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FACTORS INFLUENCING THE COMPRESSIVE STRENGTH OF FLY ASH-BASED GEOPOLYMER CONCRETE

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ABSTRACT

This paper describes the effects of several factors on the properties of fly ash based geopolymer concrete, especially the compressive strength. The test variables included were the age of concrete, curing time, curing temperature, quantity of superplasticizer, the rest period prior to curing, and the water content of the mix.

The test results show that the compressive strength of geopolymer concrete does not vary with age, and curing the concrete specimens at higher temperature and longer curing period will result in higher compressive strength. Furthermore, the commercially available Naphthalene-based superplasticizer improves the workability of fresh geopolymer concrete. The start of curing of geopolymer concrete at elevated temperatures can be delayed at least up to 60 minutes without significant effect on the compressive strength. The test data also show that the water content in the concrete mix plays an important role.

Keywords: Compressive strength; Fly ash; Geopolymer concrete.

INTRODUCTION

The global cement industry contributes around 1.35 billion tons of the greenhouse gas emissions annually, or about 7% of the total man-made greenhouse gas emissions to the earth's atmosphere [1,2]. Therefore, one of the most challenging issues faced by the concrete industries in the future is the impact of cement production on the environment.

McCaffrey [2] suggested three alternatives to reduce the amount of carbon dioxide (CO_2) emissions from the cement industries, i.e. to decrease the amount of calcined material in cement, to decrease the amount of cement in concrete, and to decrease the number of buildings using cement. Likewise, Mehta [3] also proposed two stages in the production of environmentally friendly concrete. A short-term effort, also known as '*industrial ecology*', is an attempt to use fewer natural resources, utilise less energy, and minimise the carbon dioxide emissions. The long-term view is to reduce the impact of unwanted industrial by-products by lowering the rate of material consumption.

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The development of geopolymer concrete is an important step towards the production of environmentally friendly concretes. Geopolymer is an inorganic alumino-silicate compound, synthesized from materials of geological origin or from by-product materials such as fly ash, rice husk ash, etc., that are rich in silicon and aluminium [4]. The geopolymer concrete is produced by totally replacing the Ordinary Portland Cement (OPC). Therefore, the use of geopolymer technology not only substantially reduces the CO_2 emissions by the cement industries, but also utilises the waste materials such as fly ash. It is to be noted that fly ash, one of the possible sources for making geopolymer binders, is available abundantly world wide, and yet its usage to date is very limited [1,5,6]. Consumption of fly ash in the manufacture of geopolymers is an important strategy in making concrete more environmentally friendly. For this reason, fly ash has been chosen as a base material for this project in order to better utilise this industrial waste.

As a relatively new material, the nature of fresh state of geopolymer concrete and its effect on the properties in the hardened state are yet to be studied. The fresh geopolymer concrete has a stiff consistency and high viscosity [7,8]. This paper presents research data on the effect of several parameters on the compressive strength of geopolymer concrete.

PREVIOUS RESEARCH

The chemical composition of geopolymer is similar to zeolite, but amorphous in microstructure [4]. The silicon and the aluminium atoms in the source materials are induced by alkaline solutions to dissolve and form a gel. The polymerisation process may be assisted by applied heat, and followed by drying. The geopolymer gel binds the loose coarse aggregates, fine aggregates and other un-reacted materials together to form the geopolymer concrete. The chemical reaction period is substantially fast.

Davidovits [9,10] claims that the Egyptian Pyramids were built by casting geopolymer on site. He also reported that this material has excellent mechanical properties, does not dissolve in acidic solutions, and does not generate any deleterious alkali-aggregate reaction even in the presence of high alkalinity [4]. Some of the immediate applications of geopolymer concrete are marine structures, pre-cast concrete products such as railway sleepers, sewer pipes, pre-fabricated units for the housing market etc., as well as waste containment or encapsulation.

Only limited research data on geopolymer concrete are available in the literature. Earlier work by the authors [11,12] reported the manufacturing process and the effect of various parameters such as curing temperature, curing time, sodium silicate-to-sodium hydroxide ratio, sodium hydroxide-to-free water ratio and the age of concrete on the compressive strength of geopolymer concrete.

EXPERIMENTAL WORK

Materials

In the experimental work, class F-fly ash obtained from Collie Power Station, Western Australia, was used as the base material. Table 1 shows the chemical composition of the fly ash, as determined by X-Ray Fluorescence (XRF) analysis.

Table 1. Composition of fly ash as determined by XRF (mass %)

SiO_2	Al_2O_3	Fe_2O_3	CaO	Na_2O	K_2O	TiO_2	MgO	P_2O_5	SO_3	LOI*)
53.36	26.49	10.86	1.34	0.37	0.80	1.47	0.77	1.43	1.70	1.39

*) Loss on ignition

Analytical grade sodium hydroxide in flake form (NaOH with 98% purity), and sodium silicate solution (Na_2O = 14.7%, SiO_2 = 29.4% and water = 55.9% by mass), were used as the alkaline activators. In order to avoid the effect of unknown contaminants in the mixing water, the sodium hydroxide flake was dissolved in distilled water and the activator liquid was prepared at least one day prior to its use. To improve the workability of fresh concrete, a commercially available naphthalene-based superplasticizer was used. Four types of locally available aggregates, i.e. 20 mm aggregate, 14 mm aggregate, 7 mm aggregate, and fine sand, in saturated surface dry condition were mixed together. The grading of this combined aggregate had a fineness modulus (FM) of 5.0.

Manufacture and Test of Specimens

The aggregates and the fly ash were mixed dry in a pan mixer for 3 minutes. The alkaline solutions and the superplasticizer were mixed together, then added to the solid particles in the mixer, and mixed for another 3 to 5 minutes. The fresh concrete had a stiff consistency and was glossy in appearance. The mixture was cast in 100x200 mm cylinder steel moulds in three layers. Each layer received 60 manual strokes and vibrated for 10 seconds on a vibrating table. Five cylinders were prepared for each test variable.

Immediately after casting, the samples were covered by a film, and left in room temperature for 30-60 minutes. The specimens were then cured in an oven at a specified temperature for a period of time in accordance with the test variables selected. The aim of covering the samples was to reduce the loss of water due to evaporation during curing at an elevated temperature.

At the end of the curing period, the 100x200 mm test cylinders were removed from the oven, and kept in the moulds for six hours in order to avoid drastic change of the environment. The specimens were then removed from the moulds, left to air dry at room temperature until loaded in compression at the specified age in a universal test machine. The loading rate and other procedures used were in accordance with the details specified in the relevant Australian Standard for making and testing OPC concrete.

TEST RESULTS

Table 2. Detail of Solutions and Curing of Specimens

Concentration of NaOH solution (Molarity)	8 M
Sodium silicate/NaOH solution by mass	2.5
Curing time	24 hours
Curing temperature	60°C

In this paper, the effects of various parameters on the compressive strength of geopolymer concrete are reported. Each of the test data points plotted in various graphs corresponds to the mean value of the compressive strengths of five test cylinders in a series. The standard deviations were plotted on the test data points as the error bar.

The details of the solutions used in the mix, and the curing condition are given in Table 2, otherwise it will be stated specifically. The activator liquids-to-fly ash ratio by mass was kept constant approximately at 0.35. The coarse and fine aggregates constituted about 77 percent by mass in the mixes.

Compressive Strength at Different Ages

Figure 1 shows the effect of age of concrete on the compressive strength. Because the chemical reaction of the geopolymer gel is due to substantially fast polymerisation process, the compressive strength does not vary with the age of concrete. This observation is in contrast to the well-known behaviour of OPC concrete, which undergoes hydration process and hence gains strength over the time.

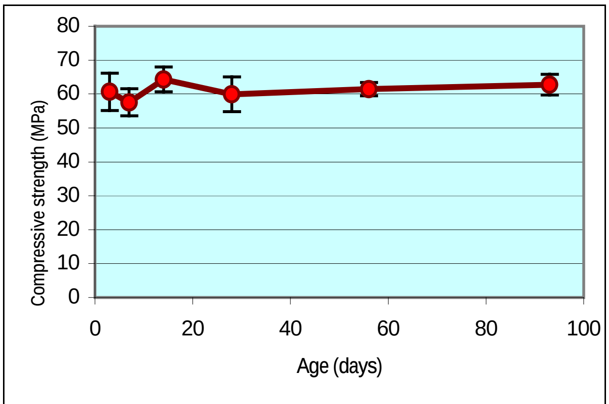

Figure 1. Compressive Strength at Different Ages

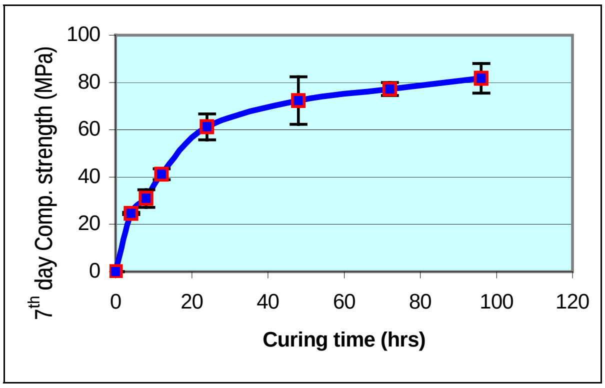

Figure 2. Influence of Curing Time on Compressive Strength

Effect of Curing Time

Figure 2 shows the influence of curing time on the compressive strength. Longer curing time improves the polymerisation process resulting in higher compressive strength. Davidovits [4] noted that when geopolymer is made using geological materials such as special metakaolin called KANDOXI as the source material, curing at a lower temperature for a shorter period of time is sufficient to achieve satisfactory results. The results shown in Figure 2 indicate that longer curing time does not produce weaker material as claimed by van Jaarsveld et al [13]. However, the increase in strength after curing for 48 hours is not significant.

Effect of Superplasticizer

In order to study the effect of superplasticizer, the other test parameters such as mix composition, curing period, curing time etc. were kept constant. The superplasticizer was added in proportion to the fly ash in the mix by mass. The cylinders were tested in compression on the 7^{th}-day after casting.

In the fresh state, the geopolymer concrete has a stiff consistency. Although adequate compaction was achievable, an improvement in the workability was considered as desirable. Tests were therefore performed to study the effect of adding commercially available naphthalene-based superplasticizer. The results of these tests are shown in Figure 3. The addition of superplasticizer improved the workability of the fresh concrete but had very little effect on the compressive strength up to about two percent of this admixture to the mass of fly ash. Beyond this value, there is some degradation of the compressive strength.

Effect of Rest Period Prior to Curing

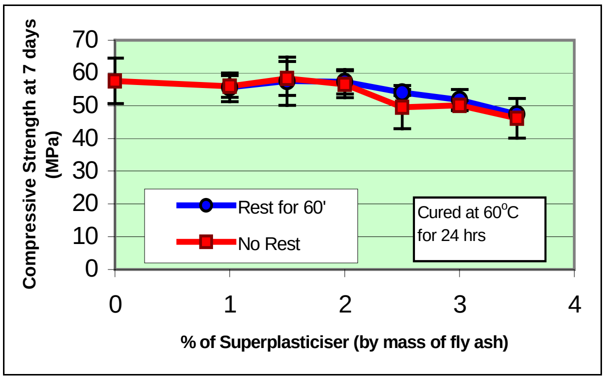

Figure 3. Effect of superplasticizer on compressive strength

Figure 3 shows two sets of data. In one set, the test cylinders were allowed to rest for 60 minutes after casting and then placed in the oven for curing at 60°C for 24 hours. In the other set, there was no rest period and the test cylinders were placed in the oven immediately after casting.

The results plotted in Figure 3 show that there is very little difference between the strengths of the two sets of specimens. This is an important outcome in practical applications of geopolymer concrete. For instance, when geopolymer concrete is used in precast concrete industry, the results in Figure 1 indicate that there is sufficient time available between casting of products and sending them to the curing room.

Effect of Water Content in the Mix

Previous research by Barbosa et al. [14] on geopolymer pastes showed that the water content in the mix played an important role on the properties of geopolymer binders. In order to study the effect of water content on the compressive strength of geopolymer concrete, several tests were performed. The details of the basic mix used in this series of tests are given in Table 3. The other details of the mixes were the same as those used in the earlier part of this paper. The percentage of the superplasticizer to the mass of fly ash was 1.5%, the delay time was 30 minutes, and there was no rest period. In order to quantify the water content in the geopolymer concrete mix, the ratio of water (H_2O)-to-sodium oxide (Na_2O) was calculated in terms of molar ratio of the oxides. Note that both H_2O and Na_2O are identified in both the activator liquids used in this study. That is, the sodium silicate is composed of H_2O and Na_2O. Also, the sodium hydroxide flake (NaOH), which was dissolved in water, can be expressed as.

$$2\ NaOH \rightarrow Na_2O + H_2O \qquad (1)$$

Table 3. Basic Mix Used in Water Content Series Tests

Concentration of NaOH solution (Molarity)	14 M
Sodium silicate/NaOH solution by mass	2.5
Curing time	24 hours
Curing temperature	30, 45, 75, 90°C

In addition, the fly ash also contained a small trace of Na_2O (see Table 1). For a given geopolymer mixture, the moles of H_2O and Na_2O from sodium silicate solution, sodium hydroxide solution, and fly ash can therefore be summed together and hence the molar ratio of H_2O-to-Na_2O can be calculated. For the basic mixture given in Table 3, this ratio was calculated as 10.0.

In order to vary the H_2O-to-Na_2O molar ratio, water was added to the basic mixture (Table 3) to yield two other values of molar ratio of H_2O-to-Na_2O. By adding extra water of 10.6 kg/m^3, the molar ratio of H_2O-to-Na_2O became 11.25, and by adding extra water of 21.2 kg/m^3, this ratio was 12.50. The 7-day compressive strengths of geopolymer concrete cylinders produced from the basic mixture and the two other mixtures as described above, are plotted in Figure 4 for different curing temperatures.

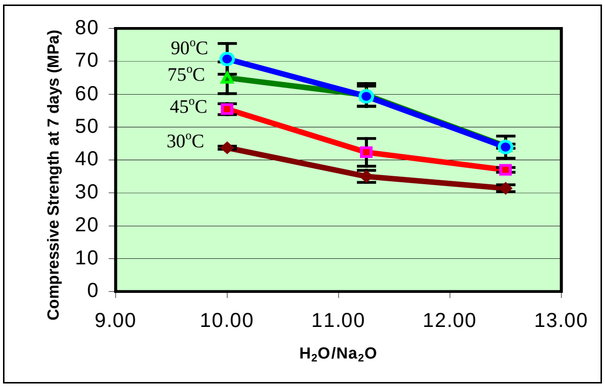

Figure 4. Effect of the molar H_2O-to-Na_2O ratio on Compressive Strength

As to be expected, the addition of water improved the workability of the mixtures. The results shown in Figure 4 clearly demonstrate the effect of the molar ratio of H_2O-to-Na_2O on the compressive strength of geopolymer concrete. The trends of these test results are similar to those observed by Barbosa et al [14] for their tests on geopolymer pastes. The results shown in Figure 4 also confirm that an increase in the curing temperature increases the concrete compressive strength. However, increasing the curing temperature from 75°C to 90°C did not show any significant gain in compressive strength.

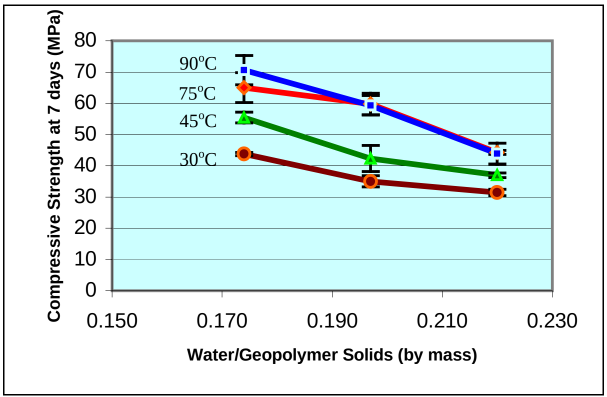

Figure 5. Effect of the Water-to-Geopolymer Solids ratio on Compressive Strength

The effect of water content is also illustrated in Figure 5 by plotting the compressive strength versus water-to-geopolymer solids ratio by mass. For a given geopolymer concrete, the total mass of water in the mixture is taken as the sum of the mass of water in the sodium silicate solution, the mass of water in the sodium hydroxide solution, and the mass of extra water, if any added to the mixture. The mass of geopolymer solids is the sum of the mass of fly ash, the mass of sodium hydroxide flake, and the mass of sodium silicate solids (the mass of Na_2O and SiO_2 in sodium silicate solution).

The test data shown in Figure 5 demonstrate that the compressive strength of geopolymer concrete decreases as the ratio of water-to-geopolymer solids by mass increases. The test trends shown in Figure 5 are somewhat analogous to the well-known effect of water-to-cement ratio on the compressive strength of OPC concrete, although the chemical processes involved in the formation of the binders of both these types of concretes are entirely different.

CONCLUSIONS

Several series of tests on geopolymer concrete were performed. Based on the experimental results reported in the paper, the following conclusions are drawn:

a. The compressive strength of geopolymer concrete does not vary with the age of concrete (Figure 1).
b. Longer curing time improves the polymerisation process resulting in higher compressive strength (Figure 2).
c. Commercially available Naphthalene-based superplasticizer can be utilised to improve the workability of the fresh geopolymer concrete without resulting in any segregation and degradation in the compressive strength (Figure 3) up to 2% of this admixture by mass of fly ash.
d. There is very little difference in compressive strengths of specimens cured immediately after casting and those sent to curing 60 minutes after casting (Figure 3).
e. Water content plays an important role in determining the compressive strength of geopolymer concrete as well as the workability of the fresh concrete (Figsure 4 & 5).
f. An increase in the curing temperature increases the concrete compressive strength, especially up to 75°C (Figs. 4 and 5).

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