Utilizing high calcium fly ash in cementless precast concrete construction with emphasis on early mechanical strength

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Abstract

Precast concrete has been proven to help speed up many construction projects. Using Portland cement in precast concrete is continuing to put CO_2 emissions into the atmosphere from the production of Portland cement. Geopolymer concrete is produced from many types of agricultural and industrial waste in Thailand such as fly ash activated by alkaline solution; it is known as green concrete and can be used in precast concrete production and reduces the use of Portland cement. Geopolymer concrete produced from high calcium fly ash, sodium hydroxide and sodium silicate was used to study early strengths after it had been cured at 60°C for 24 hours. The average compressive strengths of all geopolymer concrete mixes after curing for 24 hours ranged from 29.68 to 38.48 MPa which were above the typical precast concrete release strength of 28 MPa. The average modulus of rupture was 120% higher than that calculated with the standard design code at the same compressive strength. The average bond strengths were in the range between 7.49 to 11.03 MPa.

Keywords: agricultural waste, industrial waste, early strength, geopolymer concrete

1. Introduction

Thailand is the world's second ranked rice exporter. According to the Thai Ministry of Agriculture, Thailand's rice production is expected to be 23.3 million tons in the 2016-2017 season (Rice Department, 2016). Other main agricultural productions in Thailand are sugar cane and palm oil. Thailand expects to harvest sugar cane and palm oil amounting to 9.5 million tones and 11.6 million tones, respectively (Moacoipalm, 2016; Office of Agricultural Economics, 2016). The sugar cane is mainly exported while palm oil is mainly used in food production. The solid waste from rice, sugar cane and palm oil can be burned and results in ashes which can be used to replace cement in many cement/concrete applications. Lignite coal fly ash and bottom ash are other waste products resulting from burning lignite coal to generate electricity at Mae Moh power plant in Lampang Province. Both types of ash can be used in many concrete applications, especially fly ash. Fly ash is a preferable cement replacement due to its fineness and it yields high mechanical properties when it replaces Portland cement. It has been shown by many researchers that these ashes have mechanical properties that are suitable for replacing Portland cement which is the greatest carbon dioxide (CO_2) emission generator in the world. High amounts of CO_2 emissions are caused by the high energy required during the calcination process and transportation of raw materials.

In an effort to reduce the growth of cement binder consumption, alternative binders such as geopolymer, which uses no Portland cement, have been researched and used. Geopolymer is a network of mineral molecules found in an inorganic material rich in silicon dioxide (SiO_2) and aluminium oxide (Al_2O_3) activated by high base solutions and cured at an elevated temperature (Davidovits, 2008). Fly ash is commonly used to produce geopolymer due to its availability around the world. Fly ash is classified as either class C or class F according to its chemical composition of Silica (Si), Alumina (Al) and Calcium (Ca). In Thailand, most of the fly ash is a by-product from the lignite coal-fired Mae Moh power station in Lampang Province. This fly ash contains a relatively high calcium oxide (Ca^{2+}) content, typically around 12-25% by weight compared to type F fly ash which typically contains less than 5% calcium. According to previous research, geopolymer paste and mortar produced from this fly ash exhibited good strength and durability (P. Chindaprasirt, Chareerat, Hatanaka, & Cao, 2010; P. Chindaprasirt, Chareerat, & Sirivivatnanon, 2007; Wongpa, Kiattikomol, Jaturapitakkul, & Chindaprasirt, 2010).

The high calcium fly ash-based geopolymer concrete (HCGC) has very low slump and a relatively short setting time due to the high content of Ca^{2+} (Topark-Ngarm, Chindaprasirt, & Sata, 2014). In general, geopolymer concrete gains strength more rapidly when cured at an elevated temperature compared to ambient temperature curing (P. Chindaprasirt et al., 2010; Prinya Chindaprasirt, De Silva, Sagoe-Crentsil, & Hanjitsuwan, 2012; Pangdaeng, Phoo-ngernkham, Sata, & Chindaprasirt, 2014; Rangan, Wallah, Sumajouw, & Hardjito, 2006). The combination between a short setting time and rapid strength gain could be beneficial in many engineering applications such as repair and precast concrete (Phoo-ngernkham, Chindaprasirt, Sata, Hanjitsuwan, & Hatanaka, 2014; Songpiriyakij, Pulngern, Pungpremtrakul, & Jaturapitakkul, 2011).

Precast concrete has been used in many construction projects worldwide such as bridges, high rise buildings and prefabricated houses. Using precast members, in many scenarios, has been known to save time and the cost of construction projects. Precast concrete is preferred over traditional cast-in-place concrete for higher quality control and tighter tolerances. Early strength development of concrete is a key factor in precast concrete production since precast concrete is typically released from formwork within 24 hours from the time of casting. The early strength is needed for the lifting, transporting or prestressing of precast concrete members. According to the Precast Concrete Institute (PCI) design manual (PCI MNL-120, 2010), typical 28-day compressive strength of precast concrete is 35 MPa (5,000 psi) with a released strength of 28 MPa (3,500 psi). In many cases, early strength such as the compressive strength, modulus of rupture (MOR), modulus of elasticity (MOE) of concrete and the bond between rebar and concrete are the control factors when designing precast concrete members.

The application of precast with geopolymer concrete could prove to be the future of low carbon emission concrete structures, as seen by the first building in Australia that used geopolymer concrete for structural members (Géopolymère, 2013). Precast geopolymer concrete can be manufactured at precast yard where environment and curing of geopolymer concrete can be easily controlled. The early strength of HCGC is typically reported at the 7th and 28th days or later. In this paper, the early mechanical strengths of high calcium fly ash geopolymer paste and concrete were investigated.

2. Material and sample preparation

2.1. Fly ash (FA)

According to the chemical composition requirement ASTM C618 (2012), the fly ash from the Mae Moh power plant is classified as class F with a high calcium content. The fly ash consisted of 45.23% SiO_2, 19.95% Al_2O_3, 13.15% Fe_2O_3, and 15.51% CaO analyzed using X-ray fluorescence (XRF). The median particle size of the fly ash was 57 microns as determined by a particle size analyzer laser model Mastersizer S of Malvern Instruments Limited and 38% retained on 45 μm sieve.

2.2. Aggregate

The coarse aggregate was commercially available limestone with a maximum size of 20 mm and specific gravity of 2.65 in a saturated surface dry (SSD) condition. The fine aggregate was river sand with a specific gravity of 2.58 and fineness modulus of 2.9 in SSD condition.

2.3. Alkaline solutions

The alkali activated solutions were sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3) consisting of 15.32% Na_2O, 32.87% SiO_2 and 51.81% H_2O. The NaOH solution was prepared by mixing NaOH pellets with distilled water and stirring until all the pellets were completely dissolved and the solution was then left for 24 hours before use.

3. Mix proportions, mixing procedure, casting and curing details

3.1. Mix design

The variables used to design the mix proportions of the geopolymer paste were the alkaline liquid to fly ash (L/A) ratio, the concentration of sodium hydroxide (NH) and the ratio of sodium silicate (NS) to NaOH (NS/NH). The first series, the NaOH concentrations were 10, 15 and 20 molar while the L/A and S/H ratios were kept at 0.5 and 1.0, respectively. For the second series, the L/A was varied at 0.45, 0.50 and 0.55 while the NaOH concentration was kept at 15 molar (M) and the S/H ratio was kept at 1.0. For the third series, the S/H ratio varied at 0.5, 1.0 and 2.0 while the L/A ratio and NaOH concentration were kept at 0.5 and 15 molars, respectively. For the geopolymer concrete, the combined aggregate was 73 percent of total weight of the mix. The ratio of coarse aggregate to fine aggregate was 65:35. With the assumed unit weight of 2,300 kg/m^3, the weight of the coarse and fine aggregates was 1,091 and 588 kg/m^3, respectively. Table 1 shows the mix proportions of the geopolymer paste. Total moles of the Na_2O were calculated from the Na_2O in the fly ash, sodium hydroxide and sodium silicate solutions.

Table 1 Mix proportions of geopolymer

Mixes	L/A	FA (kg)	NH (molar)	NS/NH	NH (kg)	NS (kg)	Na_2O/FA (%)
0.5-10M-1.0	0.50	414	10	1.0	103.5	103.5	10.2%
0.5-15M-1.0	0.50	414	15	1.0	103.5	103.5	12.4%
0.5-20M-1.0	0.50	414	15	1.0	103.5	103.5	14.4%
0.45-15M-1.0	0.45	428	15	1.0	96.4	96.4	11.2%
0.55-15M-1.0	0.55	401	15	1.0	110.2	110.2	13.6%
0.5-15M-0.5	0.50	414	15	0.5	138.0	69.0	13.8%
0.5-15M-2.0	0.50	414	15	2.0	69.0	138.0	11.0%

3.2. Mixing procedure

The geopolymer pastes were mixed in a 23±2 °C controlled room. The procedure started by mixing fly ash with the NaOH solution for 5 min. A sodium silicate solution was then added to the mixture and mixing was continued for an additional 5 minutes. The geopolymer concretes were mixed in a 23±2 °C in a controlled room. Similar to the mixing of the geopolymer paste, it was started by mixing fly ash with the NaOH solution for 5 min. Coarse and fine aggregates were then added to the mixer and mixed for another 5 minutes. The sodium silicate solution was then added to the mixture and mixing was continued for an additional 5 minutes.

3.3. Casting of specimens

The geopolymer paste was cast into a 25x25x25 mm acrylic mold as a set of three samples per mold. The cast samples were put on vibrating table for 10 seconds and wrapped with thin plastic to prevent moisture being lost during curing. For the compressive strength, splitting tensile strength and modulus of elasticity tests, the geopolymer concrete was cast into 100x200 mm cylindrical steel molds in accordance with ASTM C192/C192M (2007). For the modulus of rupture test, the geopolymer concrete was cast into a 75x75x300 mm prism. For the pullout bond test, the geopolymer concrete was cast into 100x150 mm cylindrical steel molds with rebar placed vertically at the center. A 10 mm thick acrylic circular plate with a hole cut at the center was placed inside the steel mold to help align the rebar. The specimen was cast upside-down to ensure a smooth contact surface between the concrete and the bearing plate.

3.4. Curing of specimens

Both the geopolymer paste and concrete were oven cured at 60±2 °C after 2 hours delay time. The delay time was the time after the casting of sample. The delay time allows a sample to be finished and reach initial setting before transportation to the curing oven. The oven curing times were 6, 12 and 24 hours for the paste and 24 hours for the concrete.

4. Testing of specimens

4.1. Mechanical strength

4.1.1. Compressive strength of geopolymer paste

The pastes were tested for compressive strength after being oven cured at 6, 12 and 24 hours using 25x25x25 mm cubes. The compressive strengths of the paste were tested within ± 30 minutes from the time the samples were removed from the molds. The reported results were the average of three paste samples.

4.1.2. Concrete compressive strength, splitting tensile strength and modulus of elasticity

Concrete cylinders were tested for compressive strength, splitting tensile strength and modulus of elasticity according to ASTM C39/C39M (2001), ASTM C496 (2011) and ASTM C469/C469M (2010), respectively. Concrete samples were tested within ± 30 minutes from the end of 24 hours oven curing. The reported results were the average of three concrete samples.

4.1.3. Concrete modulus of rupture

The modulus of rupture was determined at the end of the curing period using a 75x75x300 mm concrete prism in accordance with ASTM C78/C78M (2010). The concrete samples were tested within ± 30 minutes from the end of 24 hours' oven curing. The reported results were the average of three concrete samples.

5. Results and discussion

5.1. Compressive strength of geopolymer paste

The compressive strength of the geopolymer paste after being oven cured at 60 °C are shown in Table 2. The compressive strengths of the geopolymer paste were 2.76-7.17 MPa, 8.58-15.05 MPa and 11.90-22.18 MPa after 60°C oven curing for 6, 12 and 24 hours, respectively. It can be seen that the compressive strength increases as the curing time increases. Figure 1 shows the comparison of the compressive strength between each affecting variable. It can be seen that the compressive strengths increased with the increase in NaOH concentration due to the increase of alumina and silica leaching. The increase of alumina and silica leaching resulted in the increased geopolymerization and thus the strength increased (Rattanasak & Chindaprasirt, 2009). At the high NaOH concentration (20M), the strength decreased due to the high concentration of hydroxide ion (OH^-) which caused aluminosilicate gel precipitation at the early stage of development (Somna *et al*., 2011). In the mix design with a similar NaOH concentration and ratio of sodium silicate to hydroxide, the higher L/A ratio yielded a lower compressive strength. This is due to the excess amount of the available solution since the dissolution of mineral starts from the surface of the fly ash and works its way inside and geopolymer gels were formed. In the mix with a similar L/A ratio and NaOH concentration, the higher S/H ratio yielded a higher compressive strength. The higher silica content affects the pH condition of the matrix and, thus, could affect the strength development of the geopolymer (P. Chindaprasirt, Jaturapitakkul, & Sinsiri, 2007).

Table 2 Compresive strength of geopolymer paste

	6 hr.		12 hr.		24 hr.	
Mixes	f_c (MPa)	Std.	f_c (MPa)	Std.	f_c (MPa)	Std.
0.5-10M-1.0	3.71	0.90	8.58	1.00	11.90	0.40
0.5-15M-1.0	3.09	0.40	11.95	0.80	18.60	3.60
0.5-20M-1.0	4.08	0.50	10.94	0.70	12.38	1.50
0.45-15M-1.0	3.54	0.30	15.05	0.60	22.18	0.20
0.55-15M-1.0	6.60	0.80	13.18	0.20	18.13	1.60
0.5-15M-0.5	2.76	0.80	12.14	0.90	15.51	0.80
0.5-15M-2.0	7.17	0.90	14.30	2.30	19.55	0.60

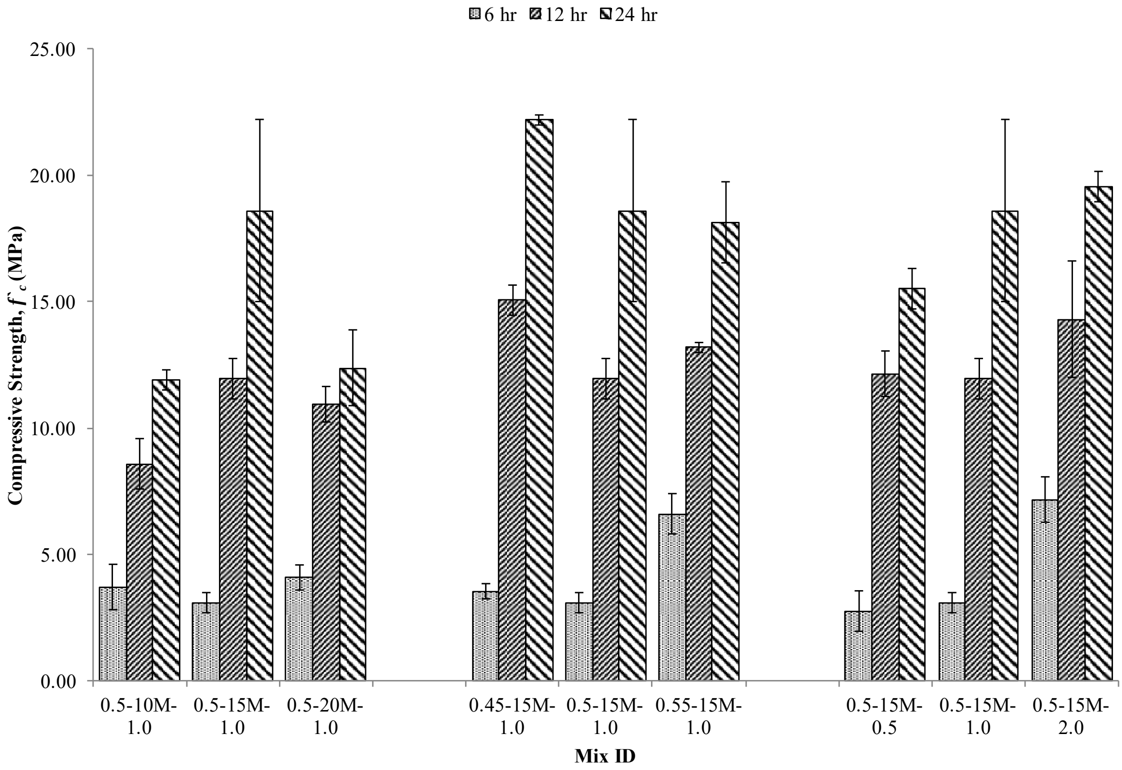

Figure 1 Compressive strength of geopolymer paste

5.2. Compressive strength of geopolymer concrete

The strengths of geopolymer concrete of different mixes were tested after 24 hours of oven curing at 60 °C. The results are shown in Table 3. As mentioned in the above section, geopolymer concrete is a good candidate for precast construction where concrete can be cured in a controlled environment. Since the precast concrete member is typically removed from formwork within 24 hours, the average compressive strengths of geopolymer concrete are compared to the release strength of precast concrete of 28 MPa (PCI MNL-120, 2010). It can be seen that the average compressive strengths of all geopolymer concrete mixes were higher than those required by the release strength of precast concrete. The early strength of geopolymer concrete can be improved by increasing the curing temperature or increasing the curing time in an elevated temperature (Chindaprasirt *et al.*, 2007a). From the results shown, it can be concluded that geopolymer concrete could be used to produce precast concrete.

Table 3 Mechanical strength of geopolymer concrete

Mixes	f_c		f_{ct}		M_r		E_c	
	(MPa)	Std.	(MPa)	Std.	(MPa)	Std.	(MPa)	Std.
0.5-10M-1.0	31.22	6.53	3.10	0.41	6.11	0.49	24000	3200
0.5-15M-1.0	29.68	3.35	2.81	0.17	5.18	0.10	24800	3600
0.5-20M-1.0	32.10	10.73	2.31	0.20	5.34	0.09	32400	3000
0.45-15M-1.0	38.48	4.66	3.39	0.25	6.78	0.53	38400	5000
0.55-15M-1.0	33.21	6.46	2.84	0.08	6.37	0.23	34000	4600
0.5-15M-0.5	33.14	1.92	3.02	0.16	8.08	0.29	33600	6400
0.5-15M-2.0	36.30	0.74	2.56	0.19	6.68	0.41	33200	4000

5.3. Splitting tensile strength and modulus of rupture

The results of the early splitting tensile strength and modulus of rupture of HCGC are shown in Table 3. Figure 2 shows a plot of the splitting tensile strength and modulus of rupture of geopolymer concrete after being oven cured at 60°C for 24 hours. The average of the ratio of $f_{ct}/(f`_c)$0.5 is 0.49 with standard deviation of 0.06 or 83% of those predicted using ACI318M-08 (2008). The splitting tensile strength will continue to increase, as reported by Topark-Ngarm et al. (2014). The average of the ratio of $f_{ct}/(f`_c)^{0.5}$ is 0.60 with standard deviation of 0.05 or 107% of those predicted using ACI318M-08 (2008). The high splitting tensile strength of geopolymer concrete was due to the low porosity of the geopolymer paste which led to higher ITZ strength between the aggregate and the paste (Lee & van Deventer, 2004). The higher splitting tensile strength leads to a higher modulus of rupture of geopolymer concrete. The average of the ratio of $f_r/(f`_c)^{0.5}$ is 1.10 with standard deviation of 0.15 or 117% of those predicted using ACI318M-08 (2008). The results indicate that the design equation underestimates the modulus of rupture of geopolymer concrete.

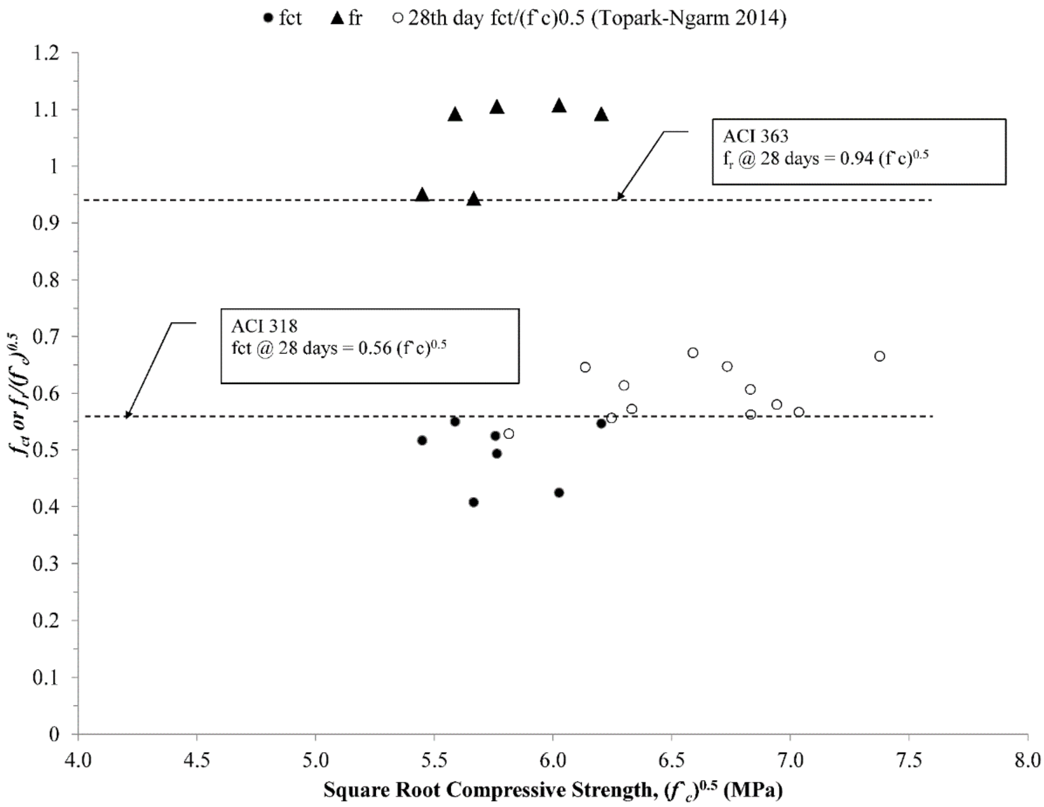

Figure 2 Splitting tensile strength and modulus of rupture of geopolymer concrete

The results for the modulus of elasticity are shown in Table 3. The values were 24,000-38,400 MPa. Figure 3 shows the plot of the modulus of elasticity against the square root of the compressive strength. It can be concluded that the modulus of elasticity increased with increasing the compressive strength. The relationship between the modulus of elasticity and $(f`_c)^{0.5}$ is shown in Eq. 1 with $R^2 = 0.71$.

$$E_c = 17000\ (f`_c)^{0.5} - 66800 \qquad \text{Eq. 1}$$

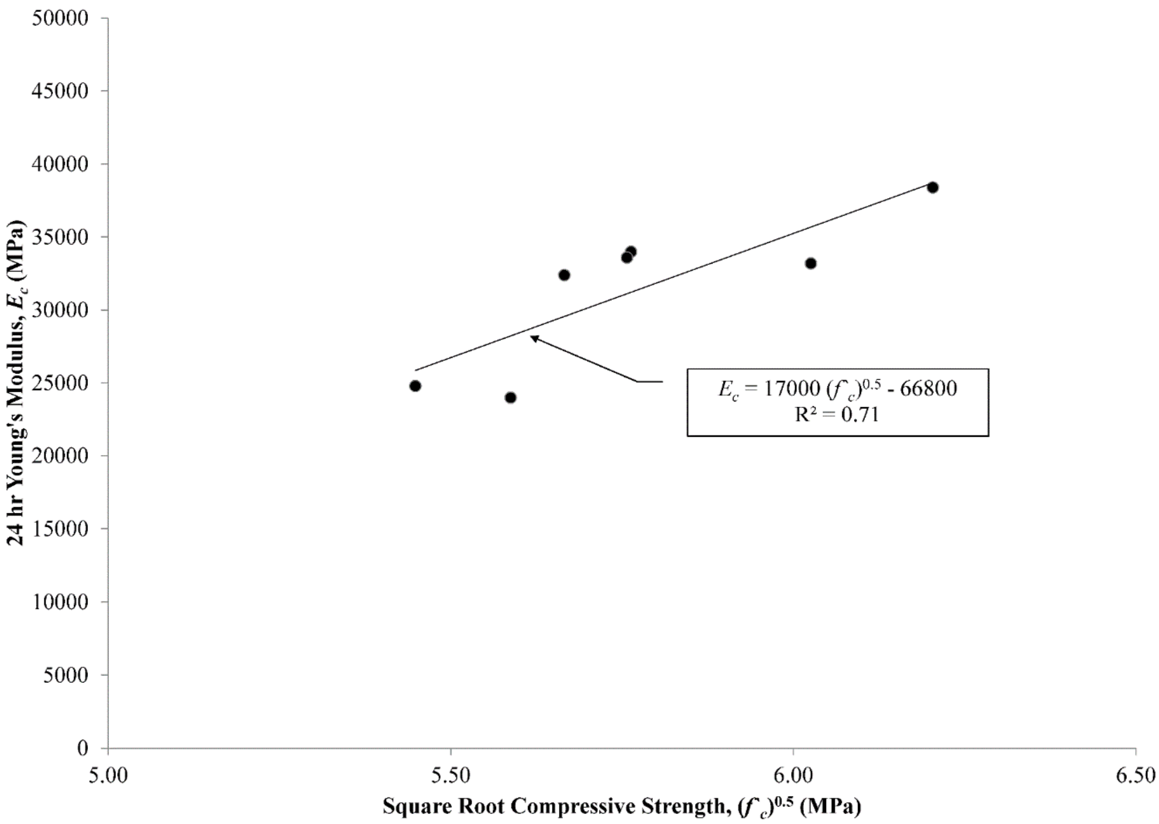

Figure 3 Modulus of Elasticity of geopolymer concrete

6. Conclusions

The paper presents the experiment of the early strength of geopolymer produced from high calcium fly ash. From the obtained results, the following conclusions can be made:

6.1. High early strength could be achieved when cured at 60 °C.

6.2. All mixes of geopolymer concrete yielded higher early compressive strength than those required by the release strength of precast concrete.

6.3. The early strength of geopolymer was influenced by the total content of Na_2O in the system.

6.4. The average splitting tensile strength at 24 hours was 89% of those predicted by the common design standard equation at 28 days.

6.5. The average modulus of rupture at 24 hours was 120% of those predicted by the common design standard equation at 28 days.

6.6. The average modulus of elasticity at 24 hours increased as the compressive strength of the geopolymer concrete increased.

6.7. The reduction in Portland cement production could reduce the amount of CO_2 emissions into atmosphere.

Acknowledgements

This work was financially supported by the Thailand Research Fund (TRF) under the TRF Senior Research Scholar, Grant No. RTA5780004. It was also supported by the Higher Education Research Promotion and National Research University Project of Thailand, Office of the Higher Education Commission, through the Advanced Functional Materials Cluster of Khon Kaen University AFM-2554-Ph.D. 54402.

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