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The effect of water binder ratio on strength development of class C fly ash geopolymer mortar prepared by dry geopolymer powder

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Abstract. The use of geopolymer binder as cement replacement material can reduce the amount of carbon dioxide gas produced during the Portland Cement manufacturing process. However, the main issue of geopolymer binder is in the mixing process of sodium silicate and NaOH which requires specialized knowledge and strict supervision. This paper reports the effect of water binder ratio on strength development of fly ash geopolymer mortar using dry geopolymer powder. Fly ash with high calcium content was used as primary material. The dry geopolymer powder was prepared by wet mixing method which was made by drying a mixture of NaOH solution and limestone for 24 hours. The variations of water to binder ratio were 0.30, 0.35, 0.40, 0.45, and 0.50. Strength properties were measured by compressive strength at the age of 7, 14 and 28 days. The results showed that the water binder ratio significantly affect the strength development of geopolymer mortar prepared by dry geopolymer powder. The water binder ratio of 0.40 gives the highest compressive strength of 10.3 MPa at 28 days. This suggests that the use of dry geopolymer powder on geopolymer mortar production can overcome the difficulties of geopolymer mortar mixing on site.

1 Introduction

Fly ash-based geopolymer binder is one innovation in replacing the role of Portland Cement (PC) binder due to its environmentally friendly characteristic [1-3]. The PC production process brings negative impact on the environment. The production of 1 ton PC produces approximately 0.7-1 ton of carbon dioxide (CO_2) gas emissions which lead to the global warming problem [4-6]. The use of fly ash as fully cement replacement material in geopolymer is an alternative to overcome this issue [7-9].

Generally, the production process of geopolymer binder is using a specific mixing method where fly ash raw material and alkali activator solution are mixed together with a specific composition, water to solid ratio, and chemical molarity ratio. The alkali activator solution is a blended between sodium hydroxide (NaOH) with a certain molarity with sodium silicate or water glass (Na_2SiO_3) solutions [7, 8, 10, 11]. However, the drawbacks of this wet mixing method are on the preparation and the mixing process of NaOH solution. The preparation of NaOH solution requires certain skill in chemistry knowledge, while the mixing process requires specific skill in geopolymer knowledge. Further, the use of water in geopolymer, known as water to solid ratio, requires a strict supervision due to its liquid characteristics of geopolymer specimen which will affect the ability to achieve its structural integrity [12]. Previous research [13] has found that the use of dry geopolymer powder becomes the an alternative to overcome such problems. According to Abdel-Gawwad and Abo-El-Enein [13], dry geopolymer powder can be prepared by mixing NaOH solution and high calcium material, such as limestone or calcium carbonate ($CaCO_3$). The dry powder is then mixed with Ground Granulated Blast-furnace Slag (GGBS) and water to produce geopolymer paste.

This paper aims to investigate the effect of water to binder ratio on strength development of fly ash-based geopolymer mortar prepared by dry geopolymer powder. The dry geopolymer powder was prepared by wet mixing method which was made by drying a blended of NaOH solution and limestone for 24 hours. The variations of water to binder ratio were 0.30 to 0.50 with 0.05 interval. The strength development of geopolymer mortar was measured by compressive strength test at 7, 14 and 28 days. This research is expected to overcome the difficulties of geopolymer specimen preparation on site.

2 Method

2.1 Materials

High calcium fly ash from Payton power plant was used as primary material. The basic material of dry geopolymer powder was a blended 10 Molar NaOH solution and limestone or calcium carbonate ($CaCO_3$). The chemical compositions of all materials were identified by X-Ray Fluorescence (XRF) test type PANalytical Minipal

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equipment. Table 1 lists the chemical composition of fly ash and limestone.

Table 1. The chemical composition of materials (mass in %).

Chemical Composition	Fly Ash	Limestone
CaO	24.1	94.9
SiO_2	13.3	-
Al_2O_3	4.5	-
Fe_2O_3	51.2	0.3
MgO	-	3.3
K_2O	0.8	-
Mn_2O_3	0.8	-
SO_3	0.4	-

Fly ash used in this research was class C fly ash with CaO content of 24.1% (>10%), the total of $SiO_2+Al_2O_3+ Fe_2O_3$ was 69.0% (>50%), and SO_3 of 0.4% (<5%) in accordance with ASTM C618 [14]. The 10 M NaOH was prepared by dissolving 400 gram NaOH pellets into one liter deionized water.

2.2 Mix proportions

The mix proportions of fly ash geopolymer mortar specimen made by dry geopolymer powder (FAG-D) and dry activators are shown in Table 2 and Table 3, respectively.

Table 2. Mix proportions of FAG-D mortar specimens

Mix	PC	Dry activators	Sand	w/b
PC	1.0	-	2.75	0.45
FAG	-	1.0	2.75	0.35
FAG-D1	-	1.0	2.75	0.30
FAG-D2	-	1.0	2.75	0.35
FAG-D3	-	1.0	2.75	0.40
FAG-D4	-	1.0	2.75	0.45
FAG-D5	-	1.0	2.75	0.50

Table 3. Mix proportions of dry activators of FAG-D mortar

Mix	NaOH	Sodium silicate	Limestone	Fly ash
FAG	0.21	0.32	-	1.0
FAG-D1	0.06	-	0.1	0.84
FAG-D2	0.06	-	0.1	0.84
FAG-D3	0.06	-	0.1	0.84
FAG-D4	0.06	-	0.1	0.84
FAG-D5	0.06	-	0.1	0.84

Mix design of first control specimen (PC) was developed in accordance with ASTM C109 [15] with the ratio of sand to binder and water to cement of 2.75 and 0.45, respectively. The second control specimen was fly ash-based geopolymer (FAG) mortar which was prepared in accordance with previous research [16] using a blended of 10 Molar NaOH and sodium silicate as alkaline activator.

Meanwhile, the mix proportions of FAG-D mortar specimens was determined according to Abdel-Gawwad and Abo-El-Enein mix [13]. The total ratio of NaOH, limestone, and fly ash was maintained to 1.0, similar to that binder ratio of PC control specimen. Instead of water to solid (w/s) ratio in traditional geopolymer specimens, the water to binder ratio (w/b) was applied for FAG-D mortar specimen due to similarity in the specimen preparation process with the normal PC specimen. The binder was calculated as the sum of NaOH, limestone and fly ash, while the water was determined as the sum water in geopolymer specimens.

2.3 Specimen preparation

The dry geopolymer material was developed by wet mixing method in accordance with the method proposed by Abdel-Gawwad and Abo-El-Enein [13], which was made by blended 10 Molar NaOH solution with limestone. The wet powder was dried in the oven at 100°C for 24 hours. The dry mixture then was pulverized into a powder form which pass Sieve No. 50 (0.297 mm).

The geopolymer mortar mixture was prepared by mixing the dry geopolymer powder with fly ash at a specific water to binder (w/b) ratio as listed in Table 2. The mixture was poured into 50 x 50 x 50 mm^3 steel molds. The specimens were left at room temperature for 24 hours prior demolding and then cured at room temperature prior to be testing.

2.4 Testing method

The strength properties of FAG-D mortar specimens were measured by the compressive strength test in accordance with ASTM C109 [15] at the age of 7, 14, and 28 days.

3 Results and discussion

3.1 Strength development

Table 4 and Figure 1 show the strength development of mortar control (PC), fly ash-based geopolymer made by NaOH and silicate (FAG), and fly ash-based geopolymer made by dry geopolymer powder (FAG-D).

Table 4. Strength development of fly ash geopolymer mortar made by dry geopolymer powder (MPa)

Mix	Strength at 7 days	Strength at 14 days	Strength at 28 days	w/b
PC	15.1 (78.0%)	16.9 (88.0%)	19.3 (100%)	0.45
FAG*	7.2 (38.4%)	12.6 (66.6%)	18.8 (100%)	0.35
FAG-D1	4.7 (60.3%)	6.6 (84.2%)	7.8 (100%)	0.30
FAG-D2	5.8 (72.7%)	7.1 (89.2%)	8.0 (100%)	0.35
FAG-D3	7.9 (76.6%)	9.7 (93.9%)	10.3 (100%)	0.40
FAG-D4	7.3 (84.3%)	8.3 (95.8%)	8.6 (100%)	0.45
FAG-D5	7.1 (82.7%)	7.3 (85.6%)	8.5 (100%)	0.50

Note: * Wardhono, 2018 [16]

The results show that FAGD mortar was the lowest compressive strength compared to that PC and FAG mortar throughout 28 days. The highest compressive strength of FAG-D mortar specimens had only achieved a compressive strength of 10.29 MPa as shown in FAG-D3 at 0.40 w/b ratio, lower than PC and FAG mortars with the strength of 19.27 and 18.84 MPa, respectively. However, all FAG-D mixes exhibited a significant increase in strength along with time.

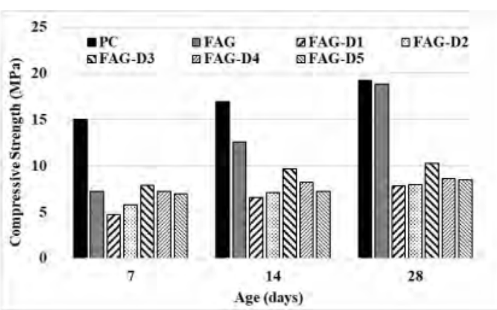

Fig. 1. Strength development of fly ash geopolymer mortar made by dry geopolymer powder

The ratio of strength development of all mortar mixtures was calculated based on the final strength at 28 days. The standard ratio of PC (control) mortar strength development is 0.78 and 0.88 at 7 and 14 days, respectively as shown in Table 3, which satisfies the graph of strength-equivalent to age in accordance with ASTM C1074 [17]. Despite FAG-D mortar showed the lowest strength performance compared to PC and FAG mortars, it demonstrated a comparable strength development ratio to that PC mortar, as shown in FAG-D2 and FAG-D3 mortars with the strength ratio of 72.7% and 76.6%, respectively, at 7 days. A further strength development at 14 days also showed a comparable strength ratio as shown in FAG-D1, FAG-D2 and FAG-D3 mortar mixtures with the strength ratio of 84.2%, 89.2% and 93.9%, respectively.

Although FAG-D1 (w/b = 0.30) exhibited the lowest strength ratio, it showed a higher ratio compared to that fly ash-based geopolymer made by NaOH and sodium silicate solutions (FAG). This indicated that the FG-D mortar had a faster initial strength compared to that FAG mortar. This might attribute to the sodium carbonate and calcium hydroxide contents as the product of NaOH and limestone reaction during dry geopolymer powder preparation. According to Abdel-Gawwad and Abo-El-Enein [13], higher content of sodium carbonate and calcium hydroxide tends to increase the liberation of calcium (Ca), silicate (Si), and aluminate (Al) from the fly ash grains. It leads to the formation of more hydration products which establish a solid microstructure of geopolymer matrix. Thus, it increases the strength of geopolymer specimen [18].

3.2 The effect of water to binder ratio

The effect of water to binder ratio (w/b) on the strength development of fly ash geopolymer made by dry geopolymer powder is shown in Figure 2.

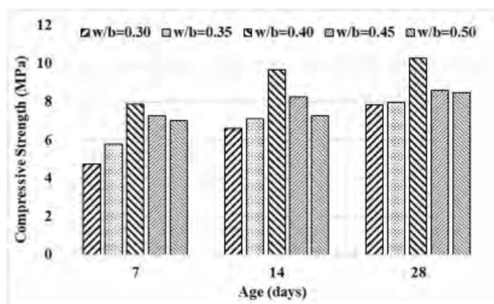

Fig. 2. The effect of water to binder (w/b) ratio to strength of fly ash geopolymer mortar made by dry geopolymer powder

The strength development was investigated at 7, 14, and 28 days with w/b ratio of 0.30 to 0.50 with 0.05 interval. It was found that the compressive strength increases with the w/b ratio to 0.40 then decreases to w/b ratio of 0.45 for all testing ages. The solubility of dry geopolymer powder as activator increased along with the increase of w/b ratio, which led to the enhancement of the geopolymerization reaction rate.

However, the increasing the w/b ratio to 0.45 tends to decrease the compressive strength of FAG-D mortars. The compressive strength of FAG-D3 (w/b ratio 0.40) decreased from 9.7 MPa to 8.3 MPa and from 10.3 MPa to 8.6 MPa at 14 and 28 days, respectively. Similar finding was also found by Abdel-Gawwad and Abo-El-Enein [13] using GGBS. The authors found that the optimum of w/b ratio was achieved by w/b ratio of 0.27. The increase the w/b ratio more than 0.27 leads to the decrease of specimen strength. According to the authors, increasing the water to cement ratio enhances the strength properties of slag-based geopolymer made by dry geopolymer activator. However, high water to cement ratio tends to decrease the compressive strength due to the increase of cement matrix porosity.

4 Conclusion

This paper investigates the effect of water to binder ratio on strength development of class C fly ash geopolymer mortar prepared by dry geopolymer powder. The conclusions obtained from the analysis can be shown as follows:

- The highest compressive strength is achieved by FAG-3 mortar specimen with the strength of 10.29 MPa at w/b ratio value of 0.40.
- The w/b ratio significantly affects the strength development of fly ash-based geopolymer made by dry geopolymer powder.
- Increasing the w/b ratio above 0.40 does not significantly affect the strength development of fly ash-based geopolymer made by dry geopolymer powder, however it tends to lower the mortar strength at higher w/b value.
- Dry geopolymer powder is an alternative to overcome the NaOH solution preparation and the mixing process on the development of geopolymer specimen.

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