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SHEAR BOND STRENGTH OF FA-PC GEOPOYLMER UNDER DIFFERENT SAND TO BINDER RATIOS AND SODIUM HYDROXIDE CONCENTRATIONS

*Tanakorn Phoo-ngernkham[1], Sakonwan Hanjitsuwan[2], Satakhun Detphan[3], Jaksada Thumrongvut[4], Cherdsak Suksiripattanapong[5], Nattapong Damrongwiriyanupap[6], Prinya Chindaprasirt[7] and Shigemitsu Hatanaka[8]

[1,3,4,5] Faculty of Engineering and Architecture, Rajamangala University of Technology Isan, Nakhon Ratchasima, THAILAND; [2] Faculty of Industrial Technology, Lampang Rajabhat University, THAILAND; [6] School of Engineering, University of Phayao, THAILAND; [7] Faculty of Engineering, Khon Kaen University, THAILAND; [8] Faculty of Engineering, Mie University, JAPAN

*Corresponding Author, Received: 26 June 2017, Revised: 29 Sept. 2017, Accepted: 20 Dec. 2017

ABSTRACT: This paper presents the effects of sand to binder (S/B) ratio and sodium hydroxide (NaOH) concentration on setting time, compressive strength, and shear bond strength of fly ash (FA)-Portland cement (PC) geopolymer binder. Geopolymer binder is manufactured from FA and PC at the ratio of 90:10 by weight of binder. The liquid alkali solution used in this study are sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3) solutions. The Na_2SiO_3/NaOH ratio of 2.0, liquid alkali solution/binder ratio of 0.60, and curing at ambient temperature are fixed in all mixes. The differences in NaOH concentrations of 5, 10 and 15M and S/B ratios of 1.00, 1.25 and 1.50 has been investigated. Test results show that the differences of NaOH concentration and S/B ratio has an effect on setting time, compressive strength and shear bond strength of FA-PC geopolymer mortar. The setting time of mortars are obviously decreased with increasing of S/B ratio whereas the setting time of mortars are obviously increased with increasing of NaOH concentration. The compressive and shear bond strengths of mortars increase as increasing of both S/B ratio and NaOH concentration up to a threshold limit. The highest slant shear strength between Portland cement concrete substrate and FA-PC geopolymer mortar is found in the mortar with 1.25 S/B ratio and 10M NaOH concentration which gives 24.1 MPa.

Keywords: Geopolymer, Fly ash-Portland cement blends, Sand to binder ratio, NaOH concentration, Shear bond strength.

1. INTRODUCTION

The applications of Portland cement (PC) is essential to the rapid urbanization in many developing countries. Advantages of PC are high mechanical performances and low cost; however, increasing of PC manufacture corresponds to energy and environmental issues. An annual publication has reported that approximately 1 ton of CO_2 emissions for each ton of the PC produced [1]. Recently, in addition to PC, geopolymer binder has been developed by several researchers as an alternative cementing agent [2, 3]. This is due to geopolymer binder has less CO_2 footprint than PC as reported by McLellan et al. [4].

Geopolymer binder is made from aluminosilicate source materials activated with high alkali solutions [5]. Many researchers [2, 3, 6] have reported that geopolymer binder can be used as cementing agent because there are many advantages i.e., high strength, excellent durability and high bonding. In Thailand, fly ash (FA) from Mae Moh power station is widely used for making geopolymer binder [7-9]; however, the production of FA geopolymer at ambient temperature gives low strength [10]. Some researchers [10, 11] reported that the temperature curing at approximately 40-75 $^{\circ}$C could enhance the degree of geopolymerization within the matrix and hence reasonable strength FA geopolymer gain. However, in reality, the use of temperature curing is difficult for the construction practice. Nowadays, the materials which consisted of calcium oxide could improve the strength development of FA geopolymer. For example, Pangdaeng et al. [10] studied on the use of PC to replace FA for making geopolymer binder cured at ambient temperature. They reported that generated heat from hydration products could help the geopolymerization process within the geopolymer system. Also, Temuujin et al. [12] reported that a coexistence of calcium silicate hydrate (C-S-H) and geopolymer gel (N-A-S-H) provided higher compressive strength of geopolymer binder than only N-A-S-H gel.

One of the important factor on the strength development of geopolymer binder is alkali solution. Hanjitsuwan et al. [13] claimed that two types of alkali solution viz., sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3) solutions were widely used for making geopolymer binder. Also, Hanjitsuwan et al. [13] explained that NaOH solution was used for leaching out of Si^{4+} and Al^{3+} ions whereas Na_2SiO_3 solution was used for condensation process to form aluminosilicate material. In addition, ratio of sand to binder is one of the important factor for considering as repair materials which related to a homogeneous matrix of geopolymer binder as reported by Thakur and Ghosh [14].

In order to utilize geopolymer binder as an alternative repair material, many researchers [2, 3, 15-19] have studied the setting time, strength development and bonding strength for proving their properties compared with commercial repair materials in the market. As mentioned, the 7-day strength requirement of rapid hardening cementitious materials was 28.0 MPa as per ASTM C928-13 [20], and the initial setting time and minimum strength requirements for repair binder were 30 minutes and 35.0 MPa, respectively, as per ASTM C881/C881M-14 [21]. Therefore, the aim of this study is to investigate the effects of NaOH concentration and S/B ratio on setting time, compressive strength and shear bond strength of FA-PC blends geopolymer mortar. The obtained results should be very beneficial to the understanding and to the future applications of geopolymer binder as fundamental of alternative repair materials.

2. EXPERIMENTAL DETAILS AND TESTING ANALYSIS

2.1 Materials

The materials used in this study are fly ash (FA) from Mae Moh power plant in northern Thailand, and ordinary Portland cement (PC) which is a commercial cement in the market. FA had specific gravity, median particle size and Blaine fineness of 2.65, 15.3 µm and 4300 cm^2/g, respectively. While, PC had specific gravity, median particle size and Blaine fineness of 3.15, 14.6 µm and 3600 cm^2/g, respectively. The liquid alkaline activators were sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3) with 13.89% Na_2O, 32.15% SiO_2, and 54.16% H_2O by weight. Fine aggregate used in this study was local river sand with specific gravity of 2.65, and fineness modulus of 2.00.

The chemical compositions of FA and PC are illustrated in Table 1. FA consists of 31.32% SiO_2, 13.96% Al_2O_3 and 15.64% Fe_2O_3, and the CaO content is high at 25.79%, thus this FA is Class C as per ASTM C618-15 [22]. In addition, physical properties of FA and PC are illustrated in Table 2.

Table 1 Chemical compositions of FA and PC

Chemical compositions	FA	PC
SiO_2	31.32	20.80
Al_2O_3	13.96	4.70
Fe_2O_3	15.64	3.40
CaO	25.79	65.30
MgO	2.94	1.50
Na_2O	2.83	0.40
K_2O	2.93	0.10
SO_3	3.29	2.70
LOI	1.30	0.92

Table 2 Physical properties of FA and PC

Materials	FA	PC
Specific gravity	2.61	3.15
Median particle size, d_{50} (µm)	15.3	14.6
Blaine fineness (cm^2/g)	4300	3600

Table 3 Mix proportions of FA-PC geopolymer mortar

Mixes	FA (kg)	PC (kg)	Sand (kg)	NaOH (kg)	Na_2SiO_3 (kg)
5M-1.00SB	90	10	100	20	40
5M-1.25SB	90	10	125	20	40
5M-1.50SB	90	10	150	20	40
10M-1.00SB	90	10	100	20	40
10M-1.25SB	90	10	125	20	40
10M-1.50SB	90	10	150	20	40
15M-1.00SB	90	10	100	20	40
15M-1.25SB	90	10	125	20	40
15M-1.50SB	90	10	150	20	40

2.2 Mix proportion of FA-PC geopolymer mortar

The mix proportions of FA-PC geopolymer mortar with different NaOH concentration and S/B ratio are shown in Table 3. Constant liquid alkali solution to binder ratio of 0.60, Na_2SiO_3/NaOH ratio of 2.0, and curing at ambient temperature are fixed in all mixes. Geopolymer binder is manufactured from FA and PC at ratio of 90:10 by weight of binder. FA was replaced by PC because it needs calcium oxide for enhancing the strength development of geopolymer binder when cured at ambient temperature as reported by Pangdaeng et al. [10]. The NaOH concentrations of 5, 10 and

15M, and sand to binder ratios (S/B) of 1.00, 1.25 and 1.50 have been investigated.

For the mixing of mortars, NaOH and Na_2SiO_3 solutions were firstly mixed together before use as liquid solution. The FA, PC, and sand were dry mixed until the mixture was homogenous. Right after, the liquid solution was added and the mixing of mortars was done for 3 minutes.

2.3 Experimental details and testing analysis

2.3.1 Setting time of FA-PC geopolymer mortar

After mixing, the setting time of FA-PC geopolymer was tested following ASTM C191-13 [23].

2.3.2 Compressive strength of FA-PC geopolymer mortar

Fresh FA-PC geopolymer mortar was casted in 50x50x50 mm^3 cube molds for compressive strength test as per ASTM C109… [24]. After that, sample has been wrapped with vinyl sheet to protect moisture loss. The samples were cured for a day and then demolded with immediately wrapped by vinyl sheet and kept in ambient temperature until testing age. The compressive strength of samples has been tested at the age of 28 days. The reported results are the average of five samples.

2.3.3 Shear bond strength between concrete substrate and FA-PC geopolymer mortar

Portland cement concrete (PCC) is a mixture of 500 kg/m^3 Portland cement, 510 kg/m^3 fine aggregate, 930 kg/m^3 coarse aggregate and 238 kg/m^3 water, respectively. The 28-day compressive strength and Young's modulus of PCC were 35.0 MPa and 27.5 GPa, respectively, which based on previous studies [2, 3]. As mentioned, fresh PCC was casted in a 50x50x125 mm^3 prism molds. After curing time for 90 day, the PCC was cut in half at 45° line to the vertical. For preparation of shear bond strength between PCC and FA-PC geopolymer mortar, fresh FA-PC geopolymer was casted into a 50x50x125 mm^3 prism mold with the other half filled with PCC. Then, samples were wrapped with vinyl sheet to protect moisture loss and kept in ambient temperature until testing age. The shear bond strength is calculated as the ratio of maximum load at failure and the bond area. The shear bond strength was tested at the age of 28 days with a constant loading rate of 0.30 MPa/s. The reported results are the average of five samples.

3. RESULTS AND DISCUSSION

3.1 Setting time of FA-PC geopolymer

The results of setting time of FA-PC geopolymer mortar with different NaOH concentration and S/B ratio are shown in Fig. 1. The initial and final setting times of FA-PC geopolymer tend to decrease with increasing of both NaOH concentration and S/B ratio. With regard to the effect of S/B ratio, it is found that an increasing of S/B ratio has an effect on setting time of FA-PC geopolymer mortar. For example, the initial and final setting times of 10M-1.00SB, 10M-1.25SB and 10M-1.50SB mortars are 19, 15, 15 min and 30, 25, 23 min, respectively. This is because an increasing of fine aggregate in the geopolymer system is related to decrease in the paste value within the matrix; therefore, the setting time of mortar decreases with increasing of S/B ratio.

For the effect of NaOH concentration, the leaching out of Si^{4+} and Al^{3+} ions are generally low at low NaOH concentration whereas the leaching out of Ca^{2+} is not interrupted. Thus, the solution was filled with calcium as reported by Rattanasak and Chindaprasirt [25]. Also, Guo et al. [26] explained that Ca^{2+} ion could react with Si^{4+} and/or Al^{3+} ions from FA to form C-(A)-S-H gels within geopolymer system. Hence, the setting time of FA-PC geopolymer is thus short. At high NaOH concentration, the leaching out of Si^{4+} and Al^{3+} ions are much higher than low NaOH concentration. In contrast, Ca^{2+} ion was hindered. Thus, the setting time of FA-PC geopolymer increases as increasing of NaOH concentration.

From this test result, it can be concluded that the rapid setting of FA-PC geopolymer is very attractive for repair work which the fast setting is normally required. As per ASTM C881/C881M-14 [21], the requiement of initial setting time for use as repair binder was 30 min. Therefore, all mixes meet the requirement of ASTM standard.

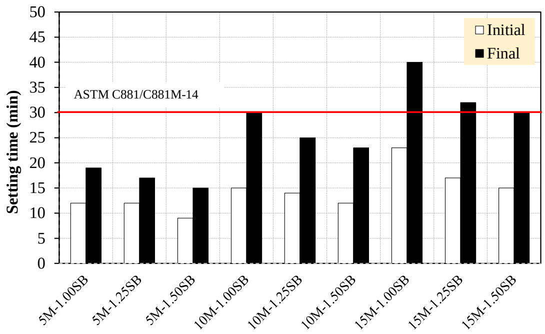

Fig. 1 Setting time of FA-PC geopolymer mortar with various NaOH concentration and S/B ratio.

3.2 Compressive strength of FA-PC geopolymer mortar

The 28-day compressive strength of FA-PC geopolymer mortar with different NaOH concentration and S/B ratio are shown in Fig. 2. According to Fig. 2, it is found that the compressive strength of FA-PC geopolymer mortar increases with increasing of both S/B ratio and NaOH concentration. For example, the 28 day-strength of 5M1.00SB, 5M1.25SB, 5M1.50SB, 10M1.00SB and 15M1.00SB mixes are 40.3, 50.4, 54.3, 46.8 and 45.1 MPa, respectively.

As for effect of NaOH concentration, it has an effect on the strength development of FA-PC geopolymer mortar. At high NaOH concentration, the leaching out of Si^{4+} and Al^{3+} ions from FA particles increase which corresponds to increasing of its strength. Hanjitsuwan et al. [13] claimed that the formation of N-A-S-H gel was improved at high NaOH concentration. Therefore, the coexistence of N-A-S-H and C-S-H gels could enhance the strength development of FA-PC geopolymer mortar [19]. However at 15M NaOH, it gives lower strength of FA-PC geopolymer mortar than that of 10M NaOH concentration. This is due to the leaching out of CaO from FA and PC was hindered at high NaOH concentration [13]. Therefore, 10M NaOH concentration is suitable alkali hydroxide for producing FA-PC geopolymer mortar. According to Figure 2, it can be concluded that the strength of FA-PC geopolymer mortar increase as increasing of S/B ratio and NaOH concentration up to a threshold limit that are 10M NaOH and 1.50 of S/B ratio. The relatively highest strength is found in the 10M1.50SB mix, which gives 65.1 MPa of 28-day compressive strength. Hence, all mixes of FA-PC geopolymer mortars meet the requirement of ASTM standard.

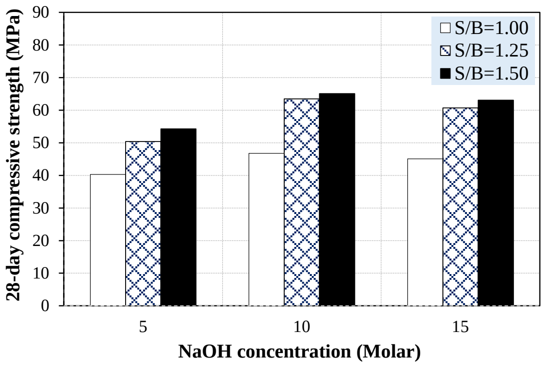

Fig. 2 Compressive strength of FA-PC geopolymer mortar with various NaOH concentration and S/B ratio.

3.3 Shear bond strength between PCC substrate and FA-PC geopolymer mortar

Test results of shear bond strength between PCC substrate and FA-PC geopolymer mortar under different NaOH concentration and S/B ratio are summarized in Fig. 3. The increase in both of NaOH concentration and S/B ratio has an effect on shear bond strength between two bonding surfaces. The improvement of shear bond strength is directly related to the behavior of its strength. For instance, the 28 day-shear bond strength of 5M1.00SB, 5M1.25SB, 5M1.50SB, 10M1.00SB and 15M1.00SB mixes are 18.2, 18.6, 15.9, 23.3 and 24.2 MPa, respectively.

With regard to effect of S/B ratio, the slant shear strength between PCC substrate and FA-PC geopolymer mortar tends to increase with increase in S/B ratio up to a threshold limit that is 1.25 of S/B ratio. As mentioned, the slant shear strength at S/B ratio of 1.50 is obviously decreased when compared to S/B ratio of 1.25. As for the effect of NaOH concentration, the slant shear strength between PCC substrate and FA-PC geopolymer mortar tends to increase with increasing NaOH concentration. However at 15M NaOH concentration, it seems to be a slight reduction. The CaO from PC could react with SiO_2 and/or Al_2O_3 from FA in the suitable NaOH concentration, hence, additional formation of C-S-H and/or C-A-S-H coexisted with N-A-S-H gels was formed [27, 28]. Thus, an enhancement of bonding strength at contact zone between PCC substrate and FA-PC geopolymer mortar was obtained. In contrast, the leaching out of CaO from FA and PC was hindered at high NaOH concentration [13]. Therefore, bonding at two surfaces slight decrease.

It can be concluded that a mixture of S/B ratio of 1.25 and NaOH concentration at 10M gives the highest slant shear strength between PCC substrate and FA-PC geopolymer mortar. As per ASTM C881/C881M-14 [21] is needed the minimum bond strength at between 7.0-10.0 MPa; therefore, all mixes of this study could develop to be a repair binding.

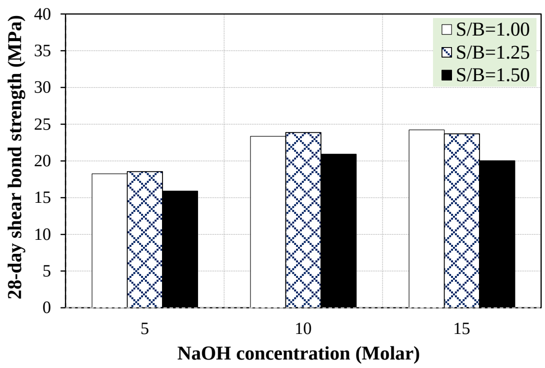

Fig. 3 Shear bond strength between PCC substrate and FA-PC geopolymer mortar with various NaOH concentration and S/B ratio.

4. CONCLUSION

This paper has provided an experimental study on setting time, compressive strength and shear bond strength of FA-PC geopolymer mortar with different NaOH concentrations and S/B ratios. Based on the obtained experimental results, the following conclusions could be drawn:

1) The NaOH concentration and S/B ratio have an effect on setting time of FA-PC geopolymer mortar. The setting time of mortars are decreased as increasing S/B ratio. While, the increasing NaOH concentration can delay the setting time of FA-PC geopolymer mortar.

2) Compressive strength of FA-PC geopolymer mortars are increased with increasing S/B ratio and NaOH concentration up to a threshold limit. The FA-PC geopolymer mortar mixed with 10M NaOH and S/B ratio of 1.50 gives the highest 28-day strength of 65.1 MPa.

3) The FA-PC geopolymer mortar with the optimum NaOH concentration and S/B ratio improve the shear bond strength between PCC substrate and FA-PC geopolymer mortar. The increase in shear bond strength is due to an enhancement of reaction products between the two surfaces. A mixture of S/B ratio of 1.25 and 10M NaOH gives the highest slant shear strength of 24.1 MPa.

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