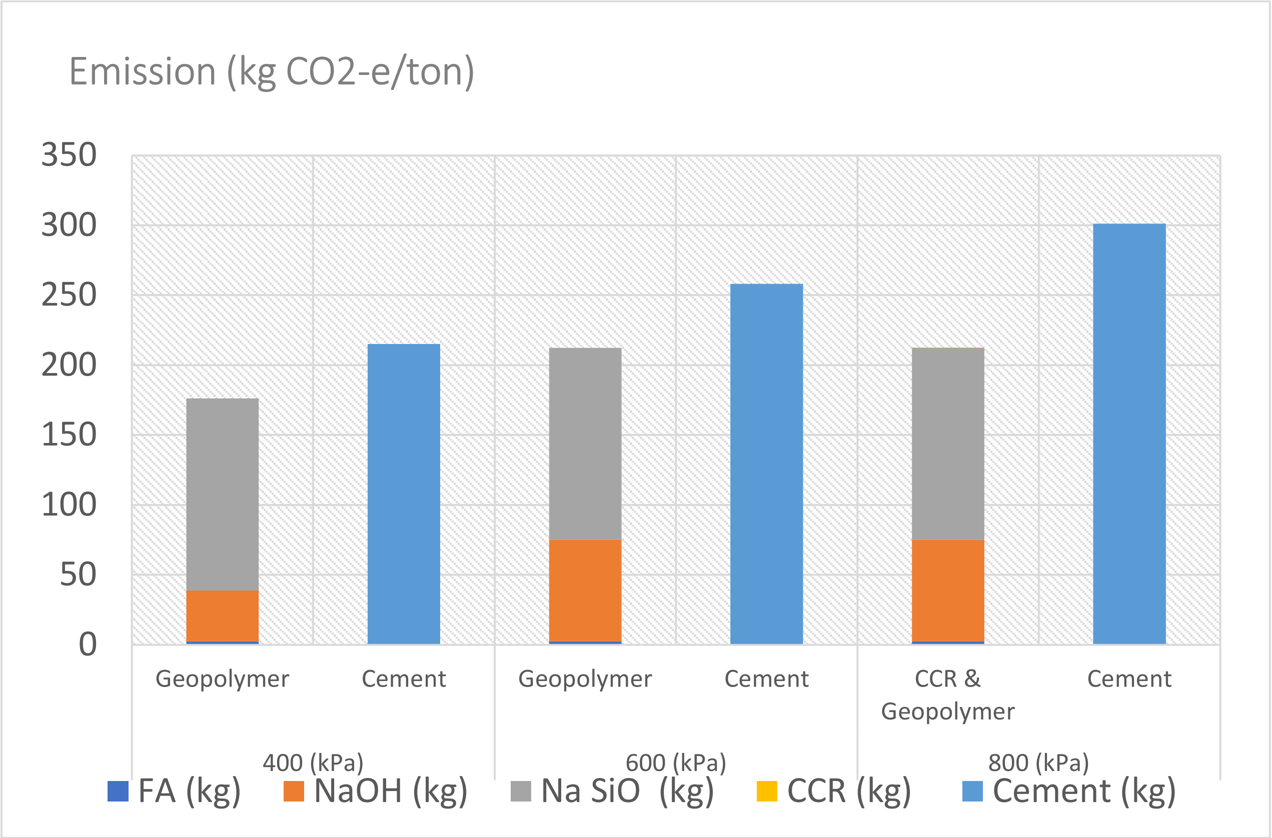


Fig. 11. The total CO_2-e of cement, geopolymer and CCR-geopolymer

Chapter III

Conclusion and Discussion

The research investigates the strength development and carbon footprints of BA-CCR geopolymer stabilized soft clay, namely soft Bangkok Clay (BC). The effects of NaOH concentration, L/BA content, water content, BA content, CCR content, temperature and curing time on strength development of geopolymer stabilized BC is investigated. The following conclusions can be drawn from this research:

1. A higher NaOH concentration can leach higher silica and alumina from BA for geopolymerization reaction for a particular BA content. For a particular NaOH concentration, the higher BA content results in higher consumed silica and alumina oxides. As such, the increase in both NaOH concentration and BA content in the geopolymeric system at a specific Na_2SiO_3/NaOH, L content and water content improves significantly the UCS.

2. For a particular NaOH concentration, the optimal Na_2SiO_3/NaOH providing the highest UCS is governed by L/BA; i.e., a higher BA content (lower L/BA) requires a more higher NaOH content for leaching silica and alumina; hence, the optimal Na_2SiO_3/NaOH decreases with BA content. The increase in L/BA initially improves the UCS of the BA geopolymer but when the L/BA is excessive of the optimal value, the UCS decreases due to the precipitation at very early stage before the poly-condensation process in geopolymer. The optimal L/BA is dependent upon the initial water content; i.e., the optimal L/BA increases with water content as the high water content dilutes NaOH concentration. The results show that the optimal ingredient providing the maximum UCS for w = LL is L/BA = 1 and Na_2SiO_3/NaOH = 70:30.

3. The UCS development with time of BA geopolymer with various ingredients of water content, Na_2SiO_3/NaOH, L/BA and NaOH concentration can be normalized by 28-day UCS, similar to that of cement stabilized clays. The proposed normalized equation is useful for approximating UCS at any curing time within 28 days. The proposed equation is on sound principles and can be refined by more test data.

4. The role of CCR on UCS development in BA geopolymer stabilized BC is classified into three zones: inactive, active and quasi-inert. The CCR contents between 7-12% are in the active zone where significant UCS development is evident. The

dissolution of $Ca(OH)_2$ concentration is hindered when CCR content exceeds the active zone. As such, the rate of UCS development decreases in CCR increases in the quasi-inert zone. The 12% CCR addition can improve UCS up to approximately 1.5 times of the original value.

5. The difference in CO_2 footprints between BA geopolymer stabilized BC and cement stabilized BC increases as the UCS increases. The emission CO_2-e of BA geopolymer stabilized BC is 22%, 23% and 43% lower than that of cement stabilized BC at UCS of 400 kPa, 600 kPa and 800 kPa, respectively. This shows the benefit of BA-CCR geopolymer as a green and strong binder alternative to Portland cement.

Appendix

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STRENGTH DEVELOPMENT OF SOFT CLAY STABILIZED WITH BAGASSE ASH AND CALCIUM CARBIDE RESIDUE BASED GEOPOLYMER MATERIALS

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STRENGTH DEVELOPMENT OF SOFT CLAY STABILIZED WITH BAGASSE ASH AND CALCIUM CARBIDE RESIDUE BASED GEOPOLYMER MATERIALS

ABSTRACT:

This research investigates strength development and the carbon footprint of Calcium Carbide Residue (CCR) and Bagasse ash (BA) geopolymer stabilized soft clay. Bangkok clay, a soft and highly compressible soft clay present in Bangkok, Thailand was investigated for stabilization with the CCR and BA geopolymers. BA is a pozzolanic material which is very rich in the oxides of silica and aluminum, and sometimes calcium. CCR is an industrial by-product obtained from acetylene gas production, high in $Ca(OH)_2$ and was used as a green additive to improve strength of the BA based geopolymer binder. The liquid alkaline activator used was a mixture of sodium silicate solution (Na_2SiO_3) and sodium hydroxide (NaOH). The influential factors studied for the geopolymerization process were Na_2SiO_3/NaOH ratio, NaOH concentration, L/BA ratio, initial water content, BA content, CCR content, curing temperature and curing time. The microstructural analyses of soft clay stabilized with BA and CCR based geopolymers is undertaken using Scanning Electron Microscopy (SEM) techniques to understand the role of influential factors controlling the strength development. Moreover, the carbon footprints of BA and CCR based geopolymers stabilized BC are calculated and compared with those of cement stabilized Bangkok clay at the same UCS values practically used in the soil improvement. The outcome of this research campaign the usage of BA-CCR geopolymer as a sustainable soil stabilizer alternative to high carbon Portland cement, which benefits in term of engineering, economic and environmental perspectives.

KEYWORDS: geopolymer, strength, soft clay, bagasse ash, calcium carbide residue, Bangkok clay, carbon footprint.

1. INTRODUCTION

Bangkok clay is one of the well-known soft clay deposits. It possesses high water content close to its liquid limit with large potential for settlement and low inherent shear strength. Several ground improvement techniques dealing with soft soil foundation have been developed over the past 30 years (Bergado et al., 2003; Bouazza et al., 2006; Shen et al., 2013a, b and c; Du et al., 2013 and 2014; Chai et al., 2014; Bo et al., 2015a and b; Wu et al., 2015). In situ deep mixing is an effective means, which has been developed over two decades primarily to effect columnar inclusions into the soft ground to transform soft ground to composite ground. The deep mixing technology was simultaneously developed in Sweden and Japan using quicklime as a hardening agent. Subsequently, ordinary Portland cement slurry was used as a cementing agent because it is readily available at reasonable cost. The influential factors, controlling the field strength of deep mixing columns such as penetration and withdrawal rates, water to cement ratio, and rate of blade rotation were extensively investigated by Horpibulsuk et al., (2004) (Ariake clay, Japan) and Horpibulsuk et al. (2011b and 2012c) (Bangkok clay, Thailand). However, the manufacturing of Portland cement is a resource exhausting and energy intensive process that releases large amount of the CO2 into the atmosphere, which cause the greenhouse gases (Davidovits 1991; Davidovits and Davidovics 2008). Therefore, the development of a new cementing agent and development of recycled construction materials derived from waste materials with low carbon dioxide release is considered an interesting issue. Commercial and industrial utilization of alkali-activated alumino-silicate cements, known as 'geopolymers' has been increasingly well-known over the past several decades as the search for high-performance and an environmentally maintainable alternative for ordinary Portland cement (J. Davidovits 1991; Phetchuay et al., 2016).

Several ground improvement techniques dealing with soft soil foundation have been developed over the past 30 years (Bergado et al., 2003; Bouazza et al., 2006; Arulrajah and Bo, 2008; Shen et al., 2013a, b and c; Du et al., 2013 and 2014; Chai et al., 2014; Bo et al., 2015a and b; Wu et al., 2015). In situ deep mixing is an effective means, which has been developed over two decades primarily to effect columnar inclusions into the soft ground to transform soft ground to composite ground. The deep mixing technology was simultaneously developed in Sweden and Japan using quicklime as a hardening agent. Subsequently, ordinary Portland cement slurry was used as a cementing agent because it is readily available at reasonable cost. The influential factors, controlling the field strength of deep mixing columns such as penetration and withdrawal rates, water to cement ratio, and rate of blade rotation were extensively investigated by Horpibulsuk et al., (2004) (Ariake clay, Japan) and Horpibulsuk et al. (2011b and 2012c) (Bangkok clay, Thailand). Previous studies also reported the similar about factor control strength such as relation between UCS is strongly depends on bulk density and pore structure in soil. In addition, many report is studied from microstructure analysis and was founded the increase in cementitious products with time is observed from the scanning electron microscope, mercury intrusion porosimetry and thermal gravity test. With time, the large pore (>0.1 micron) and total pore volumes decrease while the small pore (<0.1 micron) volumes increase because the products of cement hydration fill the gaps between soil aggregates and divide each large pore into a number of smaller ones.This shows the growth of the cementitious products filling up the large pores (Du et al., 2014; Horpibulsuk et al., 2009; Zhang et al., 2014; Jiang et al., 2016; Cai et al.,2015; Chew et al., 2004; Consoli et al, 2011).

The high unit cost and energy intensive process for the production of Portland cement are the driving forces for the constant need within the industry to seek alternative cementitious binders. The cement manufacturing process emits CO_2 into the atmosphere, which accounts for 5% of the total CO_2 released into the air (Horpibulsuk et al., 2013). The development of a new cementing agent with low carbon dioxide releases is actively sought by industry. Commercial and industrial utilization of alkali-activated aluminosilicate cements, known as ‘geopolymers’ has increasingly well-known over the past several decades because of their high performance (high strength and durability) and environmentally maintainable alternative to the ordinary Portland cement (Davidovits, 1991). Geopolymers belong to a group of materials with increased interest due to low CO_2 emission and energy consumption. The hardening process of geopolymers at ambient temperature results in materials with ceramic-like properties, such as resistance against acids and high temperatures. The silica-rich materials such as clay like kaolin (Buchwald and Kaps 2002), fly ash, and bottom ash (Davidovits et al., 1999) can be used as a precursor to react with the liquid alkaline activator. Fly Ash (FA) provides the greatest opportunity for commercial utilization of this technology due to the plentiful worldwide raw material supply, which is derived from coal-fired electricity generation (Mohapatra and Rao, 2001; Van Jaarsveld et al., 1998). Even though geopolymers have been recently used in building concrete application, its usage in geotechnical application has been very limited.

It has been reported that the mechanical properties of FA based geopolymer could be improved by high calcium additives due to the coexistence of geopolymerization products (Sodium Alumino Silicate Hydrate, N-A-S-H) and Calcium Silicate Hydrate (C-S-H) (Phoo-ngernkham et al., 2015; Phummiphan et al., 2015; Yip et al., 2005; Granizo et al., 2002; Yip et al., 2008). The Bagasse (BA) is the fibrous waste produced after the extraction of the sugar juice from cane mills. Bagasse ash is the residue obtained from the incineration of bagasse in sugar producing factories. This material usually poses a disposal problem in sugar factories particularly in tropical countries. In many tropical countries there are substantial quantities of Bagasse is rich in amorphous silica indicated that it has pozzolanic properties. Bagasse ash is a pozzolanic material which is very rich in the oxides of silica and aluminum, and sometimes calcium (Guilherme, Romildo, Eduardo, Luis, and Cristiano, 2004). Pozzolans usually require the presence of water in order for silica to combine 2 with calcium hydroxide to form stable calcium silicate, which has cementitious properties. Calcium Carbide Residue (CCR) is a waste material from acetylene gas factories, which has high calcium hydroxide [Ca(OH)2] content. It has been previously used itself as a green soil stabilizer (Horpibulsuk et al., 2012; Kampala et al. 2013 and 2014; Phetchuay et al., 2014; Vichan et al. 2013; Du et al., 2016 and Jiang et al., 2016) but not as an additive for geopolymer binder. The usage of high calcium CCR as a green additive in BA geopolymer stabilized clay is thus novel and significant in geotechnical and pavement applications.

This research attempts to examine the viability of using BA and CCR based Alkali-activated materials as a sustainable binder to improve strength of Bangkok clay. The Unconfined Compressive Strength (UCS) is used as a practical indicator to investigate the strength development. The influential factors studied include liquid alkaline activator, L content, L/BA ratio, BA content, water content, curing time, curing temperature and CCR content. The microstructural analyses of soft clay stabilized with BA and CCR based geopolymers is undertaken using Scanning Electron Microscopy (SEM) techniques to understand the role of influential factors controlling the strength development. Moreover, the carbon footprints of BA and CCR based geopolymers stabilized BC are calculated and compared with those of cement stabilized Bangkok clay at the same UCS values practically used in the soil improvement. The outcome of this research campaign the usage of BA-CCR geopolymer as a sustainable soil stabilizer alternative to high carbon Portland cement, which benefits in term of engineering, economic and environmental perspectives.

2. MATERIALS AND METHODS

2.1 Materials

2.1.1 Bangkok Clay (BC)

Bangkok Clay (BC) samples were collected from Bangkok area at a depth of 3-5 m. BC consists of 4% sand, 25% silt and 71% clay that results come from Figure 1. The specific gravity and organic content are 2.60 and 2.4%, respectively. Liquid Limit (LL) and Plastic Limit (PL) are approximately 64% and 26%, respectively. Based on the Unified Soil Classification System (USCS), the BA is classified as highly plastic (CH). The basic properties are shown in **Table 1**. The grain size distribution and chemical compositions of BC obtained from hydrometer analysis and X-ray Fluorescence (XRF) analysis are shown in **Figure 1** and **Table 2**, respectively.

2.1.2 Bagasse Ash (BA)

BA was obtained from a local Thailand supplier. It grain size distribution is shown in **Figure 1**. **Table 2** summarizes the chemical composition of BA using X-ray fluorescence (XRF). Total amount of the major components (SiO_2, Al_2O_3 and Fe_2O_3) of BA is 94.40% while the CaO content is 1.68%.

2.1.3 Calcium Carbide Residue (CCR)

CCR is a by-product from an acetylene gas (C_2H_2) production process. The main oxide of calcium carbide residue is calcium hydroxide ($Ca(OH)_2$) in a slurry form. CCR was dried by the sun and sent to landfills as waste. The CCR was oven-dried at 100 ºC for 24 h and was then ground using a Los Angeles abrasion machine. The CCR was passed through a No. 40 sieve (425 µm). The specific gravity value is 2.32. **Table 2** summarizes the chemical composition of CCR BA and BC, as obtained by conducting the X-ray fluorescence studies. The high $Ca(OH)_2$ and CaO contents of the CCR indicate that it can react with BA and produce a cementitious material (Palomo et al., 1999). The grain size distribution of the CCR compared with that of the BC is shown in **Figure 1**. The curves were obtained from laser particle size analysis, which is applicable for materials that react with water. The average grain size (D_{50}) of CCR is 0.01 mm, which is bigger than that of BC.

2.1.4 Liquid alkaline activator (L)

The liquid alkaline activator (L) is a mixture of Na_2SiO_3, which consists of 9% Na_2O and 30% SiO_2 by weight, and NaOH at various concentrations.

2.2 Sample Preparation and Testing

There are 6 series of unconfined compression test to investigate the role of influencing factors such as L content, BA content, L/BA, Na_2SiO_3/NaOH and CCR content. The testing program is summarized in **Table 3**.

2.2.1 BA geopolymer stabilized BC

The BA geopolymer binder was a combination of BA and liquid alkaline activator (Na_2SiO_3 and NaOH). The influencing factors were varied depending upon the test series. The BA contents were 20, 30 and 40% by weight of dry soil. The Na_2SiO_3/NaOH ratios were 80:20, 70:30, 60:40 and 50:50. The NaOH concentrations were 2.5, 5, 7.5, 10, 12 and 15 molars. The L/BA ratios were 1.0, 1.5 and 2.0. The initial water content (*w*) of BC varied from 1 to 2 times LL to simulate the variation of in-situ water content. The curing temperatures were 25 and 38 °C.

The sample preparation started with mixing BC and BA for 5 minutes in a mixer to ensure homogeneity of the mixture. The mixer was stopped and the mixture was mixed with the liquid alkaline activator (L) for an additional 5 minutes. The uniform BC-BA-L mixtures were transferred to cylinder molds of 38 mm in diameter and 76 mm in height for UCS test. The BA geopolymer stabilized BC samples were dismantled, wrapped within vinyl sheet and then cured at target temperatures of 25 and 38 ºC for the required curing duration. The 38 ºC temperature was used to simulate an average heat temperature in countries with a tropical climate, including Australia and Thailand (Phetchuay et al., 2014). The UCS tests were carried out on the samples after 7, 14 and 28 days of curing in accordance with ASTM C69-09. For each curing time and ingredient, at least five samples were tested under the same conditions to assure test result consistency. In most cases, the results under the same testing condition were reproducible with low mean standard deviation, SD (SD/$\bar{x}$ < 10%, where $\bar{x}$ is mean strength value).

2.2.2 CCR-BA geopolymer stabilized BC

The BA content was fixed at 30% by weight of dry soil and the Na_2SiO_3/NaOH ratio, NaOH concentration, L/BA ratio and water content were fixed at the optimal ingredient obtained from the test result of BA geopolymer stabilized BC. The CCR contents were however varied to investigate the influence of CCR on UCS development. The CCR contents were 3, 6, 9, 12 and 15%. The uniform BC-CCR-BA-L mixtures were transferred to cylinder molds of 38 mm in diameter and 76 mm in height for UCS test. The samples were also wrapped within vinyl sheets as the BA geopolymer stabilized BC and subsequently cured at 38 ºC. UCS values of BA-CCR geopolymer stabilized BC were measured after 7, 14 and 28 days of curing.

2.2.2 Cement stabilized BC

The cement contents tested were 3,6,9,12,15, 20, 25, and 30% by weight of dry soil. The initial water content of BC was fixed at LL. First, check the initial water content. second, add water from back calculation and mixing in a mixer then keep soil in close bag for a night. Third, check water content and mixing BC and BA for 5 minutes in a mixer to ensure homogeneity of the mixture. The BC-cement mixtures were transferred to cylinder molds of 38 mm in diameter and 76 mm in height and then cured at 25 ºC. UCSs of cement stabilized samples were measured after 7 days of curing. The UCS results were compared with those of BA based geopolymer stabilized BC.

3. RESULTS AND DISCUSSION

3.1 Strength of BA geopolymer stabilized BC

Figure 2 presents the effect of NaOH concentration on UCS development, which shows the relationship between 7-day UCS versus NaOH concentration at Na_2SiO_3/NaOH = 70:30, BA = 30%, L/BA = 1, *w* = LL and 38 ºC. The UCS increases with increasing NaOH concentration due to more leaching of silica and alumina ions from BA for the geopolymerization reaction. The increase of UCS with NaOH concentration in geopolymeric system has been previously reported by several researchers (Allahverdi and Khani, 2009; Hardjito et al., 2004; Yunfen et al., 2009; Guo et al., 2010). **Figure 2** shows that the NaOH concentration of 7.5 molar is regarded as alkaline fixation point for *w* = LL, beyond which the rate of UCS development declines.

The effect of BA content on 7-day UCS of the BA geopolymer stabilized BC is illustrated in **Figure 3**, which shows the UCS versus BA content of samples with Na_2SiO_3/NaOH = 70:30 and *w* = LL for various NaOH concentrations. The SiO_2 and Al_2O_3 in BA are in the amorphous phase and can effectively react with NaOH and Na_2SiO_3. For a particular NaOH concentration, the higher BA content results in higher consumed silica and alumina oxides. Hence, the UCS of the BA geopolymer stabilized BC increases as the BA content increases with the highest UCS found at the maximum input BA content of 30%.

Similar to the results presented earlier in **Figure 2**, a higher NaOH concentration yields a stronger geopolymerization reaction and subsequently higher UCS. It is evident from **Figures 2** and **3** that the increase in both BA content and NaOH concentration provides a positive impact on UCS values for all ingredients.

The effect of initial water contents, curing times, Na_2SiO_3/NaOH ratios and L/BA ratios on UCS development of BA geopolymer stabilized BC is summarized in **Table 4**. For a particular curing time, Na_2SiO_3/NaOH ratio and L/BA ratio, a higher *w* results in a lower UCS. The higher water content causes a larger spacing between clay particles (Horpibulsuk et al. 2011) and dilutes the concentration solution of NaOH (Suksiripattanapong et al., 2015); hence, the maximum UCS of BA geopolymer stabilized BC is found at *w* = LL. The maximum UCS of BA geopolymer stabilized BC is found at *w* = LL, Na_2SiO_3/NaOH = 70:30, L/BA = 1.0 and 28 days of curing. **Figure 4** shows the effect of Na_2SiO_3/NaOH and L/BA ratios on the UCS of the BA geopolymer stabilized BC at *w* = LL. For a particular L/BA, the UCS increases with increasing Na_2SiO_3/NaOH until an optimal value and then decreases. The optimal Na_2SiO_3/NaOH tends to increase with increasing L/BA ratio. For example, at L/BA = 0.5, the optimal Na_2SiO_3/NaOH is 70:30 whereas at L/BA = 2, the optimal Na_2SiO_3/NaOH is 70:30. Evidently, a higher BA content (lower L/BA) requires a larger NaOH content for leaching SiO_2 and Al_2O_3 from BA for the geopolymerization reaction.

The UCS versus L/BA relationship of 38 °C cured samples at various water contents and curing times for a particular 7.5 molar NaOH and Na_2SiO_3/NaOH of 70:30 is shown in **Figure 5** to illustrate the effect of water content on optimal L/BA. The UCS for all L/BA and water contents tested increases with curing time for all water contents tested. Typically, the UCS increases with L/BA until the optimal L/BA due to the increase in binder content.

Beyond the optimal L/BA, the UCS decreases because the excessive L/BA ratio causes the precipitation at very early stage before poly-condensation process in geopolymerization (Sukmak et al., 2013a and b). At *w* = LL, the UCS decreases significantly when L/BA is greater than the optimal value of 1.0. Whereas at higher water content (*w* > LL), the UCS gradually increases with increasing L/BA without the distinct peak even after the optimal L/BA. The clay with higher water content needs more alkalinity to produce optimal pH environment to dissolve silicon and aluminum in the amorphous phase of BA; hence, the optimal L/BA tends to increase with water content.

The typical UCS development with curing time for the BA geopolymer stabilized BC with various initial water contents, NaOH concentrations, Na_2SiO_3/NaOH ratios and L/BA ratios at 30% BA is shown in **Figure 6**. The strength development with curing time (days) in natural logarithmic scale can be expressed as a linear variation. The 28-day UCS was taken for the examination of the normalized characteristic, as previously done by Horpibulsuk et al. (2003, 2009, 2011a, 2011b, 2012b). Although the UCS values are different for different NaOH concentrations, Na_2SiO_3/NaOH ratios, L/BA ratios and water contents, the normalized strength, UCS_D/UCS_{28}, is essentially the same, where UCS_D is the UCS at any curing time and UCS_{28} is the 28-day UCS. The normalized strength of the geopolymer stabilized BC is also compared with that of the cement stabilized clays (data from Horpibulsuk et al., 2011a) in **Figure 6**. It is evident that the normalized behavior of BA geopolymer is similar to that of cement stabilized clays and the rate of UCS development of BA geopolymer stabilized clay is comparable with that of cement stabilized clay. The normalized UCS_D/UCS_{28} is presented in the form:

$$UCS_D/UCS_{28} = 0.268 \qquad \text{for } 3 < \text{curing time} < 28 \text{ days} \qquad (1)$$

with a high degree of correlation of 0.886. The proposed equation is useful to predict the target UCS values for 30% BA at any curing time when 28-day UCS is known.

3.2 Strength of BA-CCR geopolymer stabilized BC

The effect of CCR content on UCS of BA-CCR geopolymer stabilized BC at various curing times is shown in **Figure 7**. The UCS development is classified into three zone (inactive, active and quasi-inert zones). For CCR content < 7%, the UCS values for all curing times decrease with increasing CCR content while for CCR content > 12%, the UCS values slightly increase with increasing CCR content. The CCR contents between 7 and 12% are regarded as active zone, which significantly improves the UCS of the BA-CCR geopolymer stabilized BC; i.e., the UCS increases approximately 1.5 times of the original value after adding 15% CCR. The addition of a sufficient quantity of Ca^{2+} to BA based geopolymers in the form of CCR can lead to the existence of phase separated Al-substitute calcium silicate hydrate (C-(A)-S-H) and geopolymer (N-A-S-H) gel (Yip et al., 2005 and 2008; Granizo et al., 2002; and Xu and Van Deventer, 2005). Ca^{2+} is also capable of acting as charge-balancing cation within the geopolymeric binding structure (Li et al., 2010) and provides extra nucleation sites for precipitation of dissolved species and cause rapid hardening (Van Deventer et al., 2007; Lee and Van Deventer, 2002). However, the role of Ca^{2+} is more prevalent at relatively low alkalinity condition system and the dissolution of $Ca(OH)_2$ is hindered when the OH- concentration is high. As such, the insignificant strength gain is noted when CCR content is excessive of 12%.

The effectiveness of input CCR at room temperature (25 °C) is also illustrated by the comparison of UCS development between the BA-CCR geopolymer stabilized BC and BA-CCR geopolymer at two different curing temperatures (25 and 38 °C) but at the same NaOH concentration (7.5 molar), L/BA ratio (1.0), Na_2SiO_3/NaOH ratio (70:30) and water content (*w* = LL) in **Figure 8**. For both BA geopolymer and BA-CCR geopolymer, the UCS increases significantly as the temperature increases because increased temperatures enhance the geopolymerization reaction (Suksiripattanapong et al., 2015). The UCS of BA-CCR geopolymer stabilized BC is higher than that of the BA geopolymer stabilized BC for both temperatures tested. It is of interest to mention that the UCS of BA-CCR geopolymer stabilized BC at 25 °C is comparable with that of BA geopolymer stabilized BC at 38°C, showing the effectiveness of input CCR on UCS development at room temperature.

3.3 Microstructural analysis

To confirm the results of the analysis on the development of strength, this article has taken samples to test SEM and finds the interested issues. The completely geo-polymerization was showed at the suitable ratio of alkaline activator. **Figure 9 (a)** shows the chemical attack at some points on the surface of the BA and soil particles, which have a lot of small spine, exposing smaller particles, whether hollow or partially filled with other yet smaller spine from geo-polymerization. In the case of **Figure 9 (b)** are formed as the main reaction Geopolymer which can produce high early strength.

3.4 Carbon footprint evaluation

The relationship between UCS and cement content at *w* = LL is shown in **Figure 10**. The UCS increases significantly with cement content when cement content is between 3 and 30%. The carbon footprint, defined as CO_2-e emitted (kg CO_2-e/ton), of BA geopolymer and BA-CCR geopolymer stabilized BC is calculated and compared with that of cement stabilized

BC at the same UCS in **Figure 11**. The CO_2 emission calculation considered the mining, processing and manufacturing of raw materials. **Table 5** shows the mix design of cement stabilized BC, BA geopolymer stabilized BC and BA-CCR geopolymer stabilized BC at low to high UCS values of 400, 600 and 800 kPa. The emission factors of materials are presented in **Table 6**. NaOH and BA have the highest and lowest emission factor, respectively. The emission factor of CCR is assumed to be equal to that of BA (0.007 kg CO_2-e/ton), which has the similar energy consumption, related to milling and grinding, drying, and transport. **Figure 11** shows that the emission CO_2-e values of geopolymer binders (BA, Na_2SiO_3 and NaOH) are 176 and 210 kg CO_2-e/ton for UCS values of 400 kPa and 600 kPa, respectively while they are 215 and 258 kg CO_2-e/ton for cement stabilized BC. It is evident that the emission CO_2-e of BA geopolymer stabilized BC is 22% and 23% lower than that of cement stabilized BC at UCS of 400 kPa and 600 kPa, respectively. Whereas the CO_2-e of BA-CCR geopolymer stabilized BC was approximately 43% lower than that of cement stabilized BC at the same UCS of 800 kPa. In other words, the reduction in carbon footprints is evident as UCS increases. Previous research on geopolymer concrete with high compressive strength by McLellan et al. (2011) demonstrated that typical Australian geopolymer concrete has 44-64% reduction in greenhouse gas emissions when compared to OPC concrete. The research depicts the advantage of BA-CCR geopolymer over Portland cement for sustainable soil improvement in term of engineering, economic and environmental perspectives.

4. CONCLUSIONS

The paper investigates the strength development and carbon footprints of BA-CCR geopolymer stabilized soft clay, namely soft Bangkok Clay (BC). The effects of NaOH concentration, L/BA content, water content, BA content, CCR content, temperature and curing time on strength development of geopolymer stabilized BC is investigated. The following conclusions can be drawn from this research:

1. A higher NaOH concentration can leach higher silica and alumina from BA for geopolymerization reaction for a particular BA content. For a particular NaOH concentration, the higher BA content results in higher consumed silica and alumina oxides. As such, the increase in both NaOH concentration and BA content in the geopolymeric system at a specific Na_2SiO_3/NaOH, L content and water content improves significantly the UCS.

2. For a particular NaOH concentration, the optimal Na_2SiO_3/NaOH providing the highest UCS is governed by L/BA; i.e., a higher BA content (lower L/BA) requires a more higher NaOH content for leaching silica and alumina; hence, the optimal Na_2SiO_3/NaOH decreases with BA content. The increase in L/BA initially improves the UCS of the BA geopolymer but when the L/BA is excessive of the optimal value, the UCS decreases due to the precipitation at very early stage before the poly-condensation process in geopolymer. The optimal L/BA is dependent upon the initial water content; i.e., the optimal L/BA increases with water content as the high water content dilutes NaOH concentration. The results show that the optimal ingredient providing the maximum UCS for w = LL is L/BA = 1 and Na_2SiO_3/NaOH = 70:30.

3. The UCS development with time of BA geopolymer with various ingredients of water content, Na_2SiO_3/NaOH, L/BA and NaOH concentration can be normalized by 28-day UCS, similar to that of cement stabilized clays. The proposed normalized equation is useful for approximating UCS at any curing time within 28 days. The proposed equation is on sound principles and can be refined by more test data.

4. The role of CCR on UCS development in BA geopolymer stabilized BC is classified into three zones: inactive, active and quasi-inert. The CCR contents between 7-12% are in the active zone where significant UCS development is evident. The dissolution of $Ca(OH)_2$ concentration is hindered when CCR content exceeds the active zone. As such, the rate of UCS development decreases in CCR increases in the quasi-inert zone. The 12% CCR addition can improve UCS up to approximately 1.5 times of the original value.

5. The difference in CO_2 footprints between BA geopolymer stabilized BC and cement stabilized BC increases as the UCS increases. The emission CO_2-e of BA geopolymer stabilized BC is 22%, 23% and 43% lower than that of cement stabilized BC at UCS of 400 kPa, 600 kPa and 800 kPa, respectively. This shows the benefit of BA-CCR geopolymer as a green and strong binder alternative to Portland cement.

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Figure Captions

Figure 1 Grain size distribution of clay BA and CCR.

Figure 2 Effect of NaOH concentration on unconfined compressive strength.

Figure 3 Effect of BA content on unconfined compressive strength at different NaOH contents.

Figure 4 Effect of Na_2SiO_3/NaOH on unconfined compressive strength at different L/BA ratio.

Figure 5 Effect of L/BA on unconfined compressive strength at different water contents and age.

Figure 6 Strength development with time for different NaOH, LL, ratio of Na_2SiO_3/NaOH, L/BA and their generalization.

Figure 7 Effect of CCR content on unconfined compressive strength.

Figure 8 Effect of temperature on strength at w = LL

Figure 9 SEM images of clay CCR-BA geopolymer at Na_2SiO_3:NaOH = 70:30, BA = 30%, 38°C curing after 28 days of curing.

Figure 10 Relationship between strength and cement content at w = LL.

Figure 11 Total CO_2-e of cement, BA geopolymer and BA- CCR geopolymer stabilized BC

Table Captions

Table 1 Basic properties of BC.

Table 2 Chemical properties of BC, BA and CCR.

Table 3 Summary of the testing program.

Table 4 UCS test result at 7.5 molar NaOH and 30%BA**.** (kPa)

Table 5 Mixture proportions of cement, BA geopolymer and BA-CCR geopolymer for dry soil of 1 ton at various strength.

Table 6 The emission factor of material.

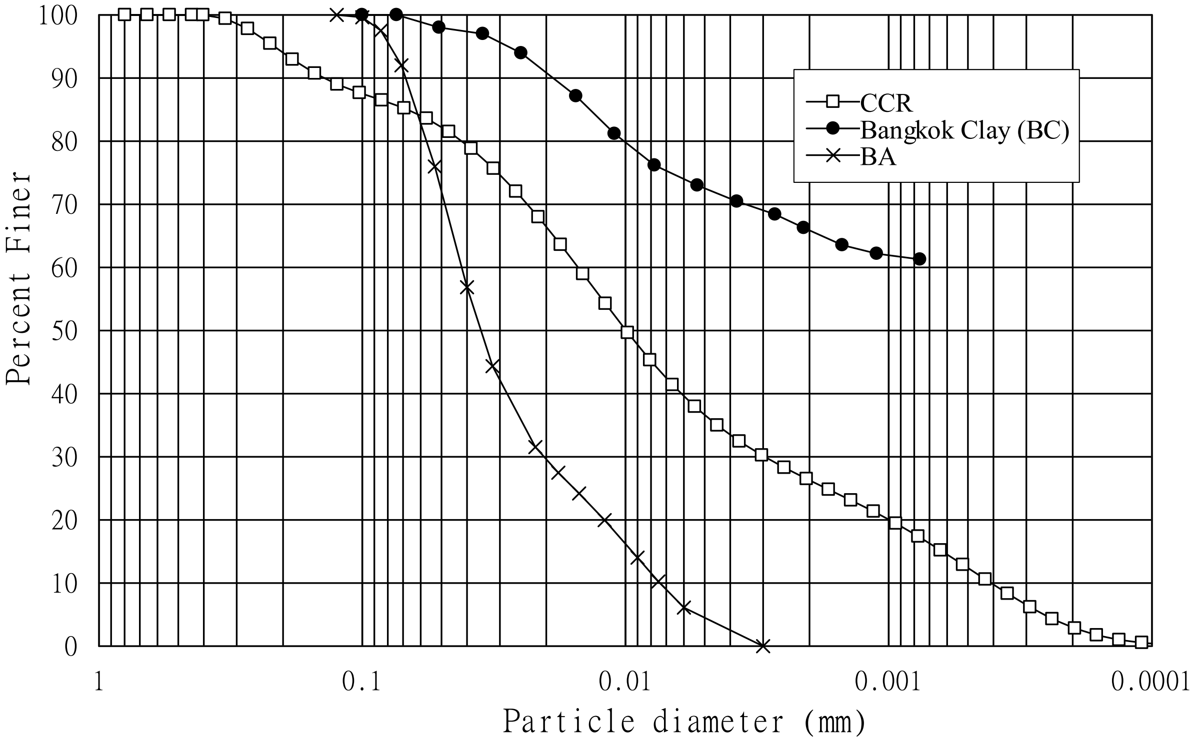


Fig. 1. Grain size distribution of clay and CCR.

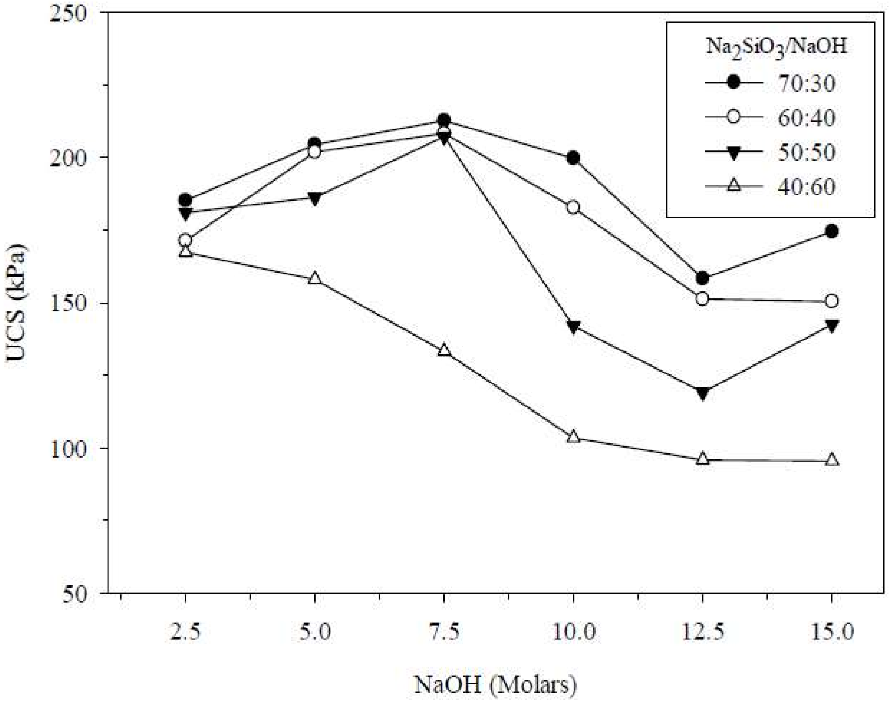


Fig. 2. Effect of solution of NaOH on compressive strength.

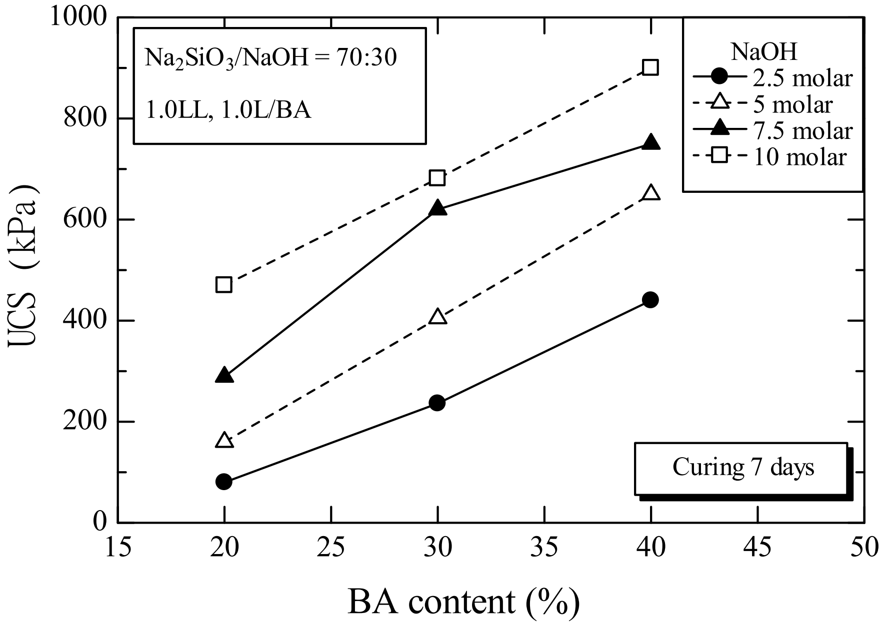


Fig. 3. Effect of BA content on compressive strength.

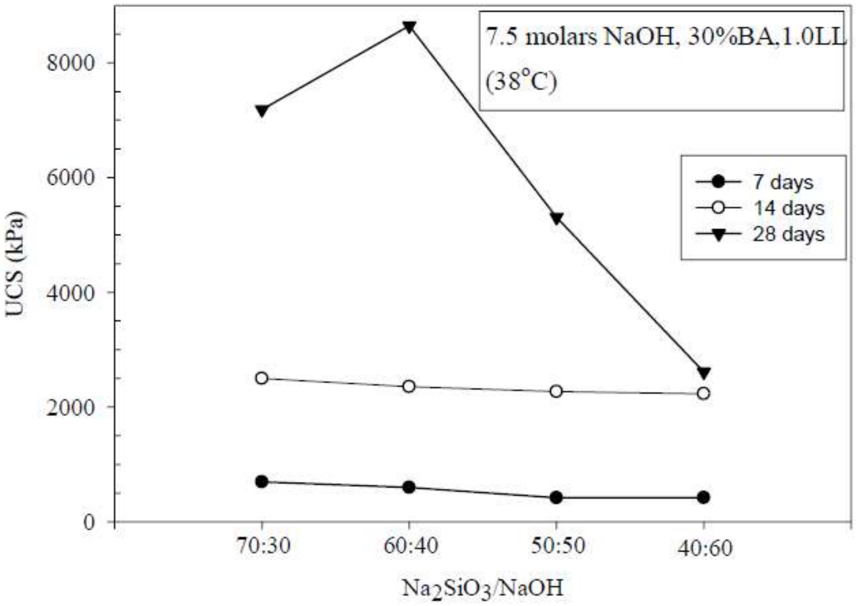


Fig. 4. Effect of liquid alkaline activator.

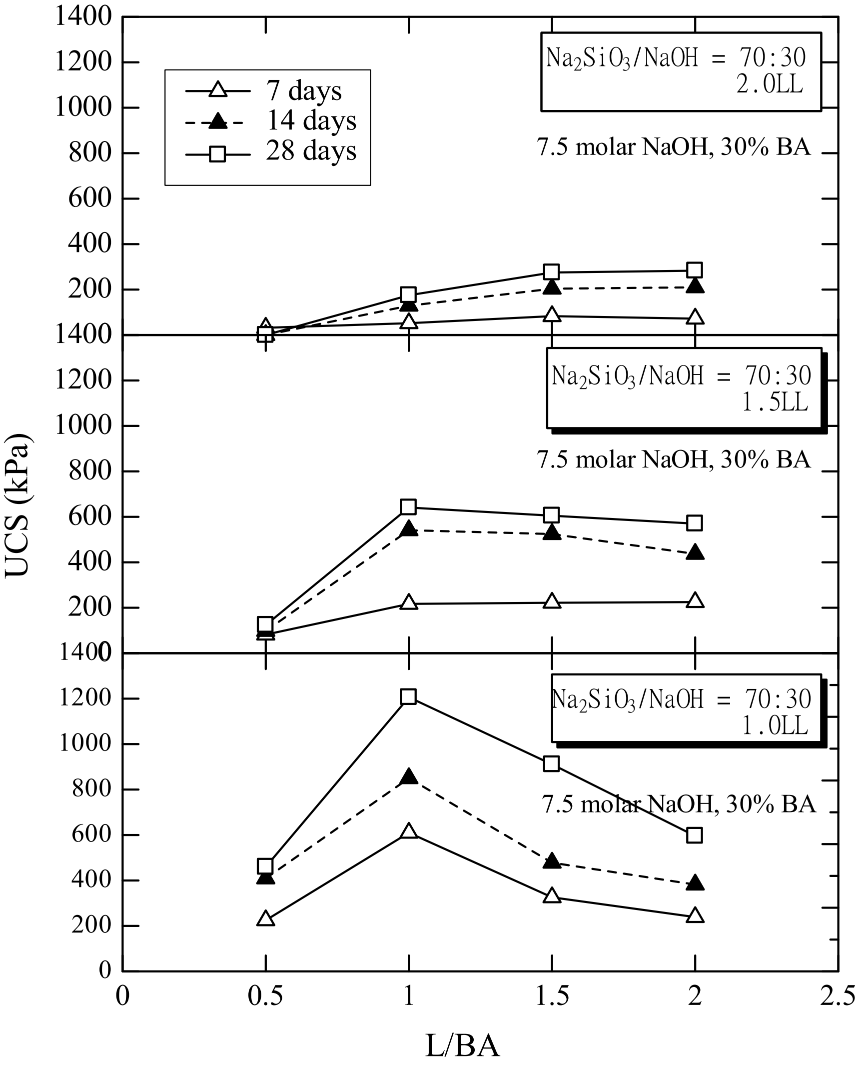
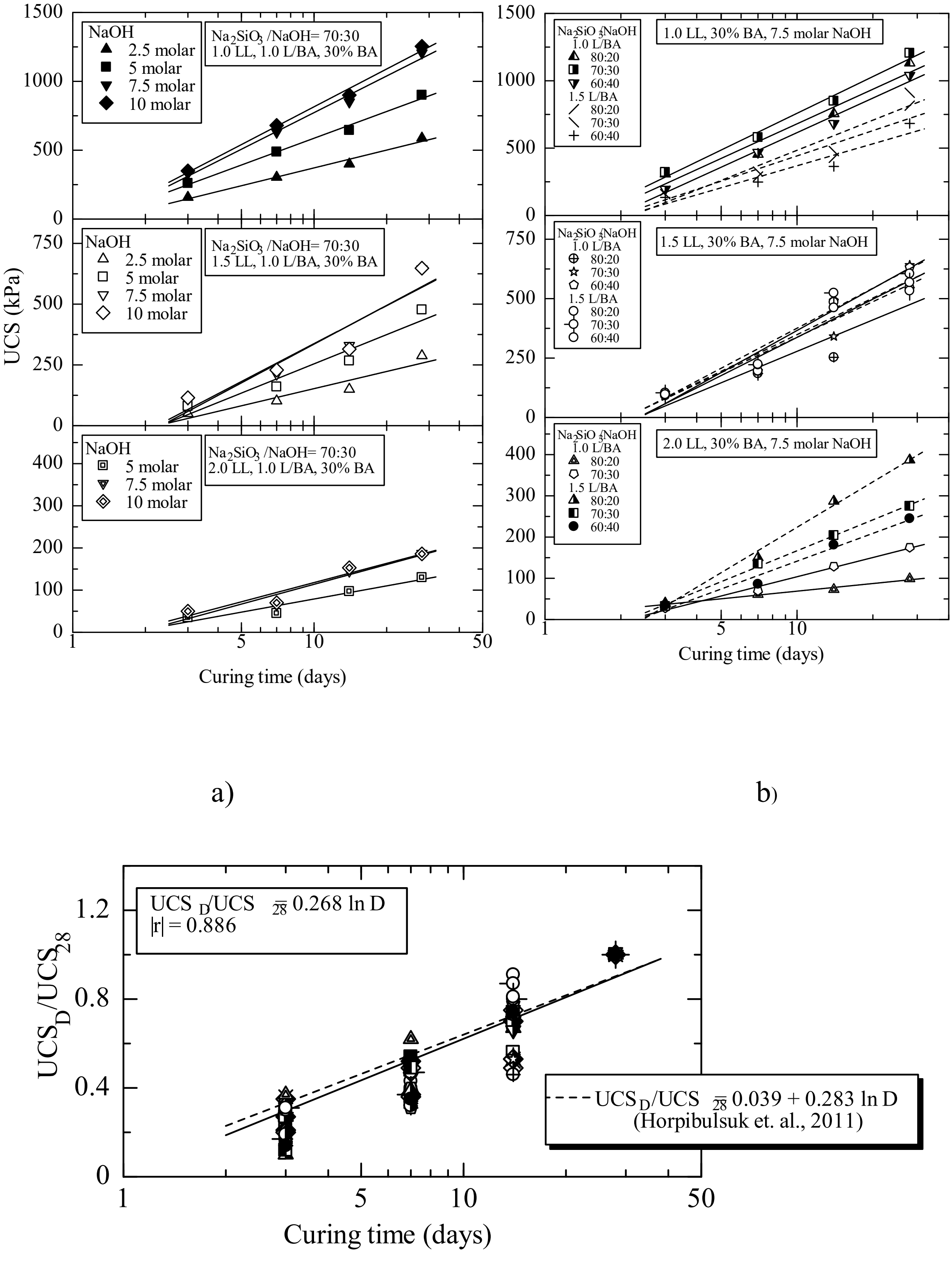


Fig. 5. Effect of liquid alkaline activator / BA at different LL.



a)

b)

c)

Fig. 6. Strength development with time for different NaOH, LL, ratio of Na_2SiO_3/NaOH, L/BA and their generalization.

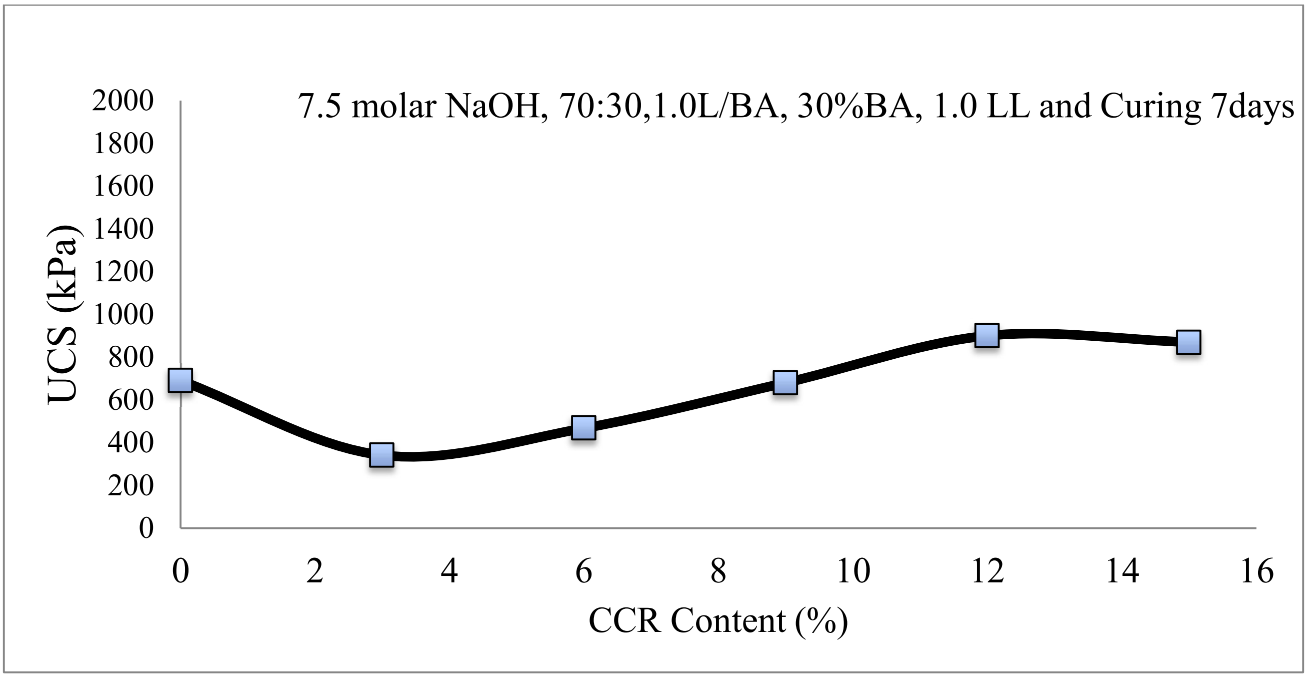


Fig. 7. Effect of CCR content on compressive strength.

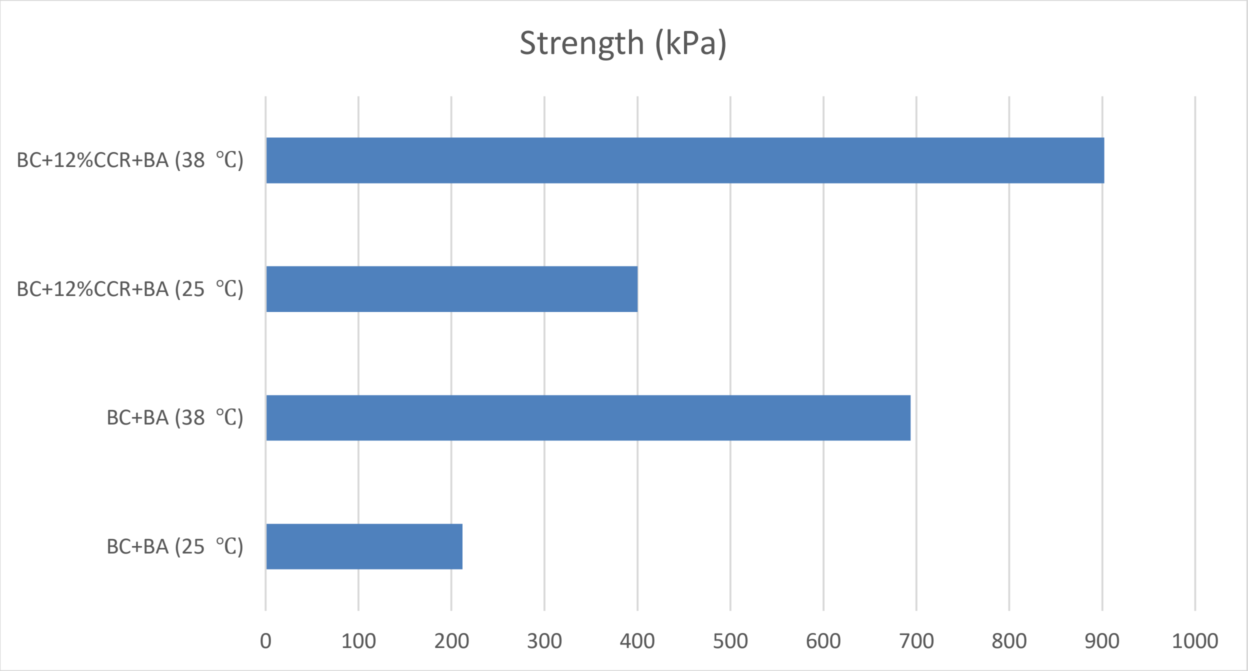
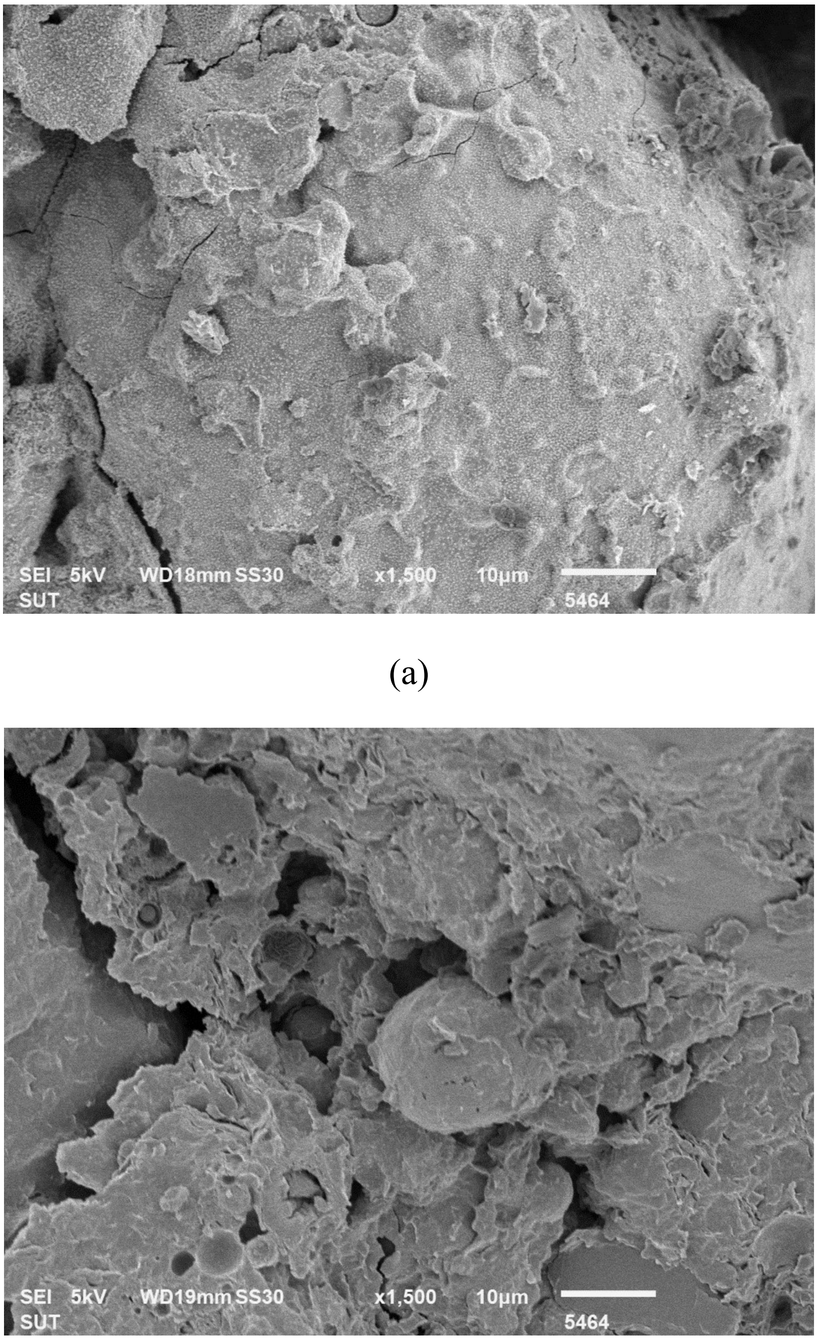


Fig. 8. The effect of temperature on strength at LL



(a)

(b)

Fig. 9. SEM images of clay CCR-BA geopolymer at Na_2SiO_3:NaOH = 70:30, BA = 30%, 38°C curing after 28 days of curing.

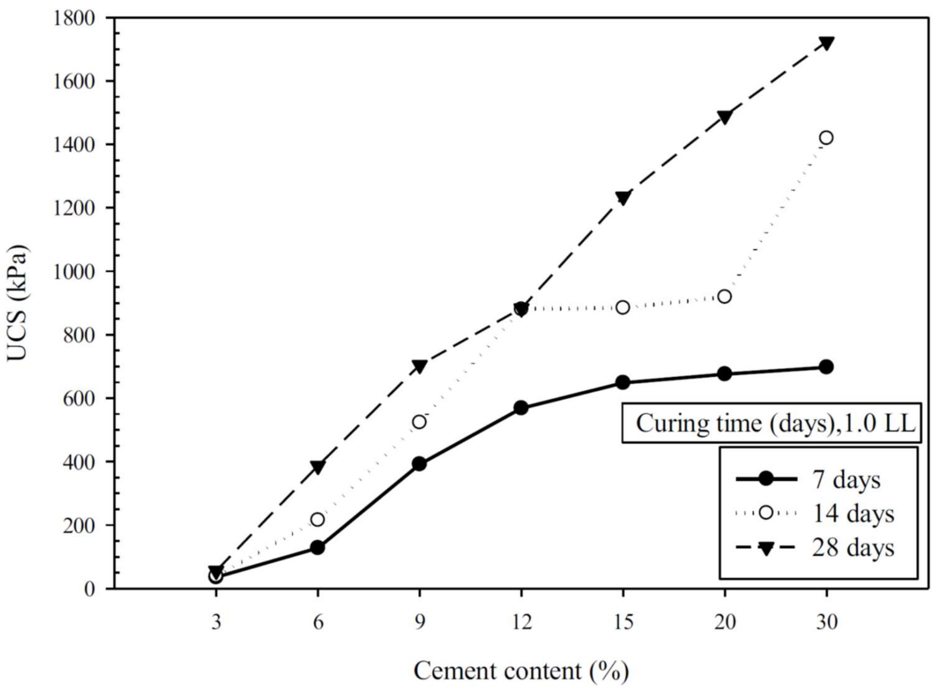


Fig. 10. The relationship between strength and cement content at liquid limit.

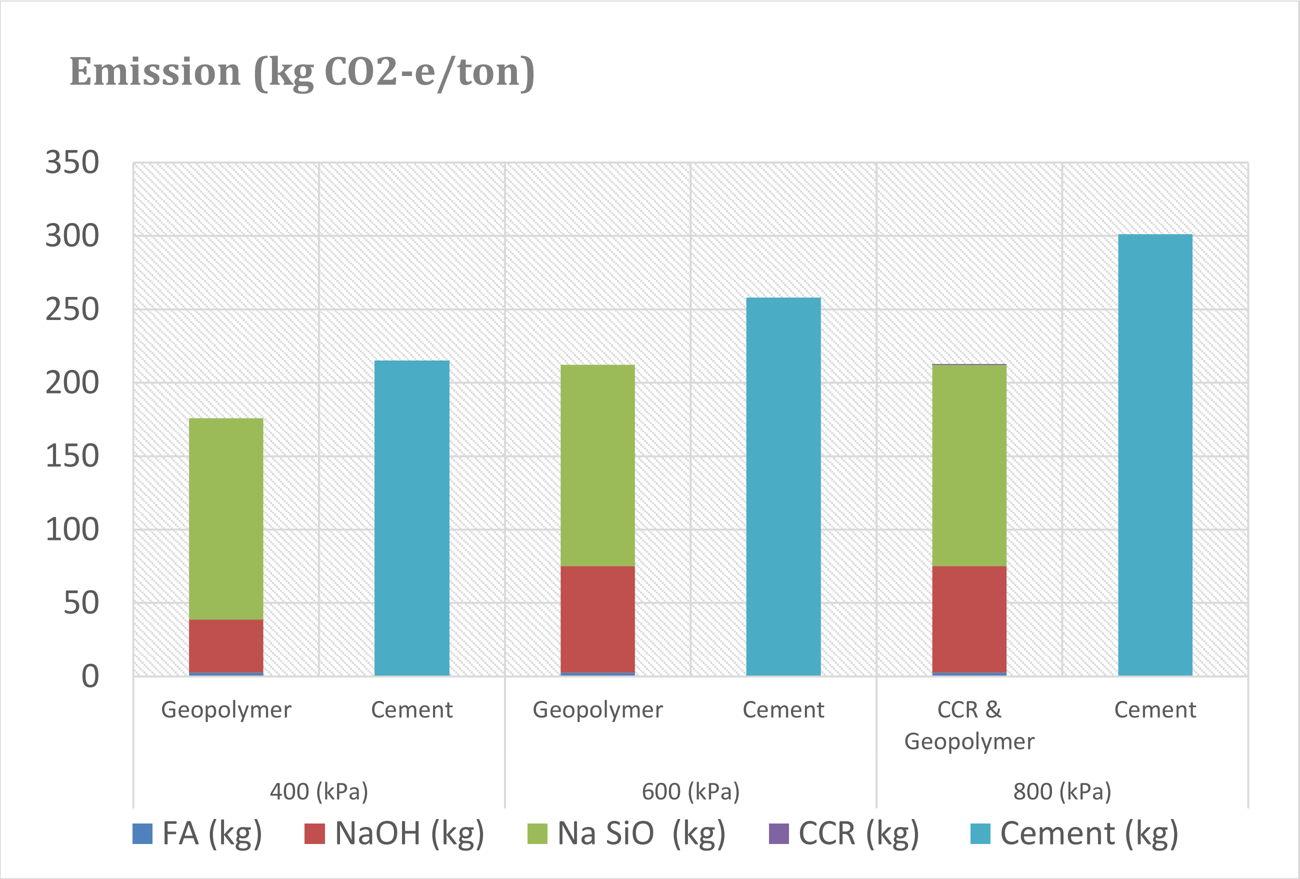


Fig. 11. The total CO_2-e of cement, geopolymer and CCR-geopolymer

Table 1 Basic properties of BC.

Properties	Characteristics
Liquid limit, LL (%)	65%
Plastic limit, PL (%)	32%
Plasticity index, PI (%)	33%
Grain size distribution	Clay 71% ; Silt 25% Sand 4%
Organic content	2.40%
Specific gravity, Gs	2.6
pH	7.2

Table 2 Chemical properties of Bangkok Clay, Bagasse ash and CCR.

Chemical composition (%)	BC	Bagasse Ash	CCR
Al_2O_3	12.760	15.380	6.941
SiO_2	66.953	66.800	19.423
SO_3	7.893	1.500	1.230
Cl	0.576	0.010	0.056
K_2O	1.387	5.500	0.721
CaO	5.642	4.000	69.660
TiO_2	1.179	0.050	0.675
Cr_2O_3	0.010	0.003	0.006
MnO_2	0.022	0.051	0.065
Fe_2O_3	3.523	3.600	1.041
CuO	0.026	0.005	0.030
ZnO	0.005	0.004	N.D.
PbO	0.010	0.004	0.013
SrO	0.013	0.020	0.044
Rb_2O	N.D.	0.004	0.017
ZrO_2	N.D.	0.014	0.007

N.D. = none detected

Table 3 Summary of the testing program.

		Series 1	Series 2	Series 3	Series 4	Series 5	Series 6
NaOH	(molar)	2.5,5, 7.5, 10, 12.5, 15	7.5	7.5	7.5	7.5	
Na_2sio_3:NaOH	(L)	70:30	80:20, 70:30 60:40, 50:50	70:30	70:30	70:30	-
Alkaline content	(L/BA)	1	1.0, 1.5, 2.0	1	1	1	-
BA	(%)	30	30	20, 30, 40	30	30	-
CCR	(%)	-	-	-	0,3, 6, 9, 12, 15	0,12	-
Cement	(%)	-	-	-	-	-	3, 6, 9 12, 15, 20,30
Water content of LL	(%)	1.0, 1.5, 2.0	1.0, 1.5, 2.0	1	1	1	1
Curing temp.	(°C)	38	38	38	38	25	25
Curing time	(days)	7, 14, 28	7, 14, 28	7	7, 14, 28	7	7

Table 4 UCS test result at 7.5 molar NaOH and 30% BA (kPa), curing 38 °C

Description	**Na_2SiO_3: NaOH**	**7 Days**			**14 Days**			**28 Days**		
		L/FA			**L/FA**			**L/FA**		
		1.0	**1.5**	**2.0**	**1.0**	**1.5**	**2.0**	**1.0**	**1.5**	**2.0**
1.0LL	80:20	439	248	225	2150	1120	985	6500	3152	2700
	70:30	694	326	277	2497	1263	1050	7185	3650	3054
	60:40	597	298	239	2354	1195	990	8647	3785	3100
	50:50	416	230	137	2231	1020	754	5306	2506	2100

Table 5 Mixture proportions of cement, geopolymer and CCR-geopolymer binders for dry soil of 1 ton at various strength.

Material	geopolymer		CCR & geopolymer	Cement		
	400 (kPa)	600 (kPa)	800 (kPa)	400 (kPa)	600 (kPa)	800 (kPa)
Bagasse ash (kg)	300	300	300	-	-	-
Sodium hydroxide (kg)	18.95	37.9	37.9	-	-	-
Sodium silicate (kg)	105.35	105.35	105.35	-	-	-
Calcium carbide Residue (kg)	-	-	42	-	-	-
Cement (kg)	-	-	-	250	300	350

Table 6 The emission factor of material.

Material	Emission factor (kg CO_2-e/ton)	Key References
Bagasse ash (kg)	0.007	(McLellan et al., 2011)
Sodium hydroxide (kg)	1.915	(Turner and Collins, 2013)
Sodium silicate (kg)	1.514	(Turner and Collins, 2013)
Calcium carbide residue (kg)	0.007	
Cement (kg)	0.86	(McLellan et al., 2011)

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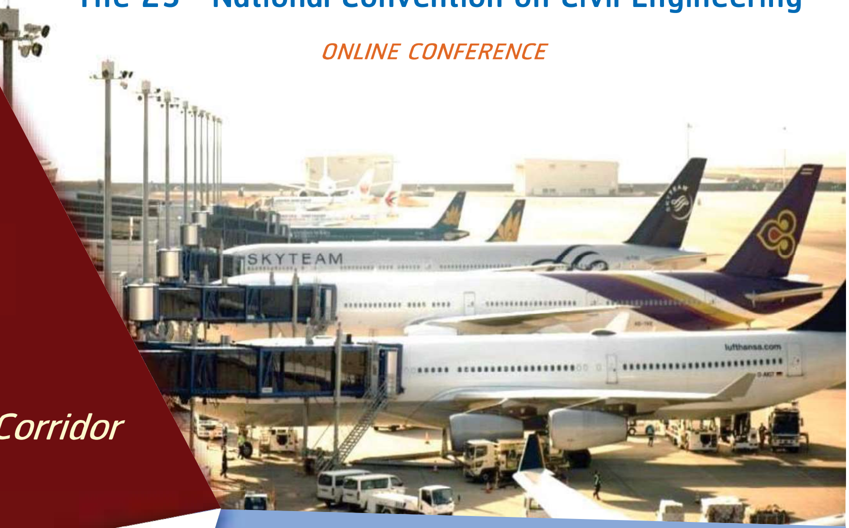
Civil Engineering and Eastern Economic Corridor for Sustainable Development



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วิศวกรรมสถานแห่งประเทศไทย ในพระบรมราชูปถัมภ์
ภาควิชาวิศวกรรมโยธา มหาวิทยาลัยบูรพา
สาขาวิชาวิศวกรรมโยธา มหาวิทยาลัยราชภัฏรำไพพรรณี
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ตารางเวลานำเสนอบทความ

วันพฤหัสบดีที่ 16 กรกฎาคม 2563

ห้องประชุม 4 - พักยา

เวลา 9:00 – 10:30 น.

สาขาวิศวกรรมปฐพี (GTE)

ประธานห้องประชุม : ผศ.ดร.ปิยะฉัตร ฉัตรตันใจ

ลำดับ	เวลา	รหัสบทความ	หัวข้อบทความ	ผู้นำเสนอ / ผู้แต่ง
1	9:00 – 9:15 น.	GTE-INV1	การเร่งระบายน้ำออกจากดินเหนียวอ่อน From surcharge loading to Vaccum PVD	ศ.ดร.พานิช วุฒิพฤกษ์
2	9:15 – 9:30 น.	GTE17	การปรับปรุงคุณภาพดินเหนียวอ่อนกรุงเทพด้วยปูนซีเมนต์ผสมผงตะกรันเหล็กและเถ้าชีวมวล จากโรงงานผลิตกระดาษ	วฤธ รัตนรุ่งโรจน์, ศุภกิจ นนทนานันท์, อัครชัย เรืองแสงทอง
3	9:30 – 9:45 น.	GTE34	สมรรถนะของเสาเข็มกรวดซีเมนต์เถ้าลอยภายใต้การอัดตัวคายน้ำ	สุวิจักขณ์ วิรัตน์, พิทยา แจ่มสว่าง
4	9:45 – 10:00 น.	GTE35	การวิเคราะห์กำลังรับแรงเฉือนไม่ระบายน้ำของดินถมบ่อถูกปรับปรุงด้วยวิธี Vacuum Consolidation Method	ศาสตร์ศิลป์ ภักดีเมฆ, ปิยวัฒน์ เงินบำรุง, สุทธิศักดิ์ ศรลัมพ์
5	10:00 – 10:15 น.	GTE41	กำลังอัดแกนเดียวของดินเหนียวอ่อนกรุงเทพผสมจีโอโพลิเมอร์จากเถ้าชานอ้อย	วีรวัฒน์ ดีสวัสดิ์, ชยกฤต เพชรช่วย, เชิดศักดิ์ สุขศิริพัฒนพงศ์, จักษดา ธำรงวุฒิ
6	10:15 – 10:30 น.	GTE42	อิทธิพลของปริมาณดินเม็ดละเอียดและปริมาณซีเมนต์ต่อกำลังอัดแกนเดียวของดินลูกรังผสมซีเมนต์	สุทธิพงศ์ คำดี, สุริยะ ทองมุณี, พีรพงศ์ จิตเสงี่ยม

กำลังอัดแกนเดียวของดินเหนียวอ่อนกรุงเทพผสมจีโอโพลิเมอร์จากเถ้าชานอ้อย

Unconfined Compressive Strength of Bagasse Ash Geopolymer Admixed in Soft Bangkok Clay

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บทคัดย่อ

งานวิจัยนี้ศึกษากำลังอัดแกนเดียวของดินเหนียวอ่อนกรุงเทพปรับปรุงด้วยเถ้าชานอ้อยจีโอโพลิเมอร์ที่แปรผันตัวแปรต่าง ๆ เพื่อหาความเป็นไปได้ในการใช้ปรับปรุงดินเหนียวอ่อนทดแทนการใช้ปูนซีเมนต์ เถ้าชานอ้อยเป็นวัสดุเหลือทิ้งที่ได้มาจากของเสียจากโรงงานอุตสาหกรรมซึ่งถูกนำมาใช้เป็นวัสดุตั้งต้นของจีโอโพลิเมอร์ สารอัลคาไลน์ที่ใช้ได้มาจากโซเดียมไฮดรอกไซด์ (NaOH) และโซเดียมซิลิเกต (Na_2SiO_3) งานวิจัยนี้ทำการศึกษาอัตราส่วนที่เหมาะสมของสารอัลคาไลน์ และความเข้มข้นของโซเดียมไฮดรอกไซด์ ใช้ปริมาณความชื้นของดินที่พิกัดเหลวของดิน และใช้ปริมาณเถ้าชานอ้อยที่ร้อยละ 30 ที่อายุบ่มต่าง ๆ จากการศึกษาพบว่าค่ากำลังอัดแกนเดียวที่อายุบ่ม 28 วัน มีค่าสูงสุดที่อัตราส่วนโซเดียมไฮดรอกไซด์ต่อโซเดียมซิลิเกตที่ 60:40 ปริมาณความเข้มข้นของโซเดียมไฮดรอกไซด์ที่ 7.5 โมลาร์ ปริมาณเถ้าชานอ้อยที่ร้อยละ 30 ของน้ำหนักดินแห้ง และปริมาณความชื้นของดินที่ขีดจำกัดเหลว

คำสำคัญ: ดินเหนียวอ่อน, เถ้าชานอ้อย, กำลังอัดแกนเดียว, จีโอโพลิเมอร์

Abstract

This research presents the unconfined compressive strength of the bagasse ash geopolymer admixed in soft clay Bangkok. The study on varies according to variables to find the possibility of using geopolymer improvement soft soil instead of using cement. Bagasse ash (BA), an industrial by-product, was used as a precursor of geopolymer. A mixture of sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3) was used as a liquid alkaline activator. This research was studied the suitable ratio between alkaline activator and sodium hydroxide concentration. The soil moisture content at the liquid limit and bagasse ash content at 30% per weight of dry soil were used in this research. The study found the highest 28 days unconfined compressive strength at the ratio of sodium hydroxide to sodium silicate at 60:40, the sodium hydroxide concentration at 7.5 molars, bagasse ash content at 30% and Liquid Limit (LL) of soil.

Keywords: Soft clay, Bagasse ash, Unconfined compressive strength, Geopolymer.

1. บทนำ

การพัฒนาโครงสร้างพื้นฐาน หรือระบบสาธารณูปโภค เช่น โครงสร้างคันดิน โครงสร้างฐานราก และโครงสร้างถนนบนชั้นดินเหนียวอ่อนในเขตกรุงเทพฯ และปริมณฑลมักประสบกับปัญหาทางด้านวิศวกรรมเนื่องจากดินเหนียวอ่อนมีปริมาณความชื้นในมวลดินสูง (ประมาณร้อยละ 60-140) และมีค่าอัตราส่วนช่องว่างสูง (Void ratio ประมาณ 2.0) [1],[2] ทำให้ความสามารถในการรับกำลังต่ำ และมีการทรุดตัวสูง จึงได้มีการปรับปรุงดินเหนียวอ่อนเพื่อทำให้มีการรับกำลังได้ดีขึ้น โดยทั่วไปนิยมใช้วิธีการผสมซีเมนต์ในอัตราส่วนที่เหมาะสมเพื่อใช้ปูนซีเมนต์เป็นวัสดุเชื่อมประสาน เทคนิคการปรับปรุงดินแบบนี้ช่วยเพิ่มความต้านทานการอัดตัวและการรับกำลังอัด [3],[4],[5],[6] แต่เทคนิคการใช้ปูนซีเมนต์นั้นก่อให้เกิดผลกระทบต่อสิ่งแวดล้อม ซึ่งขบวนการผลิตปูนซีเมนต์จะปลดปล่อยก๊าซคาร์บอนไดออกไซด์ทำให้เกิดสภาวะเรือนกระจกสู่ชั้นบรรยากาศ [7]

จากปัญหาที่กล่าวมา ผู้วิจัยจึงศึกษาการใช้จีโอโพลีเมอร์ประยุกต์ใช้ในการพัฒนากำลังของดินเหนียวอ่อน วัสดุจีโอโพลีเมอร์สามารถผลิตได้จากวัสดุที่มีองค์ประกอบของ SiO_2 และ Al_2O_3 และกระตุ้นด้วยสารละลายที่มีความเป็นด่าง (Liquid alkaline) เช่น โซเดียมซิลิเกต (Na_2SiO_3), โซเดียมไฮดรอกไซด์ (NaOH) และ โปแตสเซียมไฮดรอกไซด์ (KOH) ซึ่งจะทำให้มีโครงสร้างจับตัวกันเป็นสารประกอบอะลูมิโนซิลิเกตเป็นโครงสร้างกึ่งผลึกมีความแข็งแรงเมื่อแข็งตัวสามารถรับกำลังได้เช่นเดียวกับซีเมนต์ [8]

อีกทั้งงานวิจัยนี้จะศึกษาความเป็นไปได้ในการใช้เถ้าชานอ้อยซึ่งเป็นวัสดุเหลือทิ้งจากโรงงานไฟฟ้ามาใช้เป็นวัสดุตั้งต้นของจีโอโพลีเมอร์ ในการปรับปรุงกำลังรับแรงอัดของดินเหนียวอ่อนกรุงเทพ เพื่อรองรับงานโครงสร้างพื้นฐาน โดยพิจารณาตัวแปรควบคุม (ตารางที่1) ได้แก่ ปริมาณเถ้าชานอ้อย ปริมาณความชื้น ปริมาณสารละลายโซเดียมไฮดรอกไซด์ อัตราส่วนโซเดียมซิลิเกตและโซเดียมไฮดรอกไซด์ อายุบ่ม และการจำลอง

อุณหภูมิในสภาวะอากาศฤดูร้อนที่ 38±2 องศาเซียลเซียส เพื่อเปรียบเทียบกับผลทดสอบดินผสมซีเมนต์เพียงอย่างเดียวตามมาตรฐานกรมทางหลวง (กำลังอัดที่สภาวะไม่ระบายน้ำ (Su) 500 กิโลปาสกาล) [9]

2. วัสดุและการเตรียมตัวอย่างการทดสอบ

2.1 วัสดุและสารละลาย

2.1.1 ดินเหนียวอ่อนกรุงเทพ (Bangkok clay)

ดินเหนียวอ่อนกรุงเทพได้มาจากโครงการก่อสร้างโดยเก็บที่ความลึกประมาณ 3-10 เมตร มีค่าความถ่วงจำเพาะเท่ากับ 2.68 ขีดจำกัดความเหลว (LL) เท่ากับร้อยละ 63.93 ขีดจำกัดพลาสติก (PL) เท่ากับร้อยละ 25.49 ดัชนีพลาสติก (PI) เท่ากับร้อยละ 34.88 เมื่อนำมาจำแนกตามระบบ Unified Soil Classification จัดอยู่ในกลุ่มดินเหนียวที่มีพลาสติกสูง (CH)

2.1.2 ปูนซีเมนต์

ปูนซีเมนต์ปอร์ตแลนด์ธรรมดาประเภทที่ 1 ตามมาตรฐานอุตสาหกรรมปูนซีเมนต์ มอก. 15-2547 และมาตรฐาน ASTM C-150 มีค่าถ่วงจำเพาะเท่ากับ 3.15 และมีความละเอียดเท่ากับ 2,900 ตารางเซนติเมตรต่อกรัม ปูนซีเมนต์ประกอบด้วยวัสดุเชื่อมประสานหลัก ร้อยละ 90 ถึง 95 จำนวน 4 ชนิด ได้แก่ C_3S, C_2S, C_3A และ C_4AF [10]

2.1.3 เถ้าชานอ้อย

เถ้าชานอ้อยได้รับความอนุเคราะห์จากโรงงานผลิตไฟฟ้าที่อำเภอครบุรี จังหวันนครราชสีมา โดยการเผากากอ้อยที่อุณหภูมิประมาณ 600 ถึง 800 องศาเซลเซียสเพื่อผลิตกระแสไฟฟ้า ก่อนนำมาใช้ในการทดสอบได้ทำการบดโดยเครื่องบด (Los Angeles Machine) เป็นเวลา 30 นาที เถ้าชานอ้อยที่ได้มีความละเอียดอยู่ในช่วงระหว่าง 2,800 ถึง 3,000 ตารางเซนติเมตรต่อกรัม อนุภาคของเถ้าชานอ้อยที่ผ่านการบดจะมีรูปร่างเป็นเหลี่ยมมุมไม่สม่ำเสมอ [11]

2.1.4 สารละลายโซเดียมไฮดรอกไซด์ (NaOH)

NaOH เป็นสารเคมีของแข็งรูปเม็ด (bead) หรือแผ่นเกล็ด (flake) มีมวลโมเลกุล 40 กรัม/โมล ใช้กระบวนการอิเล็กโตไลซิสของเกลือในการผลิต เมื่อนำมาละลายน้ำมีฤทธิ์เป็นด่างแก่ คือสามารถแตกตัวให้อิออนโซเดียม (Na+) และอิออนไฮดรอกไซด์ (OH-) ได้หมด โซเดียมไฮดรอกไซด์มีความ ถ่วงจำเพาะประมาณ 2.12 ที่อุณหภูมิ 20 °C และมีจุดหลอมเหลว 318 °C [12]

2.1.5 สารละลายโซเดียมซิลิเกต (Na_2SiO_3)

โซเดียมซิลิเกตเป็นสารประกอบของโซเดียมออกไซด์ (Na_2O) และซิลิกอนไดออกไซด์หรือซิลิกา (SiO_2) มีสถานะเป็นได้ทั้งของแข็งและของเหลว ในการใช้งานหากเป็นของแข็งต้องละลายน้ำก่อนใช้ โดยทั่วไปมักจำหน่ายอยู่ในรูปของสารละลายโซเดียมซิลิเกต [12]

ตารางที่ 1 อัตราส่วนผสมและจำนวนตัวอย่าง

ตัวแปร	จำนวน	หมายเหตุ
อัตราส่วนเถ้าชานอ้อย	1	30% (ต่อน้ำหนักดินแห้ง)
ปริมาณความชื้นของดินเหนียวอ่อน	1	1.0LL (LL คือขีดจำกัดเหลว)
อัตราส่วนของโซเดียมซิลิเกต/โซเดียมไฮดรอกไซด์ (Na_2SiO_3/NaOH)	4	70:30, 60:40, 50:50, 40:60
ปริมาณสารละลาย/เถ้าชานอ้อย	1	(L/BA = 1)
ความเข้มข้นขอโซเดียมไฮดรอกไซด์ (NaOH)	6	2.5, 5, 7.5, 10, 12.5, 15 โมลาร์
อัตราส่วนปูนซีเมนต์	7	3%, 6%, 9%, 12%, 15%, 20%, 30%
อายุบ่ม	3	7, 14, 28 วัน
อุณหภูมิการบ่ม	2	อุณหภูมิห้อง และ 38±2 องศาเซียลเซียส
จำนวนตัวอย่างต่อ 1ส่วนผสม	3	ตัวอย่าง

2.2 การเตรียมตัวอย่างการทดสอบ

2.2.1 การเตรียมตัวอย่าง

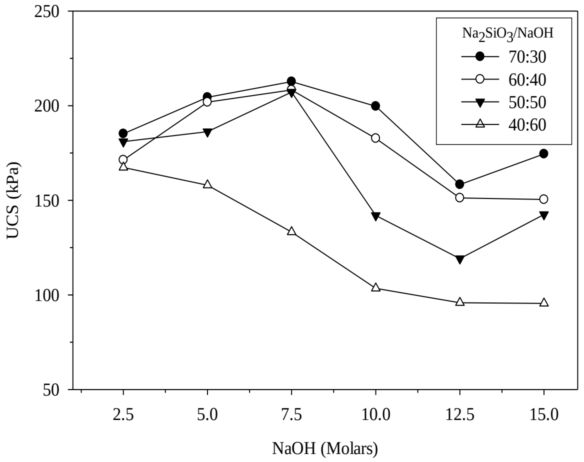
ตัวอย่างดินเหนียวจะถูกนำมาหาปริมาณความชื้นเตรียมไว้เพื่อนำมาปรับความชื้นด้วยการผสมเข้ากับน้ำตามปริมาณความชื้นที่กำหนดไว้ผสมดินเหนียวกับน้ำให้เข้ากันทิ้งไว้เป็นเวลา 24 ชั่วโมง จากนั้นนำมาผสมกับเถ้าชานอ้อยและสารละลาย ที่อัตราส่วนที่กำหนด โดยทำการผสมในหม้อผสมจนกระทั่งส่วนผสมเข้ากันดีโดยใช้ระยะเวลาผสม 3 ถึง 5 นาที จากนั้นเทตัวอย่างลงในท่อพีวีซีที่มีขนาด 38 มม. และสูง 76 มม. บ่มตัวอย่างไว้ในแบบหล่อประมาณ 24 ชั่วโมงเพื่อให้ความชื้นสม่ำเสมอและแข็งตัว จากนั้นแกะตัวอย่างออกจากแบบแล้วนำไปหุ้มด้วยแผ่นพลาสติกใสเพื่อป้องกันการสูญเสียความชื้น [13] และในการศึกษางานวิจัยนี้มีการจำลองสภาพอากาศในประเทศไทยในฤดูร้อนโดยใช้อุณหภูมิเฉลี่ยที่ประมาน 38±2 °C ในงานวิจัยนี้จึงได้นำตัวอย่างไปอบที่อุณหภูมิ 38±2 °C ตลอดจนอายุการบ่มครบตามกำหนดหลังการนั้นจึงแกะพลาสติกใสออก วัดขนาดและชั่งน้ำหนักตัวอย่าง นำไปทดสอบกำลังอัดแกนเดียวแบบไม่ถูกจำกัด (Unconfined compressive strength) [14]

2.2.2 การทดสอบกำลังอัดแกนเดียวแบบไม่ถูกจำกัด

เมื่อตัวอย่างที่เตรียมไว้มีอายุบ่มครบตามที่กำหนด จึงนำตัวอย่างจำนวน 3 ตัวอย่างมาทดสอบ แล้วนำค่าเฉลี่ยมาเป็นผลการทดสอบการทดสอบแรงอัดแกนเดียวแบบไม่ถูกจำกัดเป็นไปตามมาตรฐาน

ทล.ท.105/2525 หรือ ASTM D, 2166-06 [9] ในการทดสอบกำลังอัดแกนเดียวกำหนดอัตราการเคลื่อนที่ในแนวดิ่งเท่ากับ 1 มิลลิเมตรต่อนาทีจนกว่าตัวอย่างจะวิบัติโดยค่ากำลังที่ต้องการมีค่า Undrained Shear Strength ที่หาจาก Unconfined Compression Test ต้องไม่น้อยกว่า 500 กิโลปาสกาล ที่ 28 วัน [9]

3. ผลการทดสอบและวิเคราะห์ผลทดสอบ

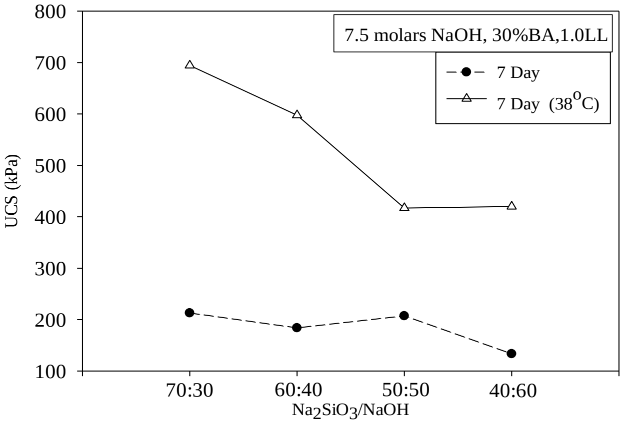


รูปที่ 1 อิทธิพลของความเข้มข้นของ NaOH ต่อกำลังอัดของดินเหนียวอ่อนผสมเถ้าชานอ้อยจีโอโพลีเมอร์ ที่มีปริมาณความชื้น 1.0LL ที่อายุบ่ม 7 วัน

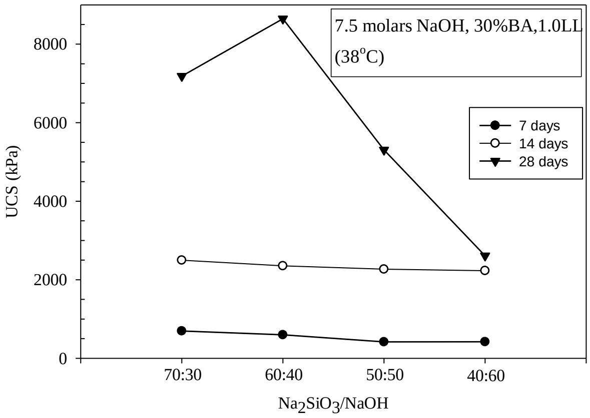
จากรูปที่ 1 กราฟแสดงอิทธิพลของอัตราส่วนปริมาณสารละลาย Na_2SiO_3/NaOH ต่อ กำลังอัดของดินเหนียวอ่อนผสมเถ้าชานอ้อย จีโอโพลีเมอร์ ที่ปริมาณความชื้นของดินเหนียวอ่อนเท่ากับ 1.0LL อัตราส่วนผสมเถ้าชานอ้อยร้อย 30 ต่อน้ำหนักดินแห้ง อัตราส่วน Na_2SiO_3/NaOH เท่ากับ 70:30, 60:40, 50:50, และ 40:60 ที่แปรผันตามความเข้มข้นของ NaOH จะพบว่าเมื่อเพิ่มความเข้มข้นของสารละลาย NaOH จะทำให้กำลังอัดเพิ่มขึ้นจนมีค่าสูงสุดที่ 7.5 โมลาร์ เป็นจุดเหมาะสมที่อัตราส่วน Na_2SiO_3/NaOH เท่ากับ 70:30, 60:40, และ 50:50 หลังจากนั้นค่ากำลังอัดมีค่าลดลงเมื่อมีความเข้มข้นของ NaOH มากกว่า 7.5 โมลาร์

จากรูปที่ 2 กราฟแสดงตัวอย่างดินเหนียวอ่อนที่ปรับปรุงด้วยเถ้าชานอ้อยจีโอโพลิเมอร์ ที่มีความเข้มข้นสารละลายโซเดียมไฮดรอกไซด์ที่เท่ากับ 7.5 โมลาร์ ที่อัตราส่วนสารละลายโซเดียมซิลิเกตต่อสารละลายโซเดียมไฮดรอกไซด์ (Na_2SiO_3/NaOH) เท่ากับ 70:30, 60:40, และ 50:50 ของตัวอย่างที่ไม่ได้นำไปอบมีค่ากำลังรับแรงอัดใกล้เคียงกันโดยพบค่าสูงสุดที่อัตราส่วน(Na_2SiO_3/NaOH=70:30) เท่ากับ 212 กิโลปาสคาล
สำหรับตัวอย่างที่ถูกนำไปอบด้วยอุณหภูมิ 40 องศาเซลเซียส พบว่ากำลังอัดมีค่าสูงสุดที่อัตราส่วนสารละลายโซเดียมซิลิเกตต่อสารละลายโซเดียมไฮดรอกไซด์ (Na_2SiO_3/NaOH) เท่ากับ 70:30 มีกำลังรับแรงอัดเท่ากับ 694 กิโลปาสคาล และพบว่าตัวอย่างที่ได้ถูกนำไปอบยังมีกำลังมากกว่าตัวอย่างที่ไม่ได้ถูกนำไปอบทุกอัตราผสมสารละสาร Na_2SiO_3/NaOH ในระยะเวลาการบ่มที่อายุ 7 วัน

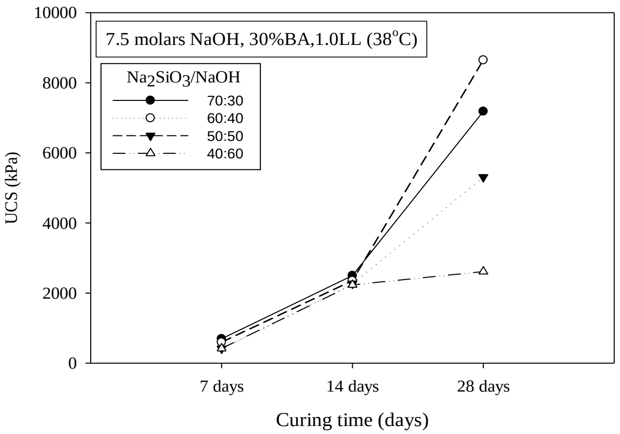
อิทธิพลของสารละลาย Na_2SiO_3/NaOH ต่อกำลังอัด แสดงให้เห็นว่าอัตราส่วน Na_2SiO_3/NaOH เท่ากับ 70:30 ที่ให้กำลังอัดสูงในช่วง 7-14 วัน แต่อัตราส่วน Na_2SiO_3/NaOH เท่ากับ 60:40 มีกำลังอัดสูงที่สุดที่อายุบ่ม 28 วัน ดังแสดงในรูปที่ 3



รูปที่ 2 อิทธิพลของอัตราส่วนสารละลาย Na_2SiO_3/NaOH ต่อค่ากำลังอัดที่ NaOH 7.5 โมลาร์, ปริมาณความชื้อ 1.0LL อายุบ่ม 7 วัน ของตัวอย่างดินที่บ่มแบบอบกับไม่อบ

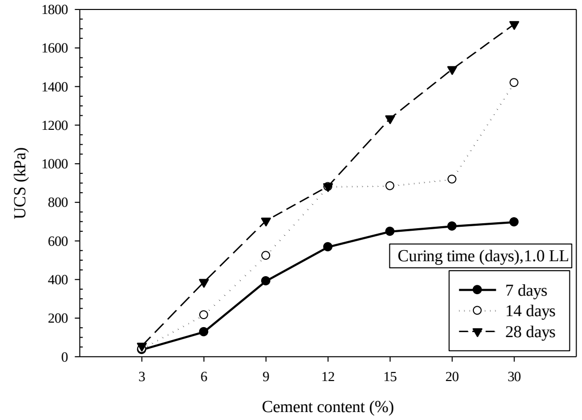


รูปที่ 3 อิทธิพลของสารละสาร Na_2SiO_3/NaOH ต่อกำลังอัดของดินเหนียวอ่อนผสมเถ้าชานอ้อย จีโอโพลีเมอร์ ที่อบด้วยอุณภูมิ 38 °C



รูปที่ 4 การพัฒนากำลังของตัวอย่างดินเหนียวอ่อนผสมเถ้าชานอ้อย จีโอโพลีเมอร์ ปริมาณความชื้น 1.0LL ที่อบด้วยอุณภูมิ 38 °C

จากรูปที่ 4 กำลังอัดมีแนวโน้มสูงขึ้นในช่วงอายุบ่ม 7 ถึง 14 วัน กำลังอัดมีความใกล้เคียงกันทุกอัตราส่วนผสมของสารละลาย Na_2SiO_3/NaOH เมื่ออายุบ่ม 28 วัน จะเห็นได้ชัดว่า อัตราส่วน Na_2SiO_3/NaOH เท่ากับ 60:40 ให้กำลังอัดสูงสุดเท่ากับ 8,647 กิโลปาสคาล และ 7,185 กิโลปาสคาล ที่อัตราส่วนอัตราส่วน Na_2SiO_3/NaOH เท่ากับ 70:30 ของตัวอย่างดินดินเหนียวอ่อนผสมเถ้าชานอ้อย จีโอโพลีเมอร์ ปริมาณความชื้น 1.0LL ที่อบด้วยอุณภูมิ 38 °C



รูปที่ 5 กราฟการพัฒนากำลังตามปริมาณของปูนซีเมนต์

จากรูปที่ 5 แสดงกำลังอัดของดินเหนียวอ่อนผสมกับปูนซีเมนต์ ที่ปริมาณความชื้นของดินเหนียวอ่อนเท่ากับ 1.0 LL ที่อายุบ่ม 7 14 และ 28 วัน โดยใช้ปริมาณปูนซีเมนต์ร้อยละ 3, 6, 9, 12, 15, 20, และ 30 ต่อน้ำหนักดินแห้ง ผลการทดสอบแสดงให้เห็นว่ากำลังอัดมีแนวโน้มสูงขึ้น ตามปริมาณของปูนซีเมนต์ที่เพิ่มขึ้น ทุกช่วงอายุบ่ม เนื่องจากปริมาณปูนซีเมนต์ที่เพิ่มขึ้นส่งผลเกิดปฏิกิริยาไฮเดรชันเพิ่มขึ้นทำให้มีกำลังอัดเพิ่มขึ้น แต่เมื่อทำการเปรียบเทียบกับกำลังอัดของดินเหนียวผสมเถ้าชานอ้อยจีโอโพลิเมอร์ในรูปที่ 4 พบว่าที่อายุบ่ม 28 วัน ดินเหนียวผสมเถ้าชานอ้อยจีโอโพลิเมอร์มีค่ากำลังอัดที่สูงกว่า

4. สรุปผลการทดสอบ

บทความนี้ศึกษากำลังอัดของดินเหนียวผสมเถ้าชานอ้อยจีโอโพลิเมอร์เพื่อทดแทนการใช้ซีเมนต์ในงานเสาเข็มดินซีเมนต์ตามมาตรฐานกรมทางหลวงที่ต้องการกำลังอัดแกนเดียวที่ 28 วัน เท่ากับ 1,000 kPa (500 kPa undrain shear strength) โดยสามารถสรุปผลการทดสอบได้ดังนี้

1) ความเข้มข้นของ NaOH ที่สูงขึ้นสามารถชะล้างซิลิก้าและอลูมินาจากเถ้าชานอ้อยเพื่อมาทำปฏิกิริยาโพลิเมอร์ไลเซชั่นได้มากขึ้นแต่จะเพิ่มขึ้นจนถึงแค่จุดเหมาะสมค่าหนึ่ง เนื่องจากปริมาณซิลิก้า อลูมินา และ Na_2SiO_3 ในระบบมีปริมาณที่จำกัดเมื่อเพิ่มความเข้มข้นของ NaOH มากเกินไปทำให้มี Na^+ และ OH^- อิสระมากเกินไปจนขัดขวางการทำปฏิกิริยา

2) อัตราส่วนผสมของสารละลาย Na_2SiO_3/NaOH ที่เหมาะสมจะส่งผลต่อการพัฒนาค่ากำลังอัดโดยค่าเหมาะสม ได้แก่ค่า 60:40 ค่าอัตราส่วนสารละลายนี้อาจเปลี่ยนแปลงได้เนื่องจากอิทธิพลของอุณหภูมิสภาพแวดล้อม อุณหภูมิที่สูงขึ้นจะช่วยแร่งการทำปฏิกิริยาโพลิเมอร์เซชั่นของจีโอโพลิเมอร์ได้ดีขึ้น

3) เมื่อเปรียบเทียบกำลังอัดที่ 28 วัน กับดินซีเมนต์พบว่าดินเหนียวผสมเถ้าชานอ้อยจีโอโพลิเมอร์มีค่ากำลังอัดที่สูงกว่าดินเดียวผสมซีเมนต์ โดยมีส่วนผสมที่ให้ค่ากำลังอัดที่ผ่านมาตรฐานกรมทางหลวงตั้งแต่อายุบ่ม 14 วัน มีค่าความเข้มข้นของ NaOH ที่เหมาะสมอยู่ที่ 7.5 molars อัตราส่วนสารอัลคาร์ไลน์ (Na_2SiO_3/NaOH) ที่เหมาะสมอยู่ที่ 60:40 ได้กำลังอัด 2,500 kPa

กิตติกรรมประกาศ

งานวิจัยนี้ได้รับทุนอุดหนุนจากสำนักงานคณะกรรมการการอุดมศึกษา และสำนักงานกองทุนสนับสนุนการวิจัย และขอขอบคุณหน่วยวิจัยเทคโนโลยีโครงสร้างพื้นฐานและการขนส่งทางราง สาขาวิศวกรรมโยธา คณะวิศวกรรมศาสตร์และสถาปัตยกรรมศาสตร์ มหาวิทยาลัยเทคโนโลยีราชมงคลอีสาน

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