The influence of molarity variations to the mechanical behavior of geopolymer concrete

by Nuroji Nuroji

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The influence of molarity variations to the mechanical behavior of geopolymer concrete

Purwanto[1,*], *Ay Lie* Han[1,2], *Nuroji*[3], and *Januarti* Jaya Ekaputri[4]

1 Introduction

The latest tendency towards environmentally friendly and green concrete underlined the facts that cement, one of the major binders in concrete, is not a green material. The carbon dioxide that results during the cement production increases global warming. The production of one ton of Portland cement results in approximately one ton of CO_2 being released into the atmosphere [1,2,3]. A solution to this problem is the exploration of alternate binding materials to replace or reduce cement use. One of the major requirements for such a material is a high silica and alumina content [4]. By introducing the geopolymer concrete technology, a part or the overall cement demand can be replaced. Geopolymer is a synthesis of natural organic materials through a polymerization process. The main constituents of this material contain silica and alumina, such as iron blast furnace slag, bottom ash, fly ash, rice husk ash,

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clay, and ground trass (a light-colored variety of volcanic ash resembling pozzolana). The silica and alumina elements in the material are subjected to a chemical reaction with an alkali solution, resulting in a geopolymer paste. The synergy between aggregates and this paste will result in geopolymer concrete [5].

The latest research in the field of geopolymer concrete is focused on the mix design methods, the effect of curing, as well as the influence of activator molarity to the concrete mechanical properties. Until recently, no standardized mix design method or formulas exist for exactly designing the targeted geopolymer concrete strength, nor is the concrete strength development as a function of concrete age readily available. One of the major reasons for this is the limitation in fly ash data mapping. The quality of the fly ash, the major component for geopolymer concrete, depends very much on its location. Factors such as the type of coal and the burning process result in differentiations in fly ash composition. The molarity directly influences the resulting concrete strength. The molarity in a solution reflects the number of dissolved material molecules in one liter or milliliter of the solution. The higher the degree of molarity, the higher the viscosity of the end solution, resulting in an increase in concrete compression strength.

2 Literature review on geopolymer concrete

Geopolymer concrete is a relatively new material that does not use cement as a binder [5, 6]. The substitute for the cement binder is a waste material from the coal burning process known as fly ash. Fly ash contains high contents of silica (Si) and alumina (Al). Activated by an alkali solution, these chemical elements transform into a binder. The mixing of geopolymer concrete closely resembles conventional concrete, the aggregate capturing 75-80% of its total mass. The silica and alumina in the fly ash with a low calcium concentration is activated by a combination of sodium hydroxide and sodium silicate solution, forming a geopolymer paste that binds the aggregates and the nonreactive materials [7].

In accordance with the ASTM C618, fly ash is categorized into three classes. Class N fly ash is obtained naturally, while class F fly ash originates from anthracite or bituminous coal burning. Class C fly ash is derived from the lignite or sub-bituminous coal burning process [8]. An activator is a substance or element that initiates the chemical reaction of another constituent. In geopolymer concrete, the activator of fly ash is a hydrated alkali element. The theoretical background for the choice of this hydrated alkali is the fact that silica is an acidic material having a pH level below 7.0. The alkali hydroxide is a basic, and the chemical reaction between these two elements will result in silica [9]. The activator is a requirement for the alumina and silica monomer (a molecule that can be bonded to other identical atoms to form a polymer) polymerization in the fly ash. The alkali functions as a precursor, by dissolution of the particles into the monomers SiO_4 and AlO_4. During the curing procedure, condensation of monomers forms a network of three-dimensional, cross bonded polymers. The inclusion of sodium hydroxide is aimed to add Na^+ ions to the polymerization [10].

3 Research methodology

The research work was conducted experimentally at the Construction and Material Laboratory, Civil Engineering Department, of the Diponegoro University and followed the steps as outlined in Fig. 1. The variable in this study was the molar concentration, set at 6, 8 and 10 molars. The specimens were 150 by 300 mm cylinders tested in compression at the ages of 7, 14, and 28 days. The geopolymer concrete cylinders were compared to conventional cement concrete cylinders having the same volumetric material proportions. These specimens functioned as controlling elements.

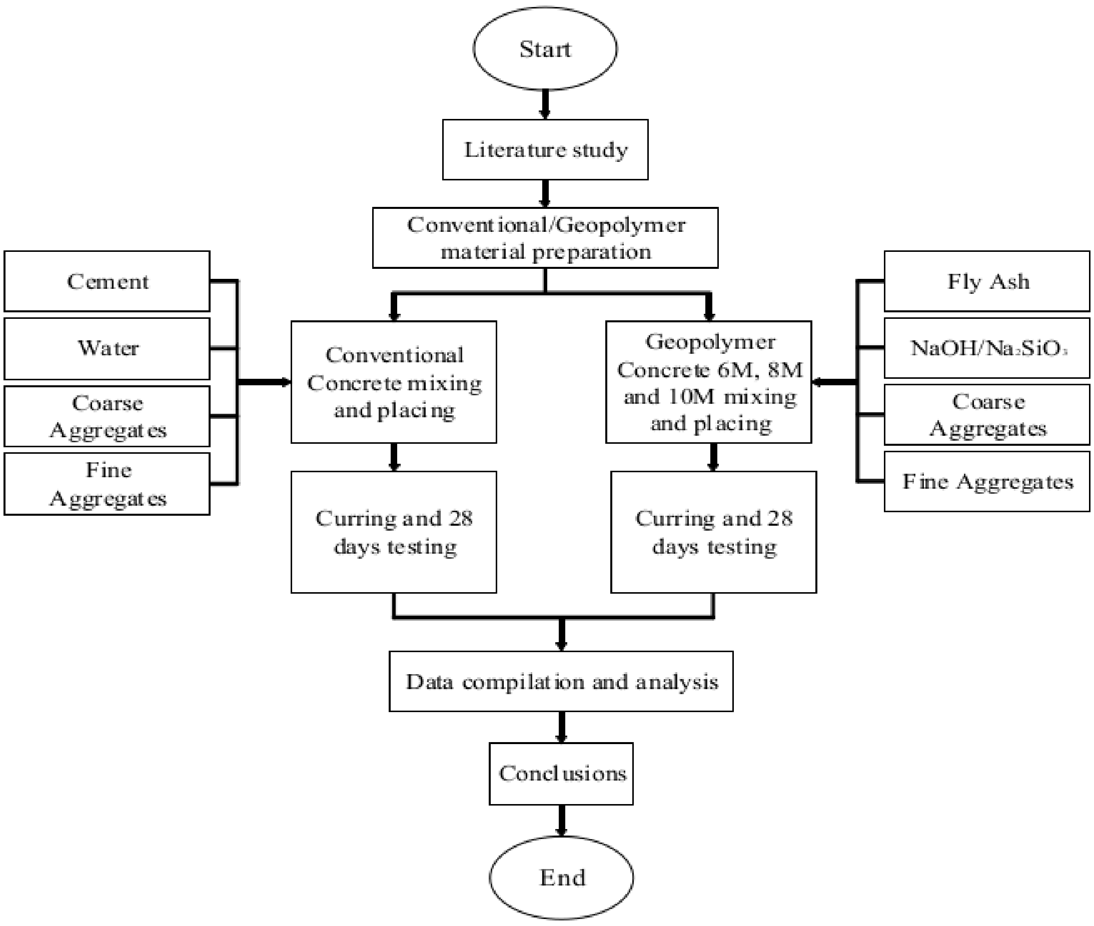

Fig. 1. Research outline.

3.1 Materials

The fly ash used in this research work originated from PT. Pembangkit Jawa Bali (PJB) Tanjung Jati B in Jepara. The fly ash has a chemical composition as listed in Table 1.

Table 1. Fly ash PJB Tanjung Jati – Jepara chemical composition.

Parameters	**Content (%)**	**Standardized to**					
		ASTM C 618			**ACI Part 1 226-3R**		
		N	**F**	**C**	**N**	**F**	**C**
Silicon dioxide (SiO_2)	76,87	70	70	50	-	70	50
Aluminum oxide (Al_2O_3)							
Iron oxide (Fe_2O_3)							
Calcium oxide (CaO)	11,48	-	-	-	-	<10	>10
Sulfur trioxide (SO_3)	2,29	4	5	5	-	5	5
Moisture content	0,33	3	3	3	-	3	3
Loss on ignition	1,66	10	6	6	-	6	6
Sodium dioxide (Na_2O)	1,12	-	1,5	1,5	-	1,5	1,5

Source: *Chemical Analysis* Varia Usaha Beton.

Examining the chemical composition in accordance with ASTM C618 [8], the fly ash from PJB Tanjung Jati B is classified as class F. The classification is based on the silicon dioxide (SiO_2), aluminum oxide (Al_2O_3) and iron oxide (Fe_2O_3) compounds that comprise a 76,87 % of the total content, thus exceeding the minimum 70 % mandated by the code for the classification of type F fly ash. The activator solution used in this study was sodium silicate (Na_2SiO_3) and sodium hydroxide (NaOH). The sodium silicate enhances the polymerization reaction, whereas the sodium hydroxide reacts with the aluminum (Al) and silica (Si) of the fly ash, resulting in a strong bond polymer [11].

3.2 Concrete mix proportions

The mix proportions of basic material for the geopolymer concrete are shown in Table 2.

Table 2. Mix proportions for geopolymer concrete.

Remarks	Volumetric Composition
Aggregate to binder and activator	70% to 30%
Coarse to fine aggregates	60% to 40%
Binder (*fly ash*) to activator (Na_2SiO_3 and NaOH)	65% to 35%
Na_2SiO_3 to NaOH (for 6, 8, 10 molars)	2 to 1

The determination of the proportion percentage to the total is as follows:
Coarse aggregate proportion = 70% x 60% = 42,0 %
Fine aggregate proportion = 70% x 40% = 28,0 %
Binder (fly ash) proportion = 30% x 65% = 19,5 %
Activator proportion = 30% x 35% = 10,5 %

Conventional concrete has identic material mix proportions. The binder (fly ash) for the geopolymer concrete here was replaced with cement, and the activator with water. The mix proportions of the basic material for the controlling concrete are shown in Table 3.

Table 3. Mix proportions for conventional concrete.

Remarks	Volumetric Composition
Aggregate to cement and water	70% to 30%
Coarse to fine aggregates	60% to 40%
Cement to water	65% to 35%

Figure 2 represents the mix proportions of basic materials for both the geopolymer concrete and the conventional concrete. The percentages are expressed in volume of concrete [12]. The specimens were denoted as 6M, 8M, and 10M for the samples having 6, 8 and 10 molars, respectively. The conventional concrete specimens were denoted as Control.

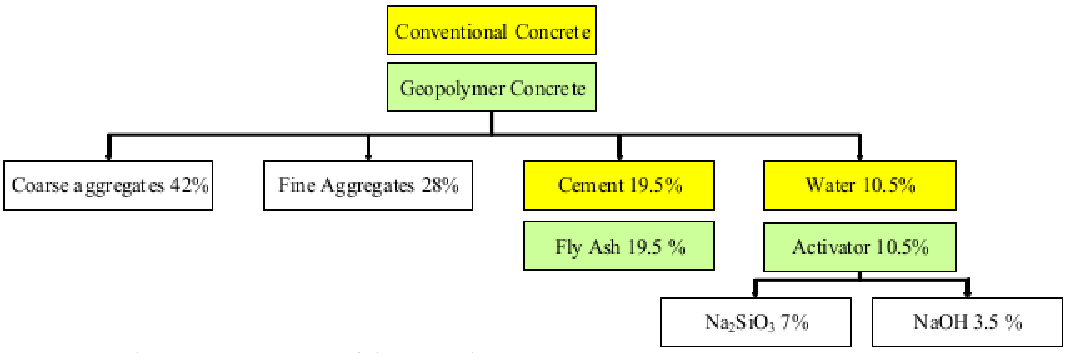

Fig. 2. Specimen concrete material proportions.

For the geopolymer concrete, three variations in molar concentrations were studied. For each category, nine cylinders were prepared, while for the conventional concrete, three cylinders were casted. The conventional concrete was especially prepared to observe the time depended progress of the geopolymer concrete strength to the 28 days compression strength.

4 Result and analyses

4.1 Specific gravity of concrete

The evaluation of specific gravity for both conventional as well as geopolymer concrete was conducted at the age of 28 days, and the data are shown in Fig 3.

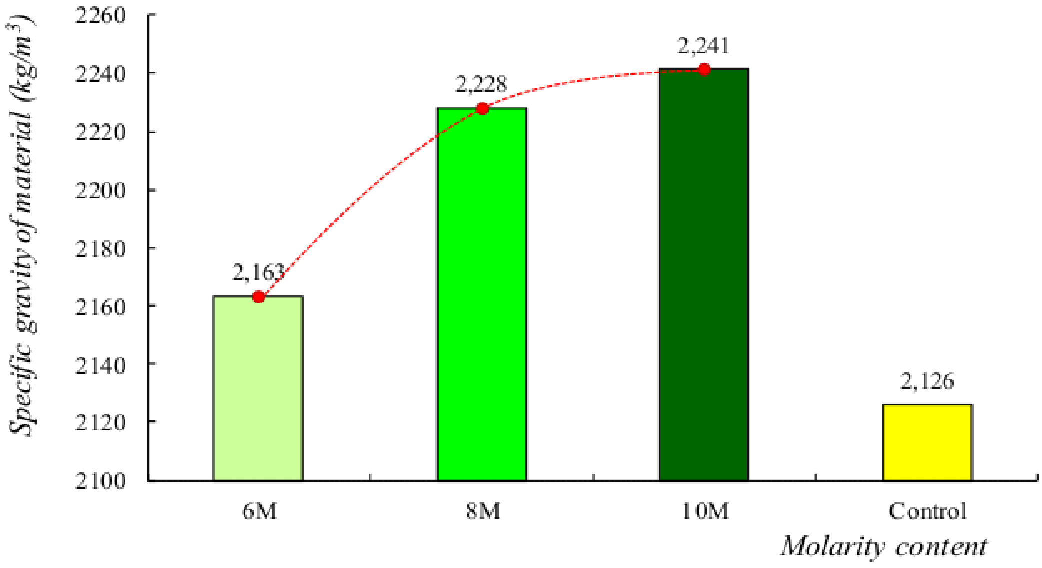

Fig. 3. Specific gravity comparison geopolymer and conventional concrete as a function of molarity.

The test results show that the specific gravity of geopolymer concrete ranges from 2163 kg/m^3 to 2241 kg/m^3. The geopolymer concrete has a higher specific gravity when compared to conventional concrete having a specific gravity of 2126 kg/m^3. Figure 3 shows that the 6, 8, and 10 molar specimens have a specific gravity increase of 1.8%, 4.8%, and 5.4% respectively, as compared to the conventional concrete. The data suggested that the specific gravity of geopolymer concrete is a direct function of the NaOH and molar content. It is known that the activator has a higher specific gravity when compared to water, used for the conventional concrete hydration activation of cement. The specific gravity of the concrete was measured using the mercury submersion method.

4.2 Compression strength

The compression strengths of the three geopolymer concrete categories were tested at the ages of 7, 14 and 28 days. The specimens 6M, 8M, and 10M had a variation in the NaOH molarity. Table 4 represents the test results.

Table 4. Compression strength.

Specimen designation	**Concrete age (days)**	**Average compression strength (MPa)**
6M	7	15.29
	14	31.33
	28	41.52
8M	7	21.14
	14	36.42
	28	45.29
10M	7	19.06
	14	35.67
	28	43.22
C	28	25.86

From the data in Table 4 it can be seen that the geopolymer concrete with the 8 molar NaOH content resulted in the highest 28 days compression strength f'_c when compared to the 6 molar and 10 molar concrete. The fluctuation in compression strength is a result of the variation in NaOH. The 6M specimen had a lower compression strength than the 8M specimens, suggesting that the molarity content influences the strength positively. On the contrary, the 10M specimen exhibited a decrease in compression strength when compared to the 8M specimen. For the 10M, difficulties in mixing and casting were encountered; the concrete mix had a very low workability level. The low workability resulted in a lower compacting degree and density of specimens when compared to the 6M and 8M specimens. This less compact concrete condition was confirmed by visual observation of the cylinders, resulting in a decrease in concrete compression (Fig 4). Figure 5 represents the comparison of 28 days compression strength.

Fig. 4. Poor compacting due to low workability for 10M specimens.

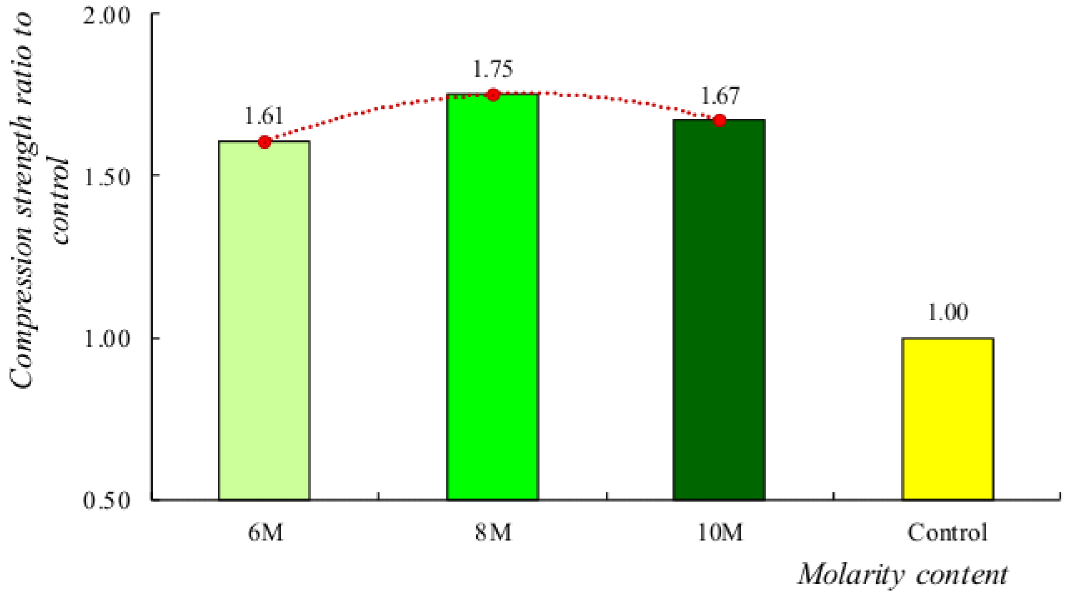

Fig. 5. Compression strength ratio to the controlling specimen as a function of molarity.

From the graph, it can be concluded that the geopolymer concrete reached a maximum at 8M. The fluctuation path as a function of molarity content followed a quadratic trajectory. Appraising the mathematical expression of this curve, it was found that an absolute maximum was reached for a molar content of 8.2 mol.

Further, an analysis of the strength development process as a function of concrete age was performed. The results are presented in Fig. 6.

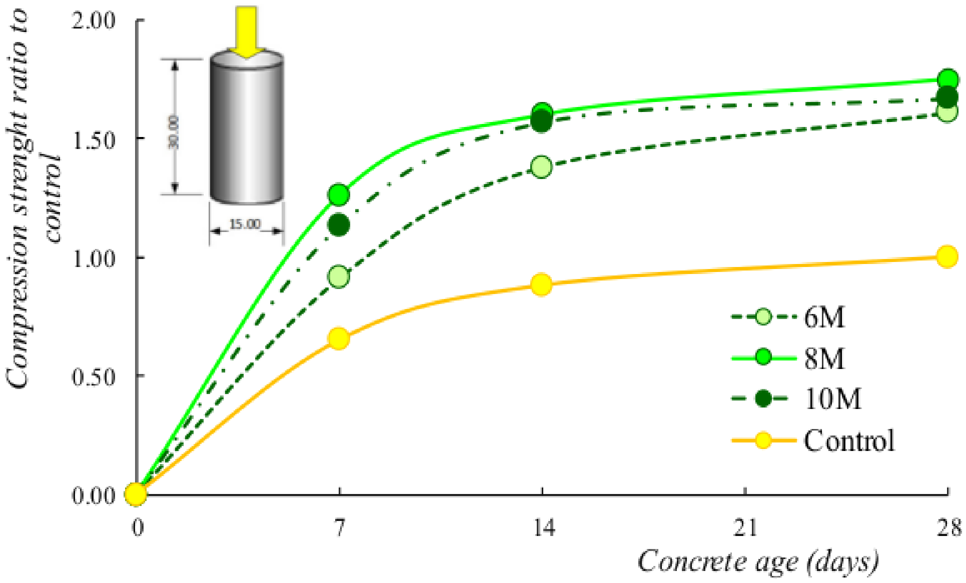

Fig. 6. Compression strength ratio development $\frac{f_c}{f'_{cc}}$.

From the data is seen that all geopolymer concretes, regardless of their molar content and development age, have a higher compression strength f'_c when compared to the controlling element strength f'_{cc}.

To examine the compression strength development, the increase in compression strength f_c relatively to the 28 days cylindrical compression strength f'_c was calculated and is shown in Table 5.

Table 5. Compression strength development ratio to 28 days $\frac{f_c}{f_c'}$.

Age	Control	6M	8M	10M
0	0	0	0	0
7	0.65	0.37	0.47	0.44
14	0.88	0.75	0.80	0.83
28	1	1	1	1

The strength development of all geopolymer concretes followed a trajectory similar to conventional concrete. For conventional concrete, the most significant increase in strength is achieved during the first quarter of the 28 days period. At 7 days, 65% of f'_c is reached. This is not the case with geopolymer concrete. All geopolymer concretes had a strength development of around 40% of f'_c at the age of 7 days suggesting that the chemical reactions for fly ash and the activator are slower, compared to the hydration of cement. Studies on curing methods [12] advised a curing method by heating. Tests conducted at the Diponegoro Laboratory using an oven with a heating capacity of 60° Celsius resulted in a 130% increase in compression strength at the age of 7 days. The specimens were oven-cured for 8 hours. The comparison specimens were cured using the wet-blanket covering method. At 14 days, the development progress of all geopolymer concrete resembled conventional concrete. The higher the molarity, the closer the values were, as can be seen in table 5.

5 Conclusion

All geopolymer concretes have a higher 28 days compression strength when compared to conventional concrete having the same volumetric material proportions. The strength of geopolymer concrete is a direct function of the molar content; however, for a 10 molars concentration, the fresh concrete mix becomes difficult to mix and cast due to the low workability of the mix. This low workability resulted in less dense concrete and a reduced compactions degree. The optimum molar concentration lays around 8 molars, and the relationship of compression strength as a function of molar content followed a convex, parabolic path. A theoretical maximum was found for a value of 8.2 molars.

The specific gravity of geopolymer concrete is a direct function of the activator and fly ash. While the fly ash has a specific gravity closely approaching cement, the activator has a much higher specific gravity compared to water. All geopolymer concretes consequently were relatively heavier than conventional concrete. The higher the molar concentration, the larger this increase in weight. Aforementioned is one of the major disadvantages of geopolymer concrete. To minimize its disadvantageous characteristic, structures attached to the ground such as foundations or road paving could be advised.

The initial strength development at ages of 7 days is below the strength rate of conventional concrete. The strengths of all geopolymer specimens were in fact below 50% of the 28 days strength f'_c. This fact should be kept in mind when planning on early strain and stress responses on the geopolymer concrete structural elements. It also makes geopolymer concrete less suitable for prestressed concrete, especially when a pre-tensioning system with very early prestressing is favored. Generally, the behavior of geopolymer concrete closely resembles conventional concrete both in terms of its mechanical and physical behavior, making this material an excellent substitute for conventional, cement concrete.

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