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Article

The Utilization of Concrete Residue with Electric Arc Furnace Slag in the Production of Geopolymer Bricks

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Abstract. The purpose of this study was to investigate the ratio of concrete residue (CR) and electric arc furnace slag (EAF) for the production of facing brick according to Thai Industrial Standard (TIS) 168-2546. These two industrial wastes contain high alumina and silica for the production of geopolymer bricks. In this research, CR and EAF were collected and homogenously mixed at the following CR to EAF ratios: 100:0, 90:10, 80:20, 70:30, and 60:40, with sodium hydroxide (10M NaOH) and sodium silicate (Na_2SiO_3) solutions as catalysts. The ratio of Na_2SiO_3 to 10M NaOH was 2.5. The mixtures were poured in molds (5 cm x 5 cm x 5 cm) and cured in plastic film at room temperature for 28 days. Then the mechanical and chemical properties of the brick specimens were analyzed, including dimensions and tolerances, wryness, deviation from right angles, water absorption, compressive strength, stains, holes, rails, and cracks, according to TIS 168-2546. The results showed that the optimum CR to EAF ratio of geopolymer bricks that was compliant to the TIS 168-2546 standard was 80:20, which had the highest compressive strength value (17.04 MPa) and the lowest water absorption (0.69%). Therefore, CR and EAF can be used as raw materials for facing bricks production.

Keywords: Electric arc furnace slag, concrete residue, geopolymer brick, economical feasibility.

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1. Introduction

Approximately 1.5 billion tons of CO_2, accounting for 5% of the total manmade CO_2 emission worldwide, has been annually emitted by the production of Portland cement clinker from cement production plants [1-4]. Various studies have been developed in an attempt to pursue environmental friendly alternative cementitious materials named geopolymers [3-11]. Geopolymer is a binding material formed by the reaction of an aluminosilicate compound with a strong alkaline solution, which undergo geopolymerization to develop a three-dimensional amorphous aluminosilicate network with high compressive strength [3-4, 12]. Concrete residue (CR) is the waste that remains after cleaning concrete production equipment, in this case, at Tratmunkong Construction Materials Co., Ltd. in the Trat province of Thailand. A high amount of CR has been generated and disposed at the dump site. The CR has major compounds including SiO_2 40.1%, CaO 20.6%, and Al_2O_3 9.6%. Ahmari et al. [13] showed that the presence of calcium (Ca) compounds in the raw material can enhance the mechanical properties of geopolymers. The CA compounds have the ability to balance the charge cations in the formation of the calcium silicate hydrate (CSH) gel or geopolymer gel [12–13]. Sirikingkaew and Supakata [14] found that the utilization of CR with fly ash is suitable for brick production, as required by the TIS 168–2546 standard [15].

Slag is formed during the production of molten steel from scrap metal in an electric arc furnace (EAF). The scrap metal is melted along with lime in refractory lined vessels. Injected carbon in the molten steel is removed as carbon dioxide, contributing to the foamy slag. Subsequently, silicon (Si) and other remaining impurities in the scrap metal combine with the added lime and injected oxygen (O) to form the slag layer on top of the molten steel. Then, at the completion of the melting in the EAF section, the slag is discharged and dumped in landfills [16]. It is estimated that approximately 10–15 wt. % of EAF slag is generated per ton of molten steel, leading to a huge amount of the slag to be disposed of each year. Considering the limitations of landfills, recycling the EAF slag waste as a green raw material for valuable products is the most desirable and environment-friendly solution to properly manage the slag.

Yi et al. [17] proposed that recycling the EAF slag into various construction and building materials, including aggregate, brick, ceramic tile, and cementing material. The results showed that adding EAF slag can increase the compressive strength of geopolymers due to fact that the CaO from the EAF slag forms an aluminosilicate network that includes a CSH structure in geopolymers [18].

To manage the solid waste from industrial sectors, EAF slag and CR are used to produce geopolymer brick. The aim of this study was to investigate the physical and chemical properties and microstructure of geopolymer bricks produced from the mixture of EAF slag and CR and their compliance with TIS 168-2546 specifications. The finding of this research should help facilitate the development of high-strength geopolymer brick using EAF slag and CR as Si, Al, and Ca sources at ambient temperatures.

2. Materials and Methods

2.1. Materials

The EAF slag used in this study was obtained from the Siam Yamato Steel Co., Ltd. in the Rayong province of Thailand. The CR was collected from a concrete production plant at Tratmunkong Construction Materials Co., Ltd., in the Trat province of Thailand. CR is the waste that remains after cleaning the equipment for concrete production originally prepared from Portland cement type I 12.5%, sand 37.5%, coarse aggregate 45.8%, and water 4.2%.

Before using the raw materials, they were crushed in a ball mill for 30 minutes, and the particles were screened for size by a laser analyzer. The EAF slag was passed through a No. 100 sieve with a diameter of 150 micrometers. The CR was sundried and passed through a No. 200 sieve with a diameter of 75 micrometers.

2.2. Preparation of Alkaline Solution

A grade of sodium silicate (Na_2SiO_3) in liquid form was obtained from the chemicals industry with 14.25% of Na_2O, 31.25% of SiO_2, and 54.50% of water by weight. The sodium hydroxide (NaOH) had 98% purity. Distilled water was used to prepare the NaOH solution with the required concentration of 10 mol/L and then was cooled down to room temperature.

The ratio of Na_2SiO_3: NaOH was 2.5 [19]. The alkaline solution was prepared for 24 hours and cooled down to room temperature before use.

2.3. Characterization of Electric Arc Furnace (EAF) Slag and Concrete Residue (CR)

The chemical composition of the EAF slag and CR was analyzed by using an X-ray fluorescence spectrometer (Bruker model S8 Tiger). The particle size of the EAF slag and CR was investigated by using a laser particle distribution analyzer (Malvern Mastersizer 3000). The patterns of the EAF slag and CR were analyzed by X-ray diffraction (D8-Discover). The Infrared spectra of the EAF slag and CR were analyzed by a Fourier Transform Infrared Spectrometer (Perkin Elmer, Spectrum One). A microstructure characterization of the materials was identified by using a scanning electron microscope (Jeol JSM-6480LV).

2.4. Preparation of Geopolymer Formulations

The geopolymer formulations of the EAF slag and CR were prepared in the proportions shown in Table 1 and then mixed.

Table 1. The proportions of the formulation mixtures (wt. %).

Name	**Electric arc furnace (EAF) slag (wt. %)**	**Concrete residue (CR) (wt. %)**
CR100	0	100
EAF10CR90	10	90
EAF20CR80	20	80
EAF30CR70	30	70
EAF40CR60	40	60

2.5. Preparation of Geopolymer Bricks

The geopolymer bricks were prepared by mixing the EAF slag and CR, as shown in Table 1, with the alkaline solution. The weight ratio of the alkaline solution to the mixed powder was fixed at 0.90 for all formulations by shaking for 10 minutes. Then, the geopolymer paste was poured into 5×5×5 cm^3 acrylic molds. In another step, the mixtures were homogenously mixed by using a vibration machine for 1 minute. The geopolymer specimens were wrapped with plastic film for 24 hours to protect them from moisture loss. Finally, after 24 hours, the specimens were removed from the acrylic molds and were cured at room temperature for 28 days.

2.6. Characterization of Geopolymer Bricks

The physical properties of the geopolymer bricks, including dimensional tolerances, general appearance, wryness, deviation from the right angle, compressive strength, water absorption, stains, holes, rails, and cracks, were determined according to Thai Industrial Standard (TIS) 168-2546 specifications. A microstructure characterization of the geopolymer bricks was identified by using a scanning electron microscope (Jeol JSM-6480LV). The mineralogical phases of the geopolymer bricks were identified by using an X-ray diffractrometer (XRD, D8- Discover). The infrared spectra of the geopolymer bricks were analyzed by a Fourier Transform Infrared Spectrometer (Perkin Elmer, Spectrum One).

2.7. Statistical Analysis

The mean and standard deviation of the data were calculated using Microsoft Excel.

2.8. Economical Feasibility

An economics analysis of the production of geopolymer bricks from the EFA slag and CR (with an optimal ratio of 20:80) was evaluated using the following equations.

The break even volume (N*)

$$N* = \frac{F}{P-V}, \quad (1)$$

where

N* is the break even volume
F is the fixed cost, Baht
P is the price per unit, Baht/unit
V is the variable cost, Baht

The payback period

$$\text{Payback period} = \frac{N*}{N}, \quad (2)$$

where

N* is the break even volume
N is the productivity yield/year

The data for fixed cost and variable cost are shown in Table 2.

Table 2. Data of fixed cost and variable cost.

Type		Cost	Source
Industrial wastes	Concrete residue	0 Baht/kg	Tratmunkong Co., Ltd., Trat
	Electric arc furnace slag	0 Baht/kg	Siam Yamato Steel Co., Ltd., Rayong
Chemicals	Sodium silicate (Na_2SiO_3)	50 Baht/kg	Roongsub Chemical Ltd.,Part., Bangkok
	Sodium hydroxide (NaOH)	300 Baht/kg	Roongsub Chemical Ltd.,Part., Bangkok
Machines	Los Angeles abrasion machine (Cooper technology Ltd.)	110,000 Baht/unit	(Cooper Technology, 2017 : online)
	Aggregate vibration screen (Gilson Porta-Screen® PS-3F)	120,000 Baht/unit	(Gilson company, 2017 : online)
	Electric concrete pan mixer (JQ350)*	25,000 Baht/unit	(Alibaba, 2017 : online)
	Laboshake (C. Gerhardt GmbH & Co. KG)	18,000 Baht/unit	(C. Gerhardt GmbH & Co. KG, 2015 : online)
	Drying oven (BINDER BD/ED/FD)	46,000 Baht/unit	(Binder, 2017 : online)

The weight of geopolymer brick per unit was 0.025 kg.

3. Results and Discussion

3.1. Characterization of Electric Arc Furnace (EAF) Slag and Concrete Residue (CR)

The chemical composition of the CR and EAF slag was analyzed by using an X-ray fluorescence spectrometer (Bruker model S8 Tiger) as shown in Table 3. The results showed that the major components of CR were CaO and SiO_2, and Al_2O_3 was a minor components, while, Fe_2O_3, CaO, and SiO_2 were the major components of EAF, and Al_2O_3 was the minor component.

Table 3. The chemical composition of electric arc furnace (EAF) slag and concrete residue (CR).

Oxides	Concrete residue (CR) (wt. %)	Electric arc furnace slag (EAF) (wt. %)
SiO_2	24.70	13.20
Al_2O_3	6.65	6.17
Fe_2O_3	2.88	34.60
CaO	27.40	21.60
Na_2O	0.30	0.13
K_2O	0.44	-
TiO_2	0.29	0.57
MnO	-	5.77
MgO	1.96	3.75
SO_3	1.88	0.28
BaO	-	0.17
P_2O_5	0.01	0.34
Cr_2O_3	-	2.38
V_2O_5	-	0.13
Cl	0.24	-

The particle size of the CR and EAF slag were investigated by using a laser particle distribution analyzer (Malvern Mastersizer 3000). The results showed that the average particle size (d_{50}) of the CR and EAF were 19.8 and 85.8 microns, respectively, as shown in Fig. 1.

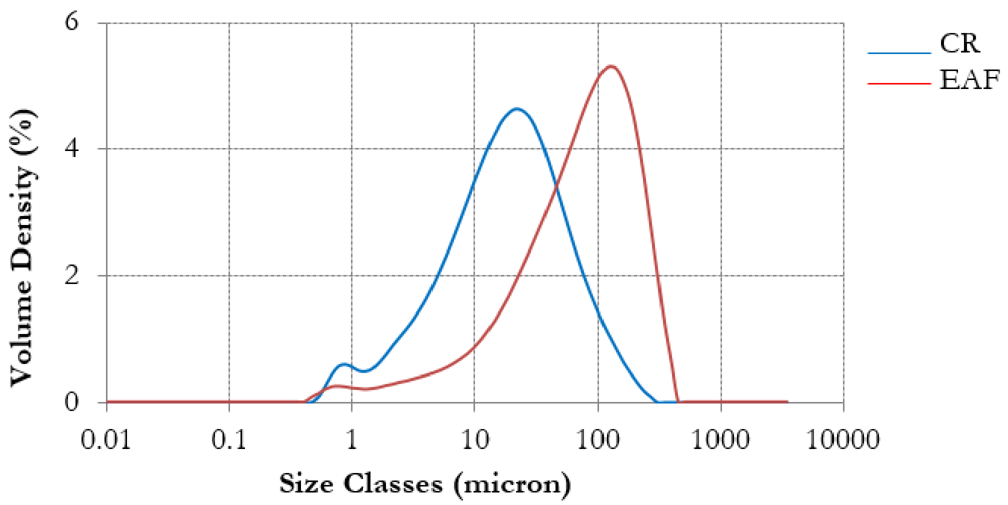


Fig. 1. The particle size of raw materials.

The X-ray diffraction patterns of the CR and EAF slag were analyzed (D8- Discover), and the results showed that the major crystalline phases of CR were quartz (SiO_2) and calcite ($Ca(CO_3)$) minerals, and the minor crystalline phases of the CR were ettringite ($Ca_6Al_2(SO_4)_3(OH)_{12}{\cdot}26H_2O$), magnesium aluminum hydroxide hydrate ($MgAl(OH)_{14}{\cdot}xH_2O$, and iron oxide chloride (FeOCl) minerals. In contrast, the major crystalline phases of the EAF were wustite (FeO) and fayalite ($Fe_2 + 2SiO_4$) minerals. Moreover, the minor crystalline phases were calcium iron oxide ($CaFe_2O_4$), bixbyite (Mn_2O_3), bredigite ($Ca_{14}Mg_2(SiO_4)_8$), and spinel ($MgAl_2O_4$) minerals.

The microstructure characterization and EDX microanalysis of the CR and EAF slag were identified by using a scanning electron microscope (Jeol JSM-6480LV). In Fig. 2, it can be observed that the microstructure of the CR particles was non-homogeneous, porous, and flaky, with a fibrous texture. Moreover, the spectrum of the CR consisted of Ca, Si, and O as the major elements, with a small amount of iron (Fe), aluminum (Al), and magnesium (Mg). The microstructure of the EAF particles had a stone-sharp morphology and was less porous. The spectra of EAF consisted of Ca, Fe, and O (as a strong peak), with a trace of Si, Al, and Mg.

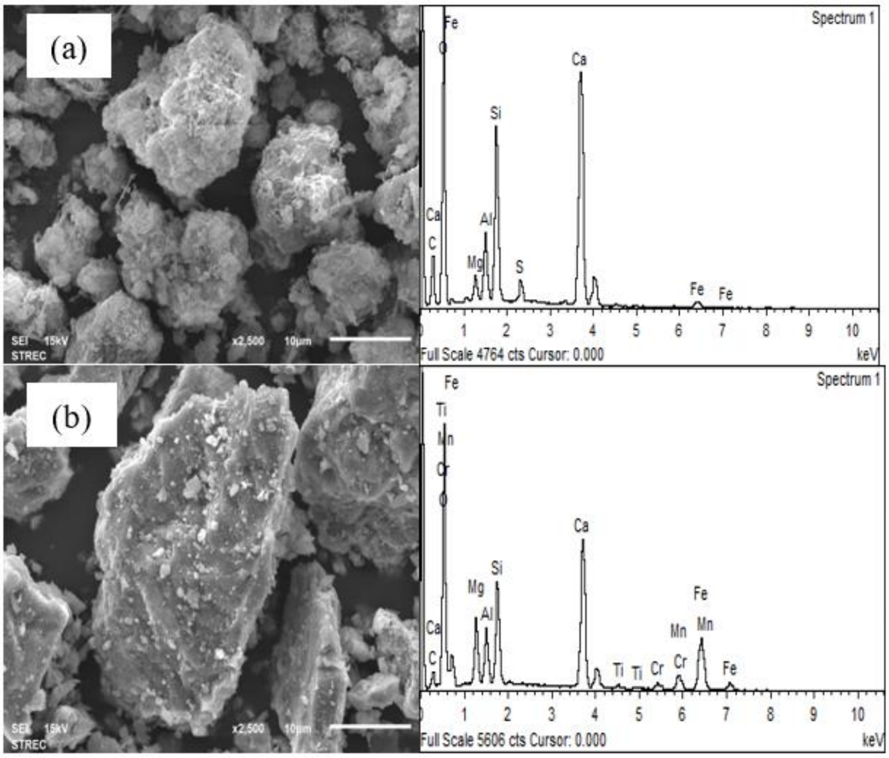


Fig. 2. The micro-structure characterization of raw materials (a) concrete residue (CR) and (b) electric arc furnace (EAF) slag.

3.2. Physical and Mechanical Properties of Geopolymer Bricks

The characteristics of geopolymer bricks of all series (CR100, CR90EAF10, CR80EAF20, CR70EAF30, and CR60EAF40), including general appearance, compressive strength, and water absorption, were compliant with TIS168-2546 specifications.

Figure 3 shows that all the geopolymer bricks had a gray and black color with smooth surfaces, except the CR that was produced from 100% CR, where some cracks were found.

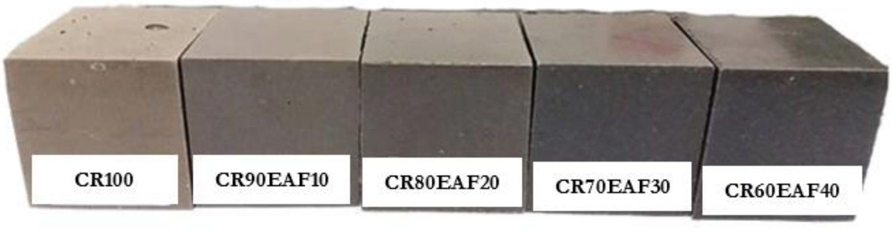


Fig. 3. The general appearance of geopolymer bricks.

The water absorption value of the geopolymer bricks, as shown in Fig. 4, followed TIS 168-2546, which should be lower than 22.0%. It can be observed that the water absorption of CR100, CR90EAF10, CR80EAF20, CR70EAF30, and CR60EAF40 were 0.96%, 0.83%, 0.69%, 1.23, and 1.35%, respectively, which were in compliance with TIS 168-2546. As expected, adding EAF slag in the geopolymer bricks led to a reduction in porosity and an increase in the strength by the formation of the geopolymer network [18]. Moreover, the CaO in the EAF slag formed CSHs with the aluminosilicate network in the geopolymer bricks [20]. The batches CR70EAF30 and CR60EAF40 showed increase values of water absorption due to high amounts of EAF slag, up to a 20% wt. increase CaO during the semi-crystalline phase, or the CSH gel-forming stage, causing porosity of the specimens.

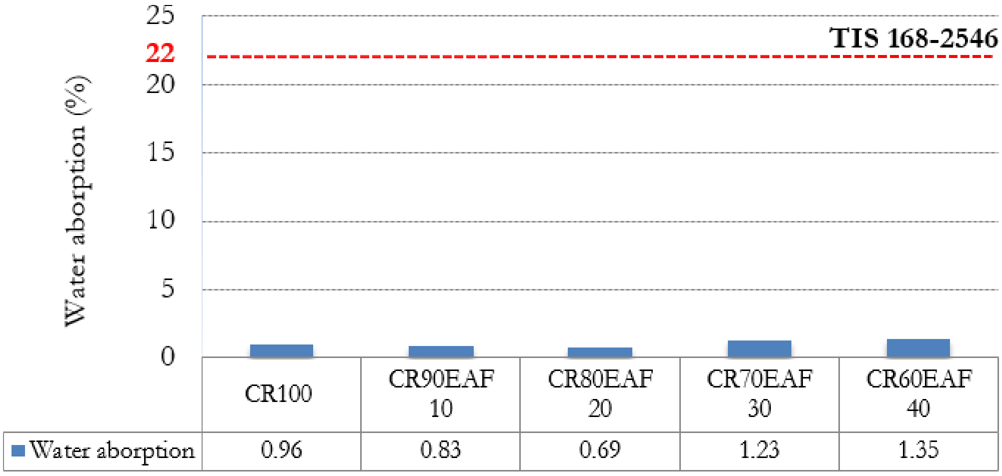


Fig. 4. The water absorption of geopolymer bricks.

The compressive strength of the geopolymer bricks, as shown in Fig. 5, follows TIS 168-2546, in which the value of compressive strength should be higher than 17.0 MPa. It can be observed that the compressive strength values of CR100, CR90EAF10, CR80EAF20, CR70EAF30, and CR60EAF40 were 12.27, 15.06, 17.04, 12.18, and 10.76 MPa, respectively, so CR80EAF20 was the only one that was compliant with TIS 168-2546. As expected, adding CR and EAF slag to the geopolymer bricks led to decreased porosity and water absorption, affecting the compressive strength. It can be concluded that the compressive strength increased when the amount of EAF was increased, except for CR70EAF30 and CR60EAF40; their compressive strength decreased due to the appearance of spaces in the batch.

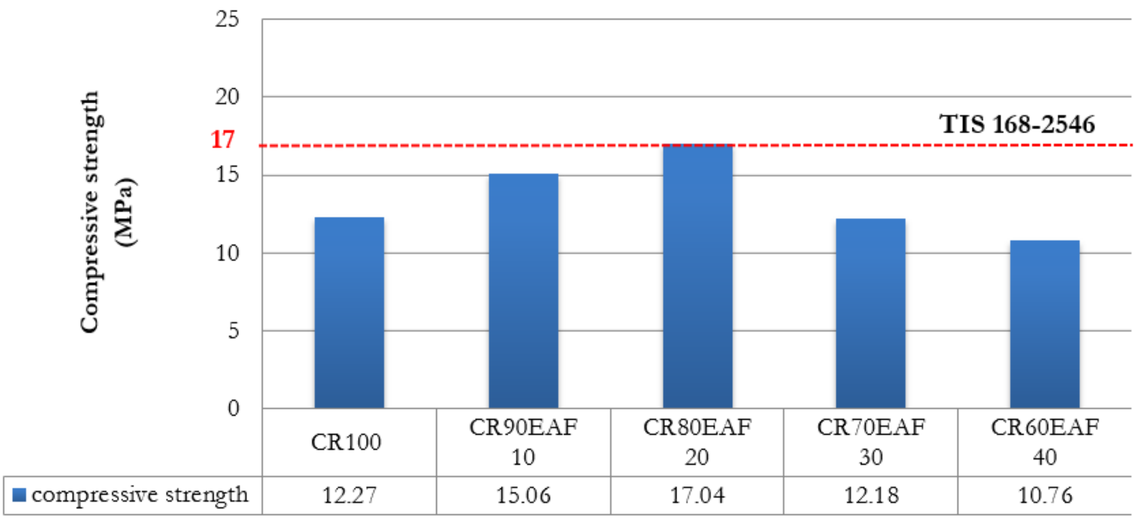


Fig. 5. The compressive strength of geopolymer bricks.

The microstructure characterization of the geopolymer bricks was identified by using a scanning electron microscope (Jeol JSM-6480LV). As shown in Fig. 6, the formation of a new phase of geopolymer appeared. Figure 6(c) showed that the geopolymer brick with 20% EAF slag (CR80EAF20) was more compact and less porous than the other batches.

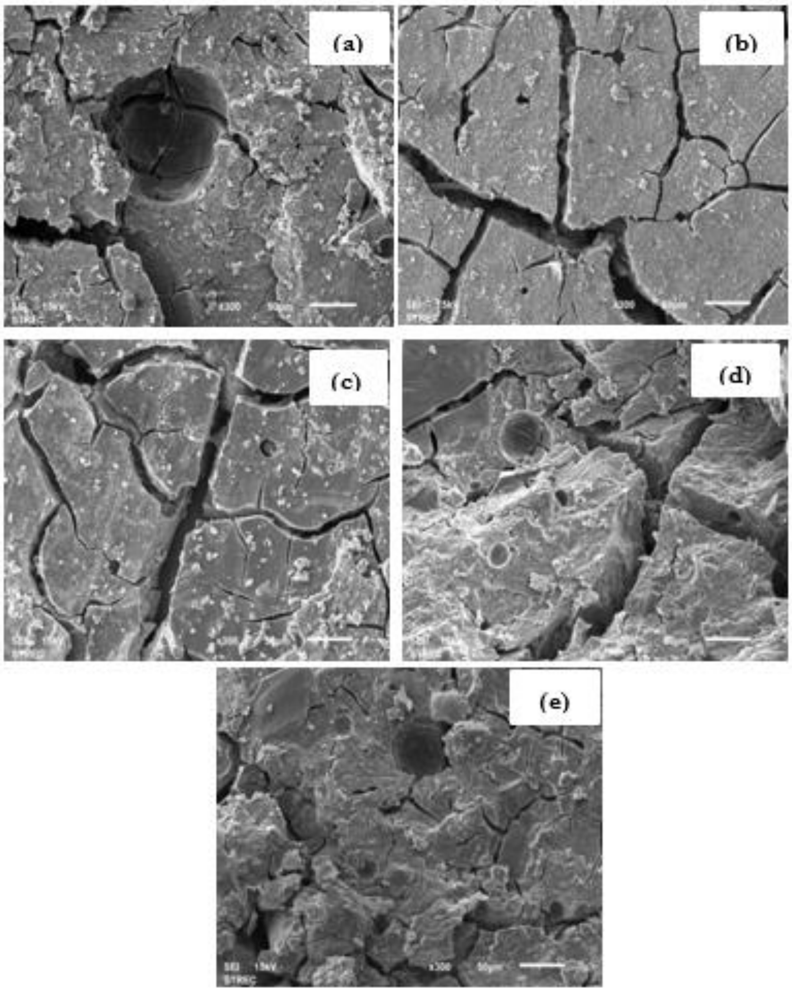
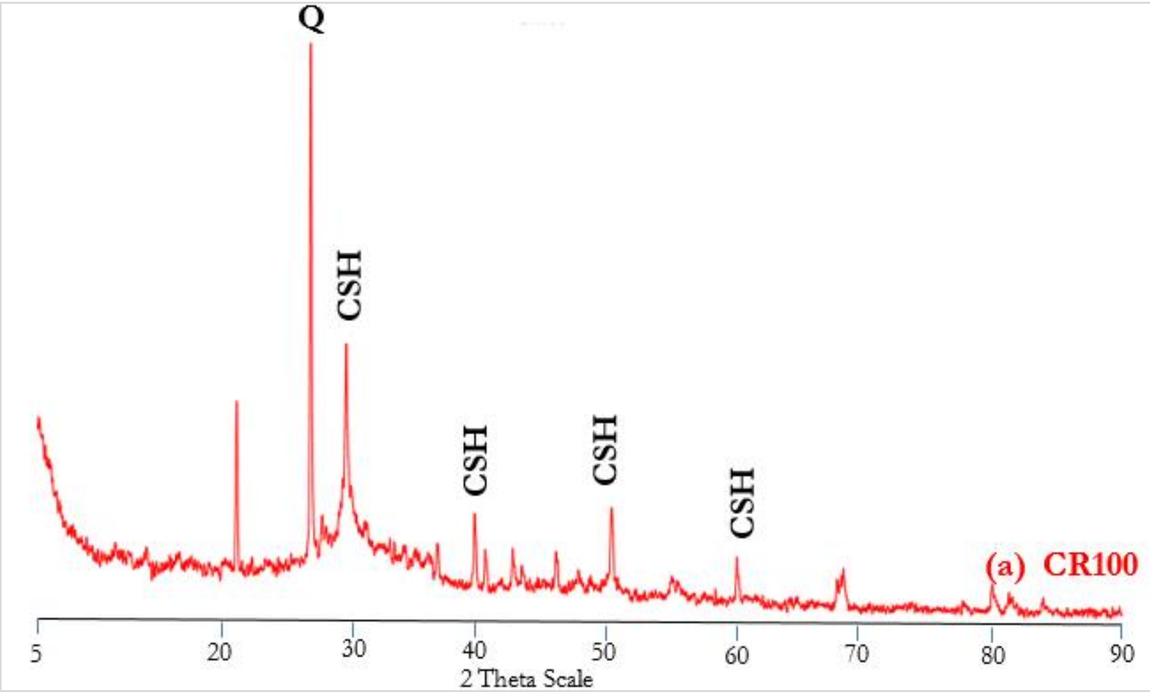
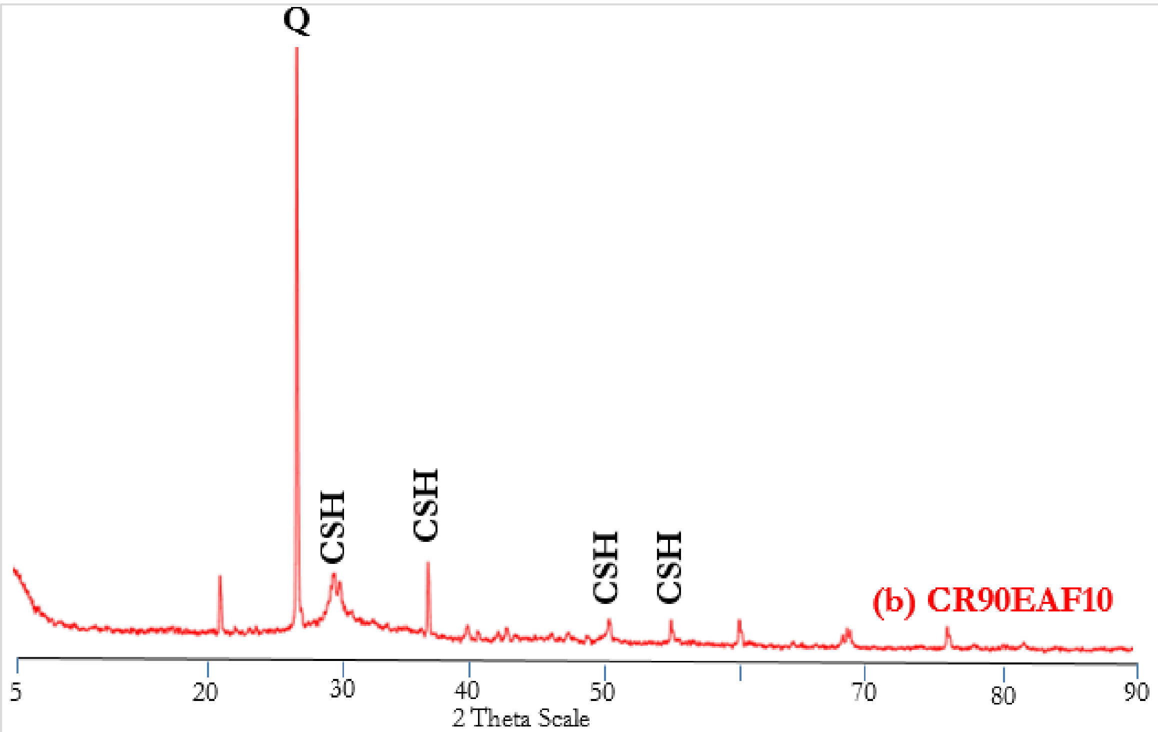
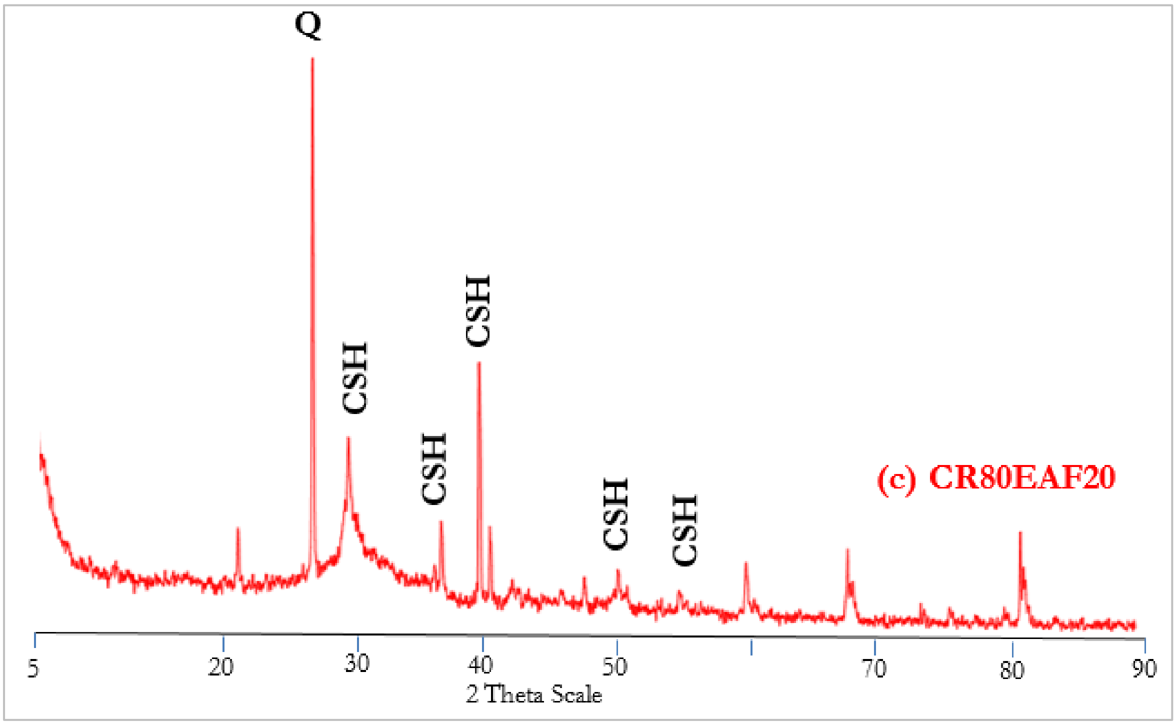


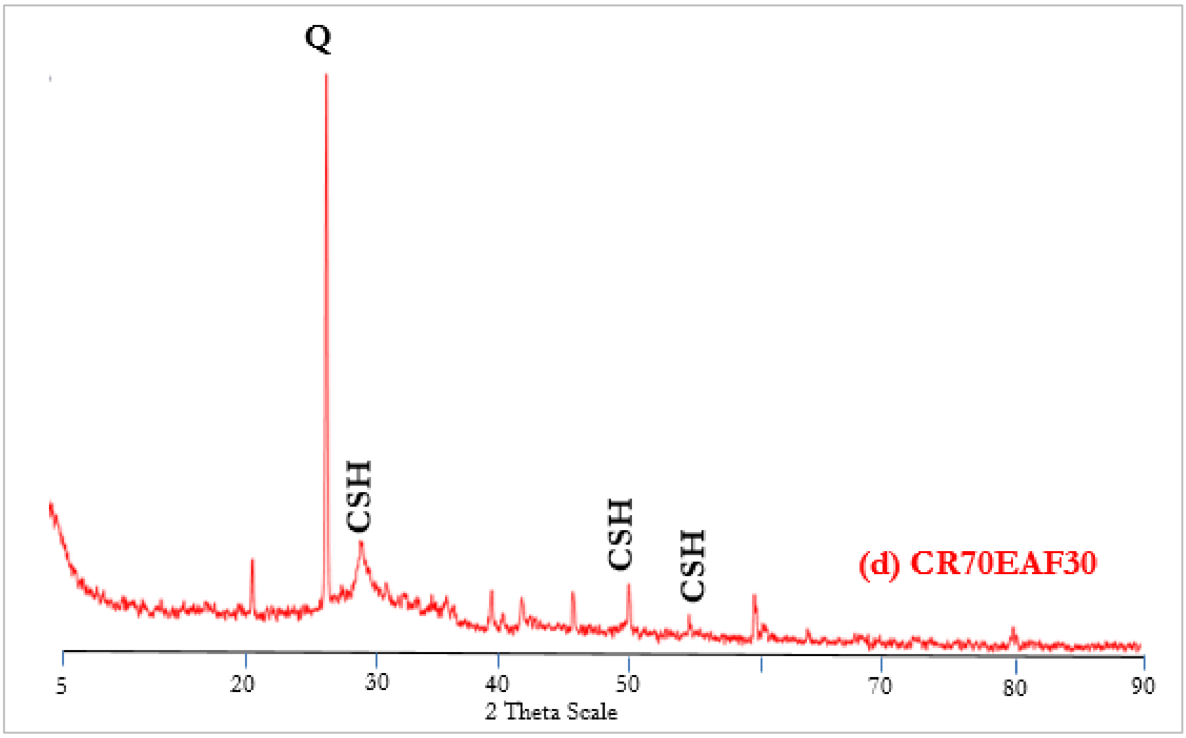
Fig. 6. The microstructure characterization of geopolymer bricks: (a) CR100, (b) CR90EAF10, (c) CR80EAF20, (d) CR70EAF30, and (e) CR60EAF40.

The mineralogical phases of geopolymer bricks were identified by using an X-ray Diffractrometer (XRD, D8- Discover). As shown in Fig. 7, quartz (SiO_2) (Q) was the major crystalline mineral phase caused by the effect of alkaline activation during the geopolymerization process. CSH phases were found at peaks of 29.2^o, 32.0^o, 42.7^o, 49.8^o, and 55.3^o [18], which were caused by sharing O atoms to develop a new form of three-dimensional amorphous aluminosilicate net. In the brick specimen CR80EAF20 with 80% CR and 20% EAF slag, this led to the new form of a CSH semi-crystalline phase and enhanced the compressive strength to a higher level than in the other batches.


Q
CSH
CSH
CSH
CSH
(a) CR100
5
20
30
40
50
60
70
80
90
2 Theta Scale


Q
CSH
CSH
CSH
CSH
(b) CR90EAF10
5
20
30
40
50
70
80
90
2 Theta Scale


Q
CSH
CSH
CSH
CSH
CSH
(c) CR80EAF20
5
20
30
40
50
70
80
90
2 Theta Scale


Q
CSH
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CSH
(d) CR70EAF30
5
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80
90
2 Theta Scale

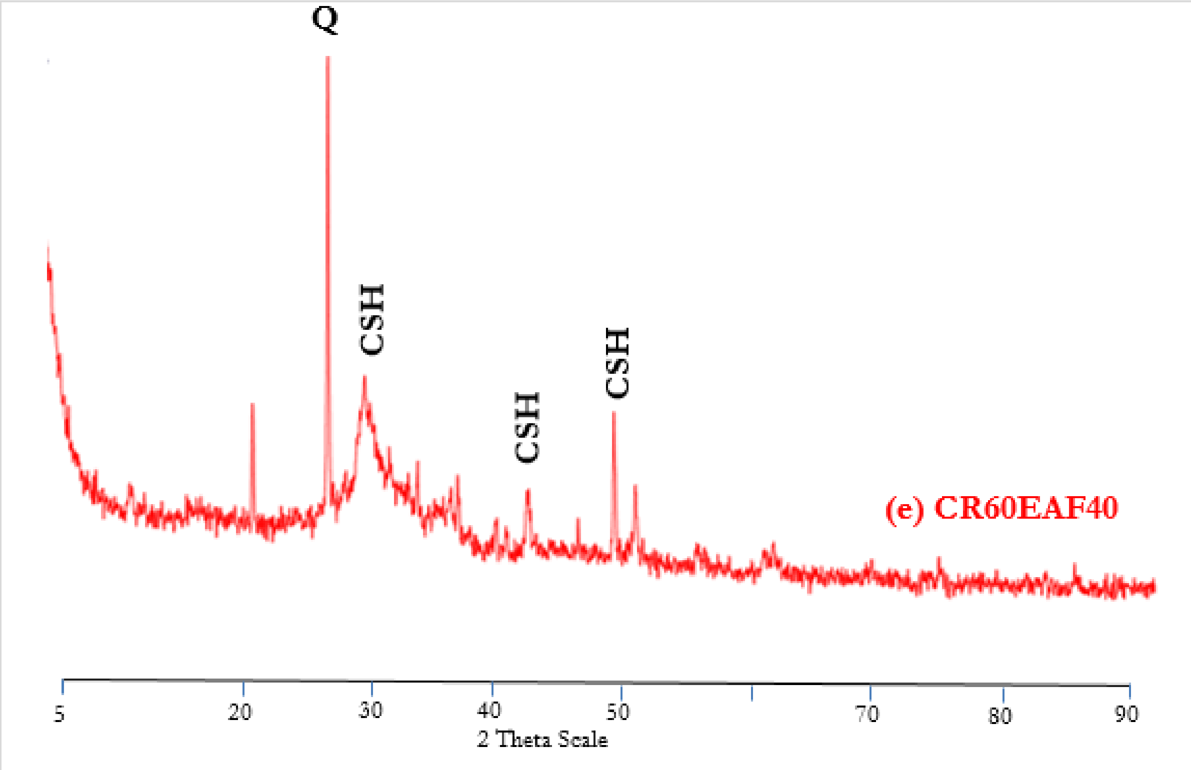

Fig. 7. The mineralogical phases of geopolymer bricks: (a) CR100, (b) CR90EAF10, (c) CR80EAF20, (d) CR70EAF30, and (e) CR60EAF40.

The infrared spectra of the geopolymer bricks were analyzed by a Fourier Transform Infrared Spectrometer (Perkin Elmer, Spectrum One). As shown in Fig. 8, the broad band of OH was found in the range of 3,460, and 1,650 cm^{-1} represented the reaction of water molecules in all the batches of geopolymer bricks. The bands at 1,424 and 1,455 cm^{-1} were caused by stretching vibrations of the O-C-O bond in the carbonate mineral (Fernandez and Palomo, 2005). In addition, the band at 975 cm^{-1} was Si-O-(Si or Al). These peaks were considered as markers of the geopolymer network during the geopolymerization process that formed the new amorphous aluminosilicate phase.

3.3. Economical Feasibility

An evaluation of the economical feasibility in terms of the break even volume (with N* indicating the point at which the total cost and total revenue are equal and the payback period, which is the length of time required to recover the cost), is presented in the Appendix. The results showed that for the geopolymer bricks made from EAF slag and CR, the CR to EAF optimal ratio was 20:80. The break even volume was 581,799 pieces, indicating the point at which total cost and total revenue are equal. The payback period was 3.91 years (47 months).

4. Conclusions

This study focused on the utilization of industrial waste for geopolymer brick production from CR and EAF slag. The geopolymerization for waste with a high alkaline solution of $NaOH/Na_2SiO_3$ was successful in producing geopolymer bricks. The following conclusions can be drawn:

1. Industrial waste consisting of CR and EAF slag can be used as raw materials for geopolymer brick production. Adding more or less than 20% wt. EAF slag will decrease the compressive strength of the bricks to lower than 17 MPa, which is the TIS 168-2546 standard.

2. The results showed that the dimensions and tolerance, wryness, deviation from the right angle, water absorption, holes, and rails of all batches of the geopolymer bricks were compliant with the requirements of the TIS 168-2546 standard. For compressive strength, only the geopolymer brick made from 80% CR and

20% EAF slag (CR80EAF20) was compliant with the standard. For stains and cracks, only CR100, the geopolymer brick made from 100% CR, was not compliant with the standard.

3. Geopolymer brick made from 80% CR and 20% EAF slag (CR80EAF20) obtained the highest compressive strength, with a value of 17.04 MPa.

4. Increasing the EAF slag up to 20% led to an increase in the porosity of the geopolymer bricks and reduced the compressive strength.

5. The break even volume was 581,799 pieces, and the payback period was 3.91 years (47 months).

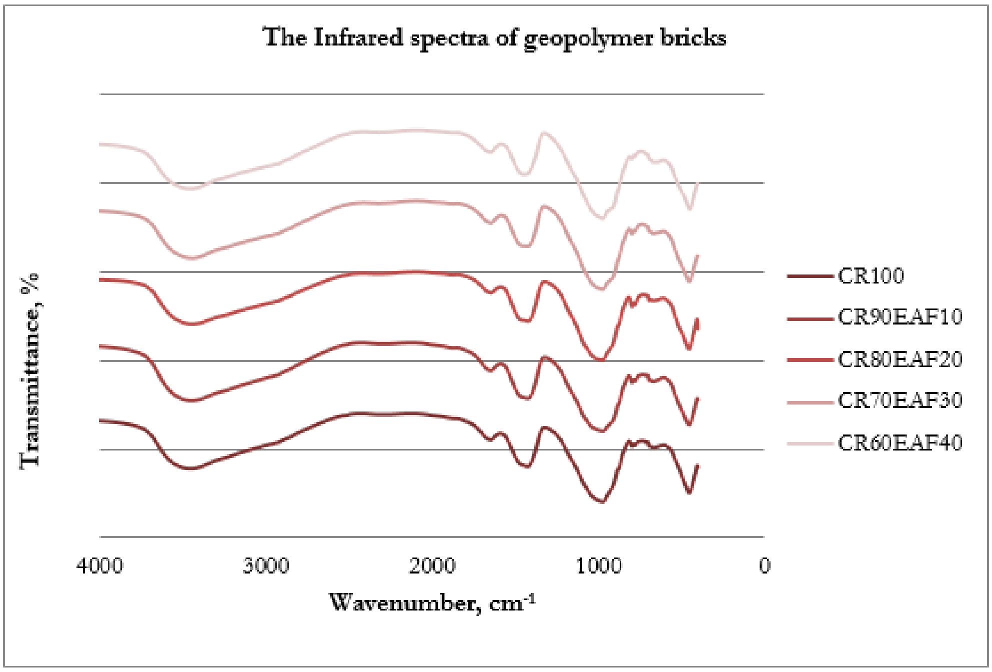

Fig. 8. The infrared spectra of geopolymer bricks.

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Appendix

The cost of geopolymer brick made from electric arc furnace (EAF) slag and concrete residue (CR).

The costs	Baht	The costs	Baht
Fixed cost		**Raw material capital**	
Drying oven	46,000 Baht	Production capacity	100 kg/day
Electric concrete pan mixer	25,000 Baht	Demand of industrial wastes/day	CR 80 kg
Los Angeles abrasion machine	110,000 Baht		EAF 20 kg
Aggregate vibrating screen Shaker	120,000 Baht	Demand of chemicals	Na_2SiO_3 64.25 kg
	18,000 Baht		NaOH 25.75 kg
Total	319,000 Baht	Industrial waste costs	CR 0 Baht/kg
			EAF 0 Baht/kg
		Chemical costs	Na_2SiO_3 50 Baht/kg
			NaOH 300 Baht/kg
		Total	350 Baht/kg
		Weight of geopolymer brick	0.025 kg/piece
		Amount of geopolymer brick	600 pieces
		Raw material capital/piece	0.583 Baht/piece
Transportation capital		**Variable expenses**	
Transportation costs	0.06 Baht/kg	Human labor	300 Baht/day
Demand of industrial wastes	CR 80 kg 4.8 Baht	Amount of geopolymer brick	600 pieces
	EAF 20 kg 1.2 Baht		
Demand of chemical	Na_2SiO_3 64.25 kg 3.86 Baht	Human labor/piece	0.5 Baht/piece
	NaOH 25.75 kg 1.55Baht		
Amount of geopolymer brick	600 pieces		
Total	11.4 Baht		
Transportation capital/piece	0.019 Baht/piece		
Other expenses		**Variable costs (V)**	
Electricity cost	0.1 Baht/kg	Raw material capital/piece	0.583 Baht/piece
Raw material	100 kg	Transportation capital/piece	0 .019 Baht/piece
Total	10 Baht	Human labor/piece	0.5 Baht/piece
Amount of geopolymer brick	600 pieces	Electricity cost/piece	0.0167 Baht/piece
Electricity cost/piece	0.0167 Baht/piece	Total	1.1187 Baht/piece
Productivity yield/year (N)		**Price/unit (P)**	
Working day	248 days/year	Facing brick cost	10 Baht
Productivity	600 pieces/day	Industrial waste1 kg	6 pieces
Productivity/year	148,800 piece/year	Facing brick/piece	1.667 Baht/piece
The break even volume (N*) $N* = \frac{F}{P-V}$	581,799 pieces	**The payback period** $\frac{N*}{N}$	3.91 years (47 months)