Study of mechanical properties of fly ash-based geopolymer concrete

H Hardjasaputra1,2, M Cornelia1, Y Gunawan1, I V Surjaputra1, H A Lie3, Rachmansyah4 and G Pranata Ng1

1 Department of Civil Engineering, Pelita Harapan University, Tangerang 15811, Indonesia
2 Department of Civil Engineering, Pradita Institute, Tangerang 15810, Indonesia
3 Department of Civil Engineering, Diponegoro University, Semarang 1269, Indonesia
4 Department of Civil Engineering, Krida Wacana Christian University, Jakarta 11470, Indonesia

E-mail: hardja@yahoo.com

Abstract. The world is facing the challenges of climate changes due to the increase in CO2 emissions. Cement production is one of the biggest contributors to CO2 emissions due to combustion processes that require high temperatures. The new development in building construction showed that fly ash based Geopolymer concrete can be as structure materials to reduce or even eliminate ordinary Portland cement concrete. This paper presented the research results of fly ash based geopolymer concrete mechanical properties, like the compressive strength, flexural strength, and Elastic Modulus. The data were collected from the test results of geopolymer concrete specimens made from 2 sources of Fly Ash with varying concentration of sodium hydroxide solution from 4 M up to 12 M. The range of achieved compressive strength was from normal to high strength concrete. The correlation between the compressive strength and flexural strength and the Elastic Modulus of geopolymer concrete will be the highlight of this paper. The mathematical formulation of compressive strength and its flexural strength and Elastic modulus will be determined and compared with normal Portland Cement Concrete.

1. Introduction
Nowadays the climate change due to increase CO2 emissions has become a major concern for the world. Cement industry is one of the industries responsible for increasing CO2 emissions globally. It is estimated that the cement industry worldwide contributes 9% of CO2 emissions. It is required to take quick and appropriate steps to reduce CO2 emissions into the atmosphere in order to reduce global warming. Variety of steps have been taken to reduce the growth of cement consumption, namely by increasing the use of pozzolanic materials such as fly ash, slag, palm oil fuel ash as cementitious materials for replacing part of the PC. Reducing the use of PCs will be more effective if we use geopolymer concrete as structural concrete. Geo-polymer concrete is made without using PC cement. Fly ash as the main ingredient of geopolymer concrete with alkaline solution will produce binder paste, which determines the concrete strength. For example, it is estimated that Electrical Steam Power Plant throughout Indonesia will produce around 2.75 million tons of fly ash per year. As a
consequence, a huge amount of fly ash is generated in thermal power plants, causing several disposal-related problem.

In this paper, the authors will report the results of research as the efforts to make Concrete Geopolymers as structural concrete. For this reason, the author will describe the mechanical properties of geopolymer concrete, namely a wide range of compressive strength, the relationship of compressive strength to flexural strength, shear strength. To get a wide range of compressive strengths between 20 MPa and 50 MPa, the data analysis came from more than one hundred concrete specimens from various mix designs.

2. Research review
For the first time the development of geopolymer concrete research conducted by J. Davidovits [1, 2]. He fully replaced the Portland cement in making concrete with fly ash, which later known as Geopolymer Concrete. The name “geopolymer” itself came from the polymerization process that occurs between the alkaline solution, silica, and aluminum in fly ash that forming a structural binder paste. The alkaline solution will work as the activator solution which is consists of sodium silicate (Na$_2$SiO$_3$) and sodium hydroxide (NaOH) [1, 2].

3. Material

3.1. Fly ash
Fly ash used in this research originated from Electrical Steam Power Plant - Suralaya. The fly ash was light brown color. The X-Ray Fluorescence (XRF) results showed the chemical composition of fly ash which consisted of 38.79% SiO$_2$; 21.84% Fe$_2$O$_3$; 18.51% Al$_2$O$_3$ and 12.23% CaO. The result of Scanning Electron Microscope (SEM) showed that the fly ash particles were spherical in size smaller than 30 μm, as seen in the figure 1.

![Figure 1. Fly ash and SEM image [3].](image)

| Formula | Concentration |
|---------|---------------|
| SiO$_2$ | 38.79%        |
| Fe$_2$O$_3$ | 21.84%    |
| Al$_2$O$_3$ | 18.51%    |
| CaO    | 12.23%        |
| SO$_3$ | 2.41%         |

Table 1. Chemical composition of fly ash from electrical steam power plant suralaya [3].
3.2. Alkaline solution (activator)

The alkaline solution plays a crucial role in the polymerization reaction. It serves as activator for polymerization reaction between fly ash and alkaline solution to form geopolymer structural paste binder. The alkaline solution used in this study was the mixture sodium silicate (Na₂SiO₃) and sodium hydroxide (NaOH) solution. For making NaOH solution, NaOH chips with 98% NaOH content were dissolved in clean water according to the desired Molarity concentration. It has been shown that higher concentration of NaOH yields higher compressive strength [4]. It should be noted that NaOH solution was then left 24 hours before use, while the mixture NaOH solution and sodium silicate gel (Na₂SiO₃) can be prepared few hours before concrete mixing. To have a wide range of geopolymer concrete strength, this study used 5 different concentrations of NaOH solution like 2M, 4M, 8M, 12M and 16M.

3.3. Aggregate

Like aggregate for normal concrete, commercially limestone with maximum size of 10 mm and specific gravity 2.57 was used as coarse aggregates. For fine aggregates, white sand from Bangka Island with specific gravity of 2.56 and fineness modulus 2.9 was used in this study. It should be noted that the coarse and fine aggregates were in SSD condition.

4. Mixing proportion

In this study, the geopolymer concrete mixture referred to the design of normal concrete according to the standard of concrete mix design SNI 03-2834-2000 as the reference. The concrete mixtures were calculated to obtain concrete compressive strength with the category of normal concrete to high concrete. The mix designs used, as can be seen in the table 2, were taken from several research papers of the authors [3-5].

The important factor that must be considered in calculating the mix design is the concentration of sodium hydroxide. From the various studies, it can be concluded that the concentration of sodium hydroxide or the NaOH Molarity greatly affected the compressive strength of concrete. However, on the other side, the NaOH molarity has a low water content, so the amount of NaOH concentration will greatly affect the workability of fresh geopolymer concrete.

In table 2 can be seen the variation of NaOH molarity used which are between the lowest Molarity of NaOH 2M and the maximum Molarity of NaOH 16M. It was expected that the various concrete strengths would be obtained from the category of normal to high strength concrete. The workability of fresh concrete were maintained by keeping the ratio of alkaline solutions to fly ash weight to be 0.51.

| Table 2. Geopolymer concrete mix design (kg/m³). |
|---------------------------------------------|
| **No** | **Material** | **NaOH Molarity** |
|       |              | 2M       | 4M       | 6M       | 8M       | 12M      | 16M      |
| 1     | Coarse Aggregate (kg) | 849.06   | 850.84   | 852.46   | 853.95   | 1131.88  | 1133.70  |
| 2     | Fine Aggregate (kg)   | 723.28   | 724.79   | 726.17   | 727.44   | 610.03   | 611.01   |
| 3     | Fly Ash (kg)          | 467.82   | 468.80   | 469.69   | 470.51   | 429.51   | 430.20   |
| 4     | Na₂SiO₃ (kg)          | 178.94   | 179.32   | 179.66   | 179.97   | 161.07   | 161.33   |

| Formula | Concentration |
|---------|--------------|
| TiO₃    | 1.76%        |
| K₂O     | 1.66%        |
| P₂O₅    | 0.93%        |
| Cl      | 0.67%        |

| Formula | Concentration |
|---------|--------------|
| BaO     | 0.05%        |
| SnO₂    | 0.03%        |
| NiO     | 0.02%        |
5. Mixing process

It should be noted that NaOH solution was made 24 hours before use, while the mixture of NaOH solution and sodium silicate gel (Na₂SiO₃) can be prepared few hours before concrete mixing. Coarse and fine aggregates were prepared under SSD conditions. The mixing process was begun with mixing fly ash and alkaline solution for 5-10 minutes. When the fly ash and alkaline solution had become a paste and were well distributed, then fine aggregates and coarse aggregates were poured into the mixer gradually. The mixing process until the formation of homogeneous fresh concrete took 10-15 minutes.

6. Test specimens

In accordance with the objectives of the research to obtain the mechanical properties of geopolymer concrete there were 3 types of concrete specimens, which have been made as following:

- Cylinder concrete specimens with the dimension of 100/200 mm, for compressive strength
- Mini beam concrete specimens with cross section size of 60x60 mm and length of 300 mm, for flexural strength tests
- I-beam concrete specimens with cross section size 75x110 mm and length of 500 mm, for shear strength tests.

7. Test results and discussions

In this study, the authors collected data from 30 concrete cylinders 100/200 mm, 60 mini beams, 6 I-beams. To achieve wide range of compressive strength, the test specimens were maintained using 2 types of curing methods, either with room temperature or steam curing. From all test data, a description of Mechanical Properties of geopolymer concrete will be evaluated, namely the correlation of the grade of NaOH Molarity to the compressive strength, the compressive strength to flexural strength, shear strength.

7.1. Compressive strength and sodium hydroxide concentration (NaOH molarity)

Based on the curing method used, each mix design of NaOH Molarity will produce 2 different compressive strength namely room temperature and steam curing. The average compressive strength for each NaOH molarity used was plotted in the picture 2. The test results of all test objects showed that steam curing produced a compressive strength higher than the room temperature curing. Compressive strength produced from all specimens showed that high strength geopolymer concrete could be produced starting with the 8M NaOH Molarity. The highest compressive strength of 67 MPa was produced with molarity of NaOH 16M.

| NaOH Molarity | Curing method | Compressive strength (MPa) | Average (MPa) |
|---------------|--------------|----------------------------|--------------|
| 2M            | Room Temperature Curing (RTC) | 39.00 | 36.60 | 35.90 | 47.09 | 39.65 |
| 4M            | Room Temperature Curing (RTC) | 28.70 | 33.40 | 30.90 | 46.45 | 34.86 |
| 6M            | Room Temperature Curing (RTC) | 26.59 | - | - | - | 26.59 |

Table 3. Test result of 28 days old concrete compressive strength.
NaOH Molarity | Curing method | Compressive strength (MPa) | Average (MPa) |
---|---|---|---|
8M | Room Temperature Curing (RTC) | 49.64 52.82 | - - 51.23 |
12M | | 58.55 39.45 | - - 49.00 |
16M | | 58.55 64.91 | - - 61.73 |
2M | Steam Curing (SC) | 35.64 | - - 35.64 |
4M | | 53.00 48.00 48.50 | 50.90 50.10 |
6M | | 49.70 46.00 41.90 | 61.72 49.83 |
8M | | 63.64 62.36 | - - 63.00 |
12M | | 66.18 63.64 | - - 64.91 |
16M | | 63.64 70.00 | - - 66.82 |

In accordance with the resulting compressive strength data, it could be drawn a linear line equation to show the relationship between compressive strength and NaOH Molarity. From the figure two linear equations were obtained, namely for the room temperature curing with the equation:

\[
 f_c' = 2.0612 (\text{NaOH-M}) + 36.57
\]  
(1)

and for the steam curing with the equation

\[
 f_c' = 2.2911 (\text{NaOH-M}) + 24.744
\]  
(2)

7.2. Compressive strength and flexural strength
In accordance with the standards for structural concrete, it is also necessary to examine the relationship between compressive strength and flexural strength of concrete. In accordance with SNI 2847-2013 Design Standards for structural concrete [6], the flexural strength of normal concrete can be determined based on the equation:

\[
 fr = 0.623 \sqrt{f_c'}
\]  
(3)
To study the relationship between compressive strength and specific flexural strength for geopolymer concrete, the authors collected 134 data on compressive strength and flexural strength. The data is derived from various geopolymer concrete studies that have been reported in various research papers [3-5]. On figure 4 can be seen the results of inclusion of all data points of compressive strength and flexural strength of each geopolymer concrete specimen. Based on the results of statistical analysis and regression of the 134 test results could be obtained a nonlinear equation for the calculation of flexural strength:

\[ f_r = 0.5f_c^{0.705} \]  

To simplify the equation to be square root of compressive strength in accordance to the equation 3 (SNI 2847-2013), the authors derived the equation to be:

\[ f_r = 1.05\sqrt{f_c'} \]  

as an equation to determine the flexural strength of geopolymer concrete.

**Figure 3.** Compressive strength of geopolymer concrete versus flexural strength.

### 7.3. Compressive strength and shear strength

Like flexural strength, geopolymer concrete shear strength is important to be determined for structural concrete analysis. For normal concrete, based on SNI 2847-2013 [6] the shear strength of concrete is calculated from the equation:

\[ V_c = 0.17\sqrt{f_c'} \]  

Same as for normal concrete, it is also necessary to determine the shear strength of geopolymer concrete based on its compressive strength. In this paper the magnitude of geopolymer concrete shear strength was taken from 6 I-beam specimens made from geopolymer concrete and reinforced either with steel bars or FRP, to secure beam collapse due to its shear failure. Table 4 showed compressive and shear strength test results of all I beams.
Figure 4. Geopolymer concrete flexural strength specimens.

For a comparative study of geopolymer concrete shear strength to normal concrete shear strength, the all I beams test data were included in the normal concrete shear strength graph based on ACI 445-99R report [7]. Figure 5 shows that all the geopolymer concrete shear strength were greater than the normal concrete shear strength specified in SNI 2847-2013 [6].

Table 4. Shear strength to compressive strength of geopolymer concrete.

| No | Name                | Compressive Strength (MPa) | Shear Strength (MPa) | $\frac{v_c}{\sqrt{f_c'}}$ |
|----|---------------------|----------------------------|----------------------|---------------------------|
| 1  | GCSB - 12 M - TUL 1 | 57.53                      | 1.44                 | 0.19                      |
| 2  | GCSB - 12 M - TUL 2 | 35.38                      | 3.11                 | 0.52                      |
| 3  | GCSB - 12 M - TUL 3 | 35.38                      | 2.82                 | 0.47                      |
| 4  | GCSB - 12 M - TUL 4 | 43.91                      | 2.42                 | 0.37                      |
| 5  | GCSB - 12 M - FRP 1 | 43.91                      | 1.99                 | 0.30                      |
| 6  | GCSB - 12 M - FRP 2 | 43.91                      | 1.93                 | 0.29                      |
Figure 5. Graph of comparison of shear strength between geopolymer and normal concrete [7].

8. Conclusion

Based on the results of the tests obtained in this study, the following conclusions can be taken as followings:

- The results of this study produced 3 values of concrete mechanical properties which are very much needed on structural reinforced geopolymer concrete design, namely compressive strength, flexural strength and shear strength.
- Same as normal concrete, geopolymer concrete mixture can be designed to have the desired compressive strength. In this study, the tested concrete cylinder specimens achieved compressive strength from 25 MPa to up to 70 MPa. It means, the geopolymer concrete could be categorized as normal to high strength concrete.
- Steam curing method was proven to increase compressive strength between 20%-30% higher than room temperature curing.
- The achievement of geopolymer concrete strength is closely related to the concentration of NaOH solution. The correlation between the geopolymer concrete compressive strength and NaOH molarity can be written as the equation (1) for temperature curing and equation (2) for steam curing.
- This study also produced a correlation between compressive strength and flexural strength. Based on structural design standard for normal concrete (SNI 2847-2013) the flexural strength was determined using equation: $f_{cr} = 0.623 \sqrt{f'_c}$. The results of the study showed that the flexural strength of the geopolymer concrete was greater than flexural strength of normal concrete. For this reason the flexural strength with compressive strength can be calculated by the equation: $f_{cr} = 1.05 \sqrt{f'_c}$.
- Same as flexural strength, the results of this study indicated that the shear strength of geopolymer concrete is greater than normal concrete shear strength, which was specified by the equation $V_c = 0.17 \sqrt{f'_c}$. To determine the equation of geopolymer concrete shear strength more precisely, further research is needed.
Acknowledgement
This research was funded by Directorate for Research and Community Service, Directorate General of Research and Development Strengthening, Ministry of Research, Technology, and Higher Education of the Republic of Indonesia, No.: 026/AKM/PNT/2019.

References
[1] Joseph D 2013 Geopolymer Cement (France: Institut Géopolymère)
[2] Joseph D 1994 Properties of Geopolymer Cements 1st Int. Conf. on Alkaline Cements and Concretes p 131–49
[3] Harianto Hardjasaputra and Esteriana E 2018 Research on the mix design of geopolymer based on suralaya fly ash concrete to compressive and bending strength Jurnal Ilmiah Teknik Sipil (In Indonesian) 22(1) 24–33
[4] Rachmansyah, Harianto Hardjasaputra and Melanie Cornelia 2018 Experimental study of effect additional water on high performance geopolymer concrete MATEC Web of Conf. vol 27
[5] Harianto Hardjasaputra, Ivan F, Judith I, Melanie Cornelia and Rachmansyah 2018 The effect of using palm kernel shell ash and rice husk ash on geopolymer concrete MATEC Web of Conf. vol 21
[6] SNI 2847:2013 2013 Structural Concrete Design Standard for Building (Jakarta: Badan Standardisasi Nasional Indonesia (In Indonesian))
[7] ACI-ASCE Committee 445 1999 Recent Approaches to Shear Design of Structural Concrete (American Concrete Institute: Farmington Hills) MI58333