Development of Geopolymer Bricks from Synergistic Use of Bagasse Ash and Concrete Residue as an Alternative for Industrial Waste Management

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Abstract

This research studies the feasibility of enhancing the physical and mechanical properties of bagasse-ash-based-geopolymer bricks with concrete residue. The effects of concrete residue were investigated using five different proportions of bagasse ash to concrete residue: 100:0, 90:10, 80:20, 70:30 and 60:40 by weight. A 10 molar concentration of sodium hydroxide and a sodium silicate (Na_2SiO_3) solution were used as an alkaline solution with a mass ratio of Na_2SiO_3/NaOH of 2.5. The geopolymer bricks were cured at 65°C for 24 hours in an oven and then at room temperature for 28 days. The chemical composition and particle size distribution of the bagasse ash and concrete residue were then analyzed. Using the TIS 168-2546 specification, the physical and mechanical properties, microstructure and crystal structure of the geopolymer bricks were then tested. The results showed significant improvements in water absorption and compressive strength of geopolymer bricks when concrete residue was added. The maximum compressive strength (8.83 MPa) and the minimum water absorption (0.86%) were found in geopolymer bricks with a 40% concrete residue.

Keywords: Geopolymer bricks, Bagasse ash, Concrete residue, Industrial waste

Introduction

In Thailand, approximately 53 million tons of industrial waste is produced per year (Department of Industrial Works, 2015). This enormous quantity of industrial waste is a serious concern not only because of the difficulty of disposal but also because it poses a serious environmental problem. Brick production is an alternative way to use such industrial waste. There are three methods for producing bricks from waste: firing, cementing and geopolymerization. Producing bricks using the firing technique requires high kiln temperatures, while the cementing technique to produce bricks requires large amounts of cement. These two techniques also have the drawbacks of high energy consumption and large emissions of greenhouse gases. By contrast, geopolymerization relies on the chemical reaction of amorphous silica and alumina-rich solids with a high alkaline solution at ambient or slightly elevated temperatures to form amorphous to semi-crystalline aluminosilicate inorganic polymers or geopolymers (Zhang, 2013); this brick production method consumes less energy and produces fewer environmental effects than the other two techniques.

Bagasse ash (BA) is a by-product generated by burning bagasse in the boilers of sugar plants (Lin, Ho, Cheng, Huang, & Huang, 2012). In Thailand, the sugar industry generates approximately 0.6 million tons of BA per year (Jaturapitakkul, 2015). BA has been typically disposed because other uses for this waste are still limited. BA contains constituents such as silica and alumina (Tippayasam et al., 2010), which are desirable constituents for geopolymerization. BA has been used in the production of geopolymer material (Rukzon & Ngenprom, 2010), geopolymer mortar (Rukzon & Chindaprasirt, 2014) and geopolymer paste (Tippayasam, Leonelli, & Chaysuwan, 2014). It has been observed that using 100% BA to produce geopolymers is inappropriate because of the low compressive strength results (Tippayasam et al., 2010; Tippayasam et al., 2014). Thus, BA has been used in combination with other aluminosilicate minerals such as fly ash and blast furnace slag in the production of geopolymers. Studies have shown that the highest compressive strength was produced by using a fly-ash-to-BA ratio of 80:20 by weight (Somna, 2014) and 50:50 by weight (Tippayasam et al., 2010). Using BA combined with blast furnace slag to make geopolymer pastes and mortars resulted in good mechanical performance (Castaldelli et al., 2013, 2014). However, very little research has been conducted on the development of geopolymer bricks from BA.

Concrete residue (CR) is a waste that remains after cleaning equipment used for concrete production. For example, Tratmunkong Construction Materials Co., Ltd., in Trat Province, Thailand, generates large amounts of CR on a daily basis. All of this CR cannot be recycled by the facility, so it must be disposed in a landfill. The major constituents of concrete waste are calcium and silica compounds, with minor quantities of alumina and iron oxide (Ahmari et al., 2012). Studies show that the presence of calcium compounds in the raw material can enhance the mechanical properties of geopolymers due to the formation of a calcium silicate hydrate (CSH) gel that coexists with the geopolymer gel (Yip, Lukey, & Deventer, 2005; Ahmari et al., 2012), and the incorporation of calcium into the geopolymer network as a charge-balancing cation (Ahmari et al., 2012; Ahmari & Zhang, 2013). However, these benefits are limited to a certain amount of calcium in the geopolymeric system (Ahmari et al., 2012).

The aim of this research is to study the feasibility of producing geopolymer bricks from BA and CR through the addition of CR in amounts of 0-40% by weight to enhance the physical and mechanical properties of BA-based geopolymer bricks. The physical and mechanical properties as per the TIS 168-2546 specification, microstructure and mineralogical phases of geopolymer bricks were tested.

Methods and Materials

1. Materials

Bagasse ash was obtained from the sugar refinery at Thai Multi-Sugar Industry Co., Ltd., in Kanchanaburi Province, Thailand. Concrete residue was obtained from the concrete production plant at Tratmunkong Construction Materials Co., Ltd., in Trat Province, Thailand. The bagasse ash was dried, ground by using a Los Angeles abrasion machine for 30 minutes and then passed through a No. 200 (< 75 μm) sieve using an aggregate vibration screen. The concrete residue was dried and passed through a No. 140 (< 106 μm) sieve.

2. Alkaline solution

A 10 molar concentration of sodium hydroxide (10M NaOH) was prepared at least 24 hours before use by dissolving analytical-grade sodium hydroxide in flake form (98% purity) in distilled water. A sodium silicate (Na_2SiO_3) solution was obtained from industrial-grade sodium silicate in liquid form. The Na_2SiO_3 specification is shown in Table 1.

Table 1 The specification of Na_2SiO_3

Specification of Na_2SiO_3	
Na_2O (%)	14.25±1.0
SiO_2 (%)	31.25±1.0
Molecular ratio	1:2.00-2.30
Specific gravity at 20°C	1.490-1.560
Density at 20°C	50.0-51.5

An alkaline solution was then prepared by mixing the 10M NaOH with the Na_2SiO_3. The mass ratio of Na_2SiO_3/NaOH is 2.5 (Rukzon & Ngenprom, 2010). The alkaline solution was cooled to room temperature before use.

3. Characterization of bagasse ash and concrete residue

The chemical compositions of the bagasse ash and the concrete residue were analyzed using a Bruker model S8 Tiger X-ray fluorescence spectrometer. The particle size distribution of the BA and the CR was investigated using a Malvern Mastersizer 3000 laser particle size distribution analyzer.

4. Preparation of geopolymer bricks

The bagasse ash and concrete residue were mixed for two minutes in a bowl mixer in different proportions as shown in Table 2.

Table 2 Proportions of geopolymer bricks

Batch name	Bagasse ash (wt.%)	Concrete residue (wt.%)
BA100	100	0
BA90CR10	90	10
BA80CR20	80	20
BA70CR30	70	30
BA60CR40	60	40

The alkaline solution was poured into a bowl mixer and mixed for 10 minutes until homogeneous. The ratio of solids (bagasse ash and concrete residue) to liquid (alkaline solution) is 1.2 by weight for geopolymer bricks (Rukzon & Ngenprom, 2010). After mixing, the dough was poured into 5 x 5 x 5 cm^3 acrylic molds and compacted using a vibration table for one minute. The molds were wrapped with plastic film to reduce moisture loss, and the specimens were then left to set for 30 to 60 minutes. Afterward, the specimens were cured in an oven at 65°C for 24 hours (Rukzon & Ngenprom, 2010) and then left to cool at room temperature for 24 hours. Following this, the specimens were removed from the molds and placed in tight-fitting containers with lids to protect the specimens from air and reduce moisture loss. The specimens were then cured at room temperature for 28 days.

5. Characterization of geopolymer bricks

5.1 Physical and mechanical properties

The general appearance, compressive strength and water absorption of the geopolymer bricks were determined according to the Thai Industrial Standard (TIS) 168-2546 specification.

5.2 Microstructure

A Jeol JSM-6480LV scanning electron microscope was used for microstructure characterization of the geopolymer bricks.

5.3 Mineralogical phases

An X-ray diffractometer was used for mineralogical phase identification of the geopolymer bricks.

6. Statistical analysis

IBM SPSS Statistics was used to calculate the mean and standard deviations of the data for each parameter, and a one-way analysis of variance (ANOVA) was conducted to compare the effects of varying amounts of concrete residue on water absorption and compressive strength.

Results and discussion

1. Characterization of bagasse ash and concrete residue

Table 3 shows the chemical composition of the bagasse ash and concrete residue. The main components of bagasse ash are SiO_2 followed by Al_2O_3, CaO and K_2O, which together constitute

~61.41% of the BA's total composition. In concrete residue, the main components are CaO followed by SiO_2 and Al_2O_3, which together constitute ~61.80% of the CR's total composition. Consequently, both bagasse ash and concrete residue could be used as raw materials for geopolymer synthesis because both are rich in SiO_2 and Al_2O_3, which are essential sources of aluminosilicate that reacts with a high alkaline solution to form geopolymers.

Table 3 Chemical composition of bagasse ash and concrete residue

Chemical compound (%)	Bagasse ash	Concrete residue
SiO_2	53.5	23.1
Al_2O_3	4.55	6.70
CaO	3.39	32.0
K_2O	2.78	0.440
MgO	1.50	2.22
Fe_2O_3	1.40	3.41
P_2O_5	1.02	0.0796
SO_3	0.550	1.98
Cl	0.247	0.226
TiO_2	0.209	0.323
Na_2O	0.166	0.285

In determining particle size distribution, the results showed that the particle size of the bagasse ash ranged from 6 to 81 μm and the particle size of the concrete residue ranged from 2 to 55 μm. The specific surface areas of the bagasse ash and the concrete residue were 161.8 m^2/kg and 327.5 m^2/kg, respectively. It was observed that the median value of the particle size distribution for concrete residue was lower than that for bagasse ash, and the specific surface area of the concrete residue was higher than that of bagasse ash. In geopolymerization, the particle size of raw materials is important; the smaller the particle size, the larger the surface area, which means small particle sizes enable greater reaction than large particle sizes with small surface area (Anchaleerat, 2014).

2. Characterization of geopolymer bricks

2.1 Physical and mechanical properties

The characteristics of the geopolymer bricks from each batch including general appearance, compressive strength and water absorption as per the TIS168-2546 specification were tested as follows:

1) General appearance

The general appearance of the geopolymer bricks is shown in Figure 1. It can be seen that the geopolymer bricks from every batch were black, with a smooth surface. No cracks were found in any of the batches of geopolymer bricks, hence this material could meet the requirements of TIS-168 2546.

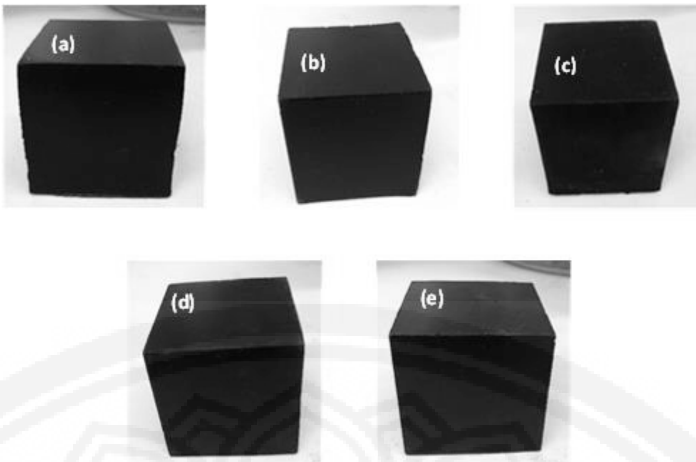

Figure 1 General appearance of geopolymer bricks: (a) BA100 (b) BA90CR10 (c) BA80CR20 (d) BA70CR30 (e) BA60CR40

2) Water absorption

The water absorption of the geopolymer bricks could not be tested according to the TIS168-2546 specification because the structure of the geopolymer bricks was destroyed in the process of drying samples; thus, the normal weight of the geopolymer bricks was used as a dried weight to calculate water absorption. As shown in Figure 2, it was observed that water absorption decreased when concrete residue was added. A statistical one-way analysis of variance (ANOVA) was conducted to compare the effects of different amounts of concrete residue on water absorption. The results found that the amount of concrete residue had a significant effect on water absorption at a level of significance of 0.05 ($p<0.0005$, $N=25$). Water absorption is an indirect indicator of open porosity (Eliche-Quesada, 2015) and the pore network of brick (Aponte, 2015). Thus, the addition of concrete residue significantly decreased the open porosity because concrete residue has a small particle size, which enables it to act as a filler in the pores and, consequently, results in a denser structure for the geopolymer bricks (Ahmari & Zhang, 2013). In addition, the surface area of concrete residue is higher than that for bagasse ash; for this reason, it is thought that when dissolution takes place, concrete residue will be more reactive (Yip, Lukey & Deventer, 2005), leading to a more compacted structure.

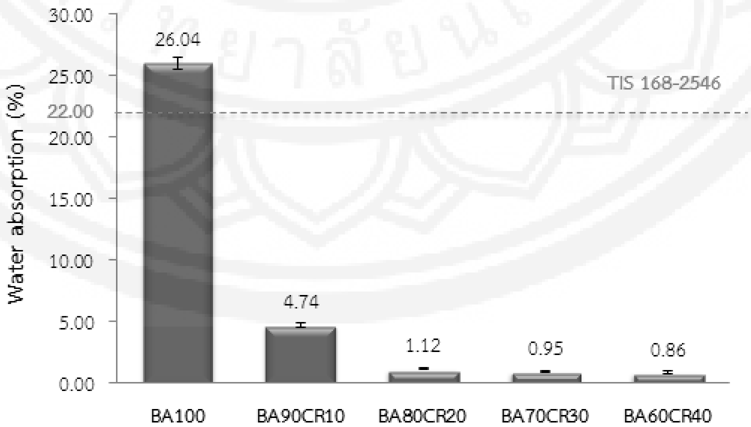

Figure 2 Water absorption of geopolymer bricks

The highest water absorption was observed in geopolymer bricks without concrete residue. This can be explained by the large particle size and low surface area of bagasse ash, which causes lower reactivity and a less-compacted structure for geopolymer bricks. According to the TIS 168-2546 specification, the standard for water absorption should be less than 22%. The results of this study showed that geopolymer bricks with concrete residue could meet this requirement but geopolymer bricks with 100% bagasse ash could not meet this requirement.

3) Compressive strength

The compressive strength of geopolymer bricks could not be tested as per the TIS168-2546 specification because the brick structure was destroyed in the process of drying samples; thus, the geopolymer bricks were tested without drying. The compressive strength of geopolymer bricks is shown in Figure 3. The maximum compressive strength was obtained in BA60CR40 (60% bagasse ash and 40% concrete residue). An increasing trend of compressive strength was observed with an increased proportion of concrete residue. A statistical one-way analysis of variance (ANOVA) was conducted to compare the effect of different amounts of concrete residue on compressive strength. The results found that the amount of concrete residue had a significant effect on the compressive strength at a level of significance of 0.05 ($p<0.0005$, $N=25$). The increased compressive strength can be explained by considering the behavior of calcium (Ca) in the concrete residue. First, Ca can form a calcium silicate hydrate (CSH) gel that coexists with a geopolymer gel and helps to bridge the gaps between the different hydrated phases and unreacted particles (Yip, Lukey, & Deventer, 2005; Ahmari et al., 2012); a CSH gel acts like a micro-aggregate for the geopolymer gel, enabling it to form a denser and more uniform binder (Kim, 2012). Second, Ca can be bonded in a geopolymer network by acting as a charge-balancing cation (Guo et al., 2010; Ahmari et al., 2012; Ahmari & Zhang, 2013). Another reason for the improved compressive strength was due to the silica and alumina in concrete residue that act as additional sources of aluminosilicate, which is conducive to the formation of a geopolymer gel (Ahmari & Zhang, 2013). Moreover, concrete residue has a small particle size that can fill small pores, react to the alkaline solution and support to form a denser structure for geopolymer bricks. However, the addition of concrete residue to enhance compressive strength in bagasse ash-based geopolymer bricks was still not effective enough to produce adequate compressive strength, which its standard value should be above 17 MPa according to TIS168-2546. The results showed that all batches of the geopolymer bricks could not meet this requirement.

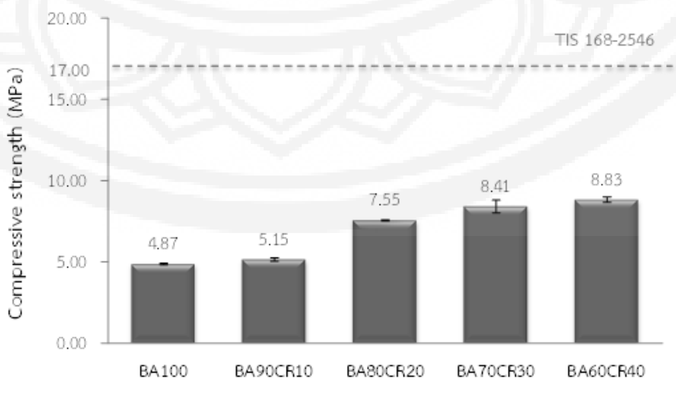

Figure 3 Compressive strength of geopolymer bricks

2.2 Microstructure

Figure 4 shows representative scanning electron micrographs of the geopolymer bricks. Geopolymer bricks of 100% bagasse ash were not compacted and featured a hollow microstructure due to the unreacted bagasse ash particles embedded in the structure; consequently, these bricks showed low compressive strength and high water absorption. It was observed that the addition of concrete residue improved homogeneity of geopolymer bricks leading to the increase of compressive strength as seen in the previous results.

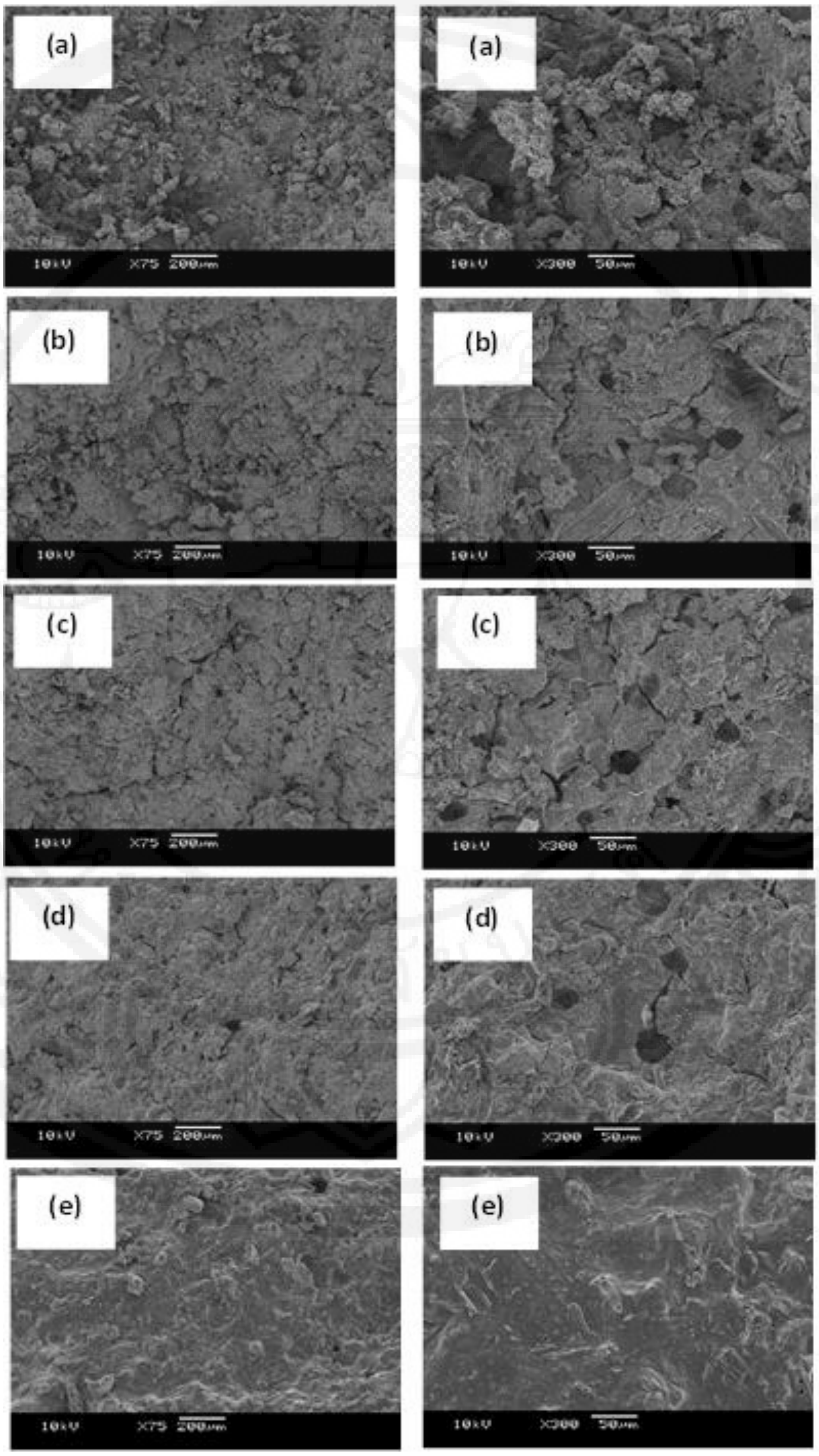

Figure 4 Scanning electron micrographs of geopolymer bricks at 75x and 300x: (a) BA100 (b) BA90CR10 (c) BA80CR20 (d) BA70CR30 (e) BA60CR40

2.3 Mineralogical phases

The XRD patterns of the geopolymer bricks are presented in Figure 5. The amorphous hump extending from about 20° (2θ) to 40° (2θ) was observed in all batches of the geopolymer bricks and is characteristic of a geopolymer gel (Ahmari et al., 2012; Anchaleerat, 2014). The hump was more pronounced in 40% concrete residue, indicating that the geopolymer content is higher. It can be seen that the high intensity of quartz (SiO_2) was due to the unreacted bagasse ash particles in the geopolymer structure. A CSH gel is characterized by three diffraction peaks at 3.04, 2.79 and 1.82 Å, respectively (Lecomte et al., 2006; Ahmari et al., 2012). One peak of CSH gel was found in 0% and 10% concrete residue, and two peaks were found in 20%, 30% and 40% concrete residue, with the peaks appearing more intense as the amount of concrete residue increased.

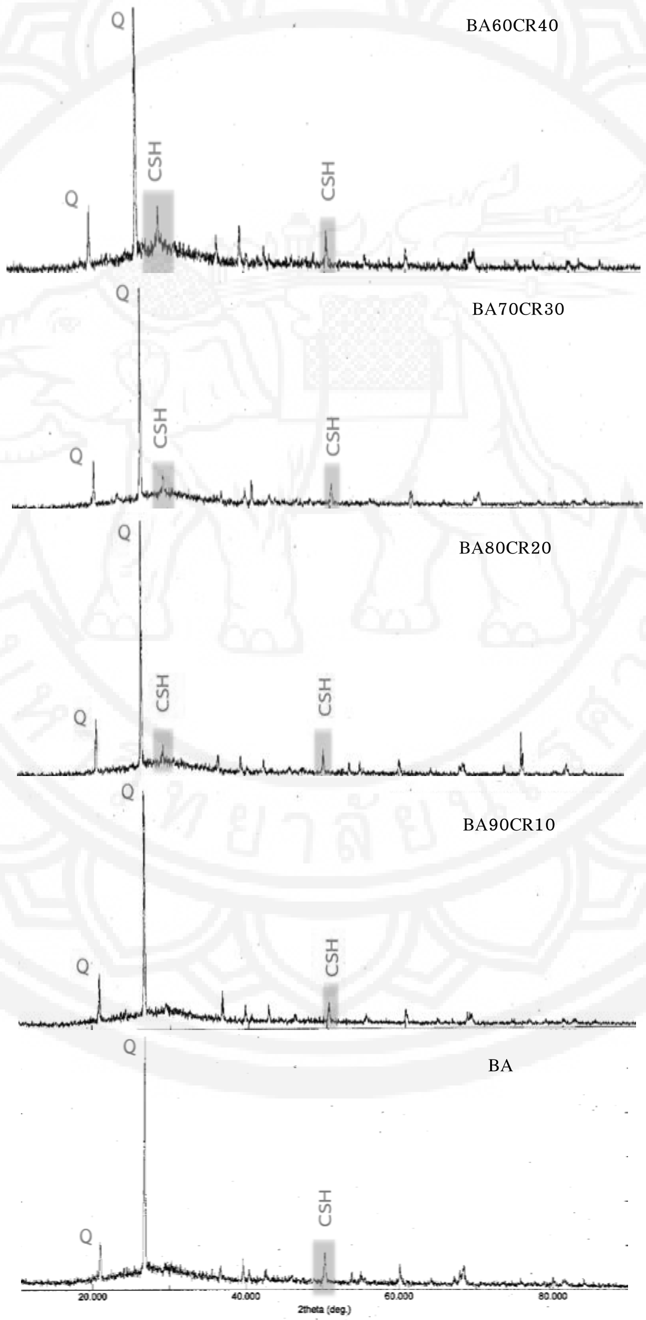

Figure 5 X-ray diffraction pattern

Conclusion and Suggestion

This study focused on the feasibility of producing geopolymer bricks from bagasse ash and concrete residue. From the experimental results and discussion of this study, the conclusion shows that bagasse ash from the Thai Multi-Sugar Industry Co., Ltd., sugar refinery in Kanchanaburi Province, Thailand, and concrete residue from the Tratmunkong Construction Materials Co., Ltd., concrete production plant in Trat Province, Thailand, could be used as raw materials for geopolymer brick production because both materials contain silica and alumina, which are important sources of aluminosilicate for geopolymerization. The addition of greater amounts of concrete residue resulted in significant improvements of water absorption and compressive strength for bagasse ash-based geopolymer bricks. The maximum compressive strength and the minimum water absorption were found in geopolymer bricks made with 40% concrete residue. This requires further study to increase the compressive strength in order to make these geopolymer bricks from bagasse ash and concrete residue more efficient and meet the TIS standard.

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References

Ahmari, S., Ren, X., Toufigh, V., & Zhang, L. (2012). Production of geopolymeric binder from blended waste concrete powder and fly ash. *Construction and Building Materials*, *35*, 718-729.

Ahmari, S., & Zhang, L. (2013). Utilization of cement kiln dust (CKD) to enhance mine tailings-based geopolymer bricks. *Construction and Building Materials*, *40*, 1002-1011.

Anchaleerat, A. (2014). *Synthesis and characterization of metakaolin based geopolymer from narathiwat and prachin clays.* (Master's Thesis). Chulalongkorn University, Bangkok.

Aponte, C. (2015). *Decreasing Water Absorption in and Environmental Analysis of Alkali Activated Bricks*. (Bachelor's Thesis). Massachusetts Institute of Technology, U.S.A.

Castaldelli, V. N., Akasaki, J. L., Melges, J. L., Tashima, M. M., Soriano, L., Borrachero, M. V., ... Payá, J. (2013). Use of slag/sugar cane bagasse ash (SCBA) blends in the production of alkali-activated materials. *Materials*, *6*(8), 3108-3127.

Castaldelli, V. N., Tashima, M. M., Melges, J. L. P., Akasaki, J. L., Monzó, J., Borrachero, M. V., ... Payá, J. (2014). Preliminary Studies on the use of Sugar Cane Bagasse Ash (SCBA) in the Manufacture of Alkali Activated Binders. *Key Engineering Materials* *600*, 689-698.

Department of industrial works. (2015). Industrial waste management plan 2015-2019. Retrieved from http://www2.diw.go.th/iwmb/

Eliche-Quesada, D. (2015). Reusing of Oil Industry Waste as Secondary Material in Clay Bricks. *Journal of Mineral, Metal and Material Engineering*, *1*, 29-39.

Guo, X., Shi, H., Chen, L., & Dick, W. A. (2010). Alkali-activated complex binders from class C fly ash and Ca-containing admixtures. *Journal of Hazardous Materials*, *173*(1), 480-486.

Jaturapitakkul, C. (2015). Industrial ash: good pozzolan material for concrete work. *TCA e-magazine*, *26*, 1-11.

Kim, E. H. (2012). *Understanding effects of silicon/aluminum ratio and calcium hydroxide on chemical composition, nanostructure and compressive strength for metakaolin geopolymers*. (Master's Thesis). University of Illinois at Urbana-Champaign, U.S.A.

Lecomte, I., Henrist, C., Liégeois, M., Maseri, F., Rulmont, A., & Cloots, R. (2006). (Micro)-structural comparison between geopolymers, alkali-activated slag cement and Portland cement. *Journal of the European Ceramic Society*, *26*, 3789-3797.

Lin, W. T., Ho, H. L., Cheng, A., Huang, R., & Huang, C. C. (2012). Using Sugarcane Bagasse Ash as Partial Cement Replacement in Cement-Based Composites. *Advanced Science Letters*, *13*(1), 762-767.

Rukzon, S., & Ngenprom, N. (2010). The Development of Risk husk ash and Bagasse Ash based geopolymeric materials. Retrieved from http://repository.rmutp.ac.th/handle/123456789/838

Rukzon, S., & Chindapras, P. (2014). Strength and Porosity of Bagasse Ash-based Geopolymer Mortar. *Journal of applied sciences*, *14*, 586-591.

Somna, K. (2014). Durability of Biomass Based Geopolymer. Retrieved from http://ir.rmuti.ac.th/xmlui/handle/123456789/400

Thai Industrial Standard Institute. (2004). *Facing bricks 168-2546*. Bangkok: Ministry of Industry Thailand.

Tippayasam, C., Boonsalee, S., Sajjavanich, S., Ponzoni, C., Kamseu, E., & Chaysuwan, D. (2010). Geopolymer development by powders of metakaolin and wastes in Thailand. *Advances in Science and Technology*, *69*, 63-68.

Tippayasam, C., Leonelli, C., & Chaysuwan, D. (2014). Effect of agricultural wastes with fly ash on strength of geopolymers. *Suranaree J. Sci. Technol*, *21*(1), 1-7.

Yip, C. K., Lukey, G. C., & Van Deventer, J. S. J. (2005). The coexistence of geopolymeric gel and calcium silicate hydrate at the early stage of alkaline activation. *Cement and Concrete Research*, *35*(9), 1688-1697.

Zhang, L. (2013). Production of bricks from waste materials-A review. *Construction and building materials*, *47*, 643-655.