FLY ASH-BASED GEOPOLYMER CONCRETE

By

B. V. Rangan

**Research Report GC 4
Engineering Faculty
Curtin University of Technology
Perth, Australia**

2008

Fly Ash-Based Geopolymer Concrete

by

Professor B. Vijaya Rangan, BE PhD FIEAust CPEng FACI
Emeritus Professor of Civil Engineering
Past Dean, Faculty of Engineering and Computing
Curtin University of Technology
PERTH, WA 6845
AUSTRALIA
Email: V.Rangan@curtin.edu.au

Abstract

The Report presents a comprehensive summary of the extensive studies conducted on fly ash-based geopolymer concrete. Test data are used to identify the effects of salient factors that influence the properties of the geopolymer concrete in the fresh and hardened states. These results are utilized to propose a simple method for the design of geopolymer concrete mixtures. Test data of various short-term and long-term properties of the geopolymer concrete are then presented. The last part of the Report describes the results of the tests conducted on large-scale reinforced geopolymer concrete members and illustrates the application of the geopolymer concrete in the construction industry. The economic merits of the geopolymer concrete are also mentioned.

1. Introduction

The global use of concrete is second only to water. As the demand for concrete as a construction material increases, so also the demand for Portland cement. It is estimated that the production of cement will increase from about from 1.5 billion tons in 1995 to 2.2 billion tons in 2010 (Malhotra, 1999).

On the other hand, the climate change due to global warming has become a major concern. The global warming is caused by the emission of greenhouse gases, such as carbon dioxide (CO_2), to the atmosphere by human activities. Among the greenhouse gases, CO_2 contributes about 65% of global warming (McCaffery, 2002). The cement industry is held responsible for some of the CO_2 emissions,

because the production of one ton of Portland cement emits approximately one ton of CO_2 into the atmosphere (Davidovits, 1994; McCaffery, 2002).

Several efforts are in progress to reduce the use of Portland cement in concrete in order to address the global warming issues. These include the utilization of supplementary cementing materials such as fly ash, silica fume, granulated blast furnace slag, rice-husk ash and metakaolin, and the development of alternative binders to Portland cement.

In this respect, the geopolymer technology proposed by Davidovits (1988) shows considerable promise for application in concrete industry as an alternative binder to the Portland cement (Duxson et al, 2007). In terms of global warming, the geopolymer technology could significantly reduce the CO_2 emission to the atmosphere caused by the cement industries as shown by the detailed analyses of Gartner (2004).

2. Geopolymers

Davidovits (1988; 1994) proposed that an alkaline liquid could be used to react with the silicon (Si) and the aluminum (Al) in a source material of geological origin or in by-product materials such as fly ash and rice husk ash to produce binders. Because the chemical reaction that takes place in this case is a polymerization process, he coined the term 'Geopolymer' to represent these binders.

Geopolymers are members of the family of inorganic polymers. The chemical composition of the geopolymer material is similar to natural zeolitic materials, but the microstructure is amorphous. The polymerization process involves a substantially fast chemical reaction under alkaline condition on Si-Al minerals, that results in a three-dimensional polymeric chain and ring structure consisting of Si-O-Al-O bonds (Davidovits, 1994).

The schematic formation of geopolymer material can be shown as described by Equations (1) and (2) (Davidovits, 1994; van Jaarsveld et al., 1997):

$$n(Si_2O_5,Al_2O_2)+2nSiO_2+4nH_2O+NaOH \text{ or } KOH \rightarrow Na^+,K^+ + n(OH)_3\text{-Si-O-Al}^-\text{-O-Si-}(OH)_3$$

(Si-Al materials)

$$(OH)_2$$

(Geopolymer precursor)

(1)

$$n(OH)_3\text{-Si-O-Al}^-\text{-O-Si-}(OH)_3 + NaOH \text{ or } KOH \rightarrow (Na+,K+)\text{-}(\text{-Si-O-Al}^-\text{-O-Si-O-}) + 4nH_2O$$

$$(OH)_2 \qquad\qquad O \quad O \quad O$$

(Geopolymer backbone)   (2)

The last term in Equation 2 reveals that water is released during the chemical reaction that occurs in the formation of geopolymers. This water, expelled from the geopolymer matrix during the curing and further drying periods, leaves behind discontinuous nano-pores in the matrix, which provide benefits to the performance of geopolymers. The water in a geopolymer mixture, therefore, plays no role in the chemical reaction that takes place; it merely provides the workability to the mixture during handling. This is in contrast to the chemical reaction of water in a Portland cement concrete mixture during the hydration process.

There are two main constituents of geopolymers, namely the source materials and the alkaline liquids. The source materials for geopolymers based on alumina-silicate should be rich in silicon (Si) and aluminium (Al). These could be natural minerals such as kaolinite, clays, etc. Alternatively, by-product materials such as fly ash, silica fume, slag, rice-husk ash, red mud, etc could be used as source materials. The choice of the source materials for making geopolymers depends on factors such as availability, cost, type of application, and specific demand of the end users.

The alkaline liquids are from soluble alkali metals that are usually Sodium or Potassium based. The most common alkaline liquid used in geopolymerisation is a combination of sodium hydroxide (NaOH) or potassium hydroxide (KOH) and sodium silicate or potassium silicate.

According to Davidovits (1994), geopolymeric materials have a wide range of applications in the field of industries such as in the automobile and aerospace, non-ferrous foundries and metallurgy, civil engineering and plastic industries. The type of application of geopolymeric materials is determined by the chemical structure in terms of the atomic ratio Si: Al in the polysialate. Davidovits (1994) classified the type of application according to the Si:Al ratio as presented in Table 1. A low ratio of Si: Al of 1, 2, or 3 initiates a 3D-Network that is very rigid, while Si: Al ratio higher than 15 provides a polymeric character to the geopolymeric material. For many applications in the civil engineering field, a low Si: Al ratio is suitable (Table 1).

TABLE 1: Applications of Geopolymeric Materials Based on Silica-to-Alumina Atomic Ratio (Davidovits, 1994)

Si:Al ratio	Applications
1	- Bricks - Ceramics - Fire protection
2	- Low CO_2 cements and concretes - Radioactive and toxic waste encapsulation
3	- Fire protection fibre glass composite - Foundry equipments - Heat resistant composites, $200^{o}C$ to $1000^{o}C$ - Tooling for aeronautics titanium process
>3	- Sealants for industry, $200^{o}C$ to $600^{o}C$ - Tooling for aeronautics SPF aluminium
20 - 35	- Fire resistant and heat resistant fibre composites

This Report is devoted to heat-cured low-calcium fly ash-based geopolymer concrete. Low-calcium (ASTM Class F) fly ash is preferred as a source material than high-calcium (ASTM Class C) fly ash. The presence of calcium in high amounts may interfere with the polymerization process and alter the microstructure (Gourley, 2003; Gourley and Johnson, 2005).

3. Constituents of Geopolymer Concrete

Geopolymer concrete can be manufactured by using the low-calcium (ASTM Class F) fly ash obtained from coal-burning power stations. Most of the fly ash available globally is low-calcium fly ash formed as a by-product of burning anthracite or bituminous coal. Although coal burning power plants are considered to be environmentally unfriendly, the extent of power generated by these plants is on the increase due to the huge reserves of good quality coal available worldwide and the low cost of power produced from these sources. Therefore, huge quantities of fly ash will be available for many years in the future (Malhotra, 2006). The chemical composition and the particle size distribution of the fly ash must be established prior to use. An X-Ray Fluorescence (XRF) analysis may be used to determine the chemical composition of the fly ash.

Low-calcium fly ash has been successfully used to manufacture geopolymer concrete when the silicon and aluminum oxides constituted about 80% by mass, with the Si-to-Al ratio of about 2. The content of the iron oxide usually ranged from 10 to 20% by mass, whereas the calcium oxide content was less than 5% by mass. The carbon content of the fly ash, as indicated by the loss on ignition by mass, was as low as less than 2%. The particle size distribution tests revealed that 80% of the fly ash particles were smaller than 50 μm (Gourley, 2003; Gourley and Johnson, 2005; Hardjito and Rangan, 2005; Wallah and Rangan, 2006; Sumajouw and Rangan, 2006; Fernandez-Jimenez et al, 2006a; Sofi et al, 2006a; Siddiqui, 2007). The reactivity of low-calcium fly ash in geopolymer matrix has been studied by Fernandez-Jimenez, et al (2006b).

Coarse and fine aggregates used by the concrete industry are suitable to manufacture geopolymer concrete. The aggregate grading curves currently used in concrete practice are applicable in the case of geopolymer concrete (Hardjito and Rangan, 2005; Wallah and Rangan, 2006; Sumajouw and Rangan, 2006; Gourey, 2003; Gourley and Johnson, 2005; Siddiqui, 2007).

A combination of sodium silicate solution and sodium hydroxide (NaOH) solution can be used as the alkaline liquid. It is recommended that the alkaline liquid is prepared by mixing both the solutions together at least 24 hours prior to use.

The sodium silicate solution is commercially available in different grades. The sodium silicate solution A53 with SiO_2-to-Na_2O ratio by mass of approximately 2, i.e., $SiO_2 = 29.4\%$, $Na_2O = 14.7\%$, and water $= 55.9\%$ by mass, is recommended.

The sodium hydroxide with 97-98% purity, in flake or pellet form, is commercially available. The solids must be dissolved in water to make a solution with the required concentration. The concentration of sodium hydroxide solution can vary in the range between 8 Molar and 16 Molar. The mass of NaOH solids in a solution varies depending on the concentration of the solution. For instance, NaOH solution with a concentration of 8 Molar consists of 8x40 = 320 grams of NaOH solids per litre of the solution, where 40 is the molecular weight of NaOH. The mass of NaOH solids was measured as 262 grams per kg of NaOH solution with a concentration of 8 Molar. Similarly, the mass of NaOH solids per kg of the solution for other concentrations was measured as 10 Molar: 314 grams, 12 Molar: 361 grams, 14 Molar: 404 grams, and 16 Molar: 444 grams (Hardjito and Rangan, 2005). Note that the mass of water is the major component in both the alkaline solutions.

In order to improve the workability, a high range water reducer super plasticizer and extra water may be added to the mixture.

4. Mixture Proportions of Geopolymer Concrete

The primary difference between geopolymer concrete and Portland cement concrete is the binder. The silicon and aluminum oxides in the low-calcium fly ash reacts with the alkaline liquid to form the geopolymer paste that binds the loose coarse aggregates, fine aggregates, and other un-reacted materials together to form the geopolymer concrete.

As in the case of Portland cement concrete, the coarse and fine aggregates occupy about 75 to 80% of the mass of geopolymer concrete. This component of geopolymer concrete mixtures can be designed using the tools currently available for Portland cement concrete.

The compressive strength and the workability of geopolymer concrete are influenced by the proportions and properties of the constituent materials that make the geopolymer paste. Experimental results (Hardjito and Rangan, 2005) have shown the following:

- Higher concentration (in terms of molar) of sodium hydroxide solution results in higher compressive strength of geopolymer concrete.

- Higher the ratio of sodium silicate solution-to-sodium hydroxide solution ratio by mass, higher is the compressive strength of geopolymer concrete.

- The addition of naphthalene sulphonate-based super plasticizer, up to approximately 4% of fly ash by mass, improves the workability of the fresh geopolymer concrete; however, there is a slight degradation in the compressive strength of hardened concrete when the super plasticizer dosage is greater than 2%.

- The slump value of the fresh geopolymer concrete increases when the water content of the mixture increases.

- As the H_2O-to-Na_2O molar ratio increases, the compressive strength of geopolymer concrete decreases (Figure 1).

.
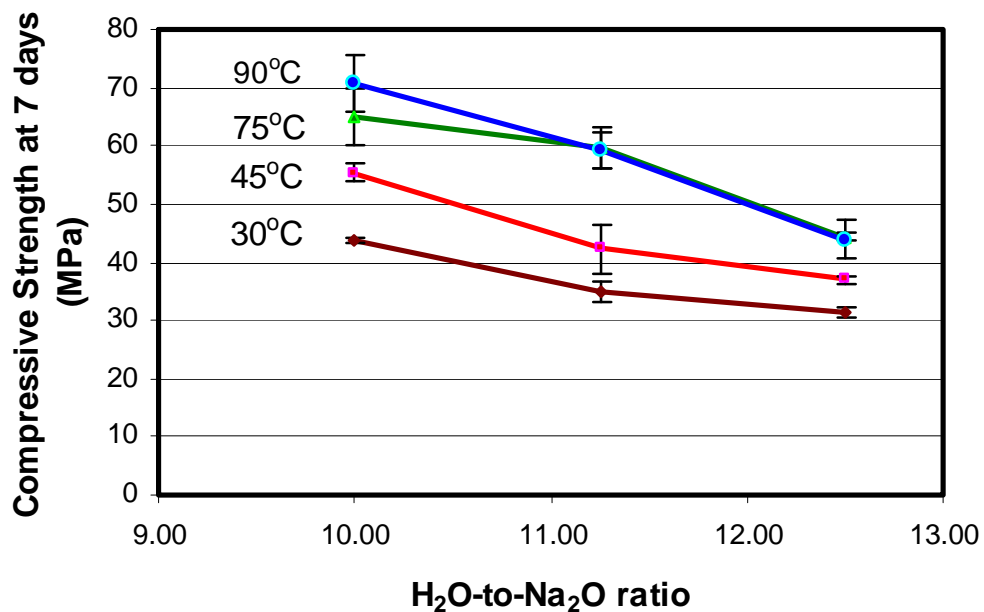
FIGURE 1: Effect of H_2O-to-Na_2O Molar Ratio on Compressive Strength (Hardjito and Rangan, 2005)

As can be seen from the above, the interaction of various parameters on the compressive strength and the workability of geopolymer concrete is complex. In order to assist the design of low-calcium fly ash-based geopolymer concrete mixtures, a single parameter called '**water-to-geopolymer solids ratio'** by mass was devised. In this parameter, the total mass of water is the sum of the mass of water contained 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 solids, and the mass of solids in the sodium silicate solution (i.e. the mass of Na_2O and SiO_2).

Tests were performed to establish the effect of water-to-geopolymer solids ratio by mass on the compressive strength and the workability of geopolymer concrete. The test specimens were 100x200 mm cylinders, heat-cured in an oven at various temperatures for 24 hours. The results of these tests, plotted in Figure 2, show that the compressive strength of geopolymer concrete decreases as the water-to-geopolymer solids ratio by mass increases (Hardjito and Rangan, 2005). This test trend is analogous to the well-known effect of water-to-cement ratio on the compressive strength of Portland cement concrete. Obviously, as the water-to-geopolymer solids ratio increased, the workability increased as the mixtures contained more water.

The test trend shown in Figure 2 is also observed by Siddiqui (2007) in the studies conducted on steam-cured reinforced geopolymer concrete culverts.

The proportions of two different geopolymer concrete mixtures used in laboratory studies are given in Table 2 (Wallah and Rangan, 2006). The details of numerous other mixtures are reported elsewhere (Hardjito and Rangan, 2005; Sumajouw and Rangan, 2006; Siddiqui, 2007).
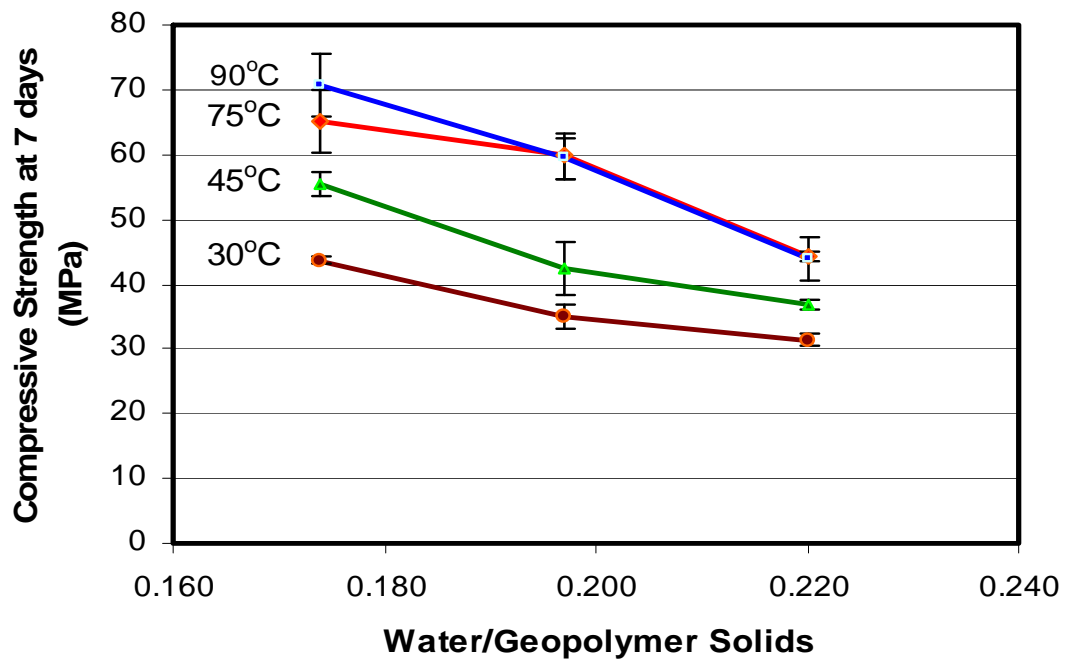
FIGURE 2: Effect of Water-to-Geopolymer Solids Ratio by Mass on Compressive Strength of Geopolymer Concrete (Hardjito and Rangan, 2005)

TABLE 2: Geopolymer Concrete Mixture Proportions (Wallah and Rangan, 2006)

Materials		Mass (kg/m^3)	
		Mixture-1	Mixture-2
Coarse aggregates:	20 mm	277	277
	14 mm	370	370
	7 mm	647	647
Fine sand		554	554
Fly ash (low-calcium ASTM Class F)		408	408
Sodium silicate solution(SiO$_2$/Na$_2$O=2)		103	103
Sodium hydroxide solution		41 (8 Molar)	41 (14 Molar)
Super Plasticizer		6	6
Extra water		None	22.5

10

5. Mixing, Casting, and Compaction of Geopolymer Concrete

Geopolymer concrete can be manufactured by adopting the conventional techniques used in the manufacture of Portland cement concrete. In the laboratory, the fly ash and the aggregates were first mixed together dry in 80-litre capacity pan mixer (Figure 3) for about three minutes. The aggregates were prepared in saturated-surface-dry (SSD) condition, and were kept in plastic buckets with lid (Figure 4).

The alkaline liquid was mixed with the super plasticiser and the extra water, if any. The liquid component of the mixture was then added to the dry materials and the mixing continued usually for another four minutes (Figure 5). The fresh concrete could be handled up to 120 minutes without any sign of setting and without any degradation in the compressive strength (Figure 6). The fresh concrete was cast and compacted by the usual methods used in the case of Portland cement concrete (Hardjito and Rangan, 2005; Wallah and Rangan, 2006; Sumajouw and Rangan, 2006). Fresh fly ash-based geopolymer concrete was usually cohesive. The workability of the fresh concrete was measured by means of the conventional slump test (Figure 7).

FIGURE 3: Pan Mixer Used in the Manufacture of Geopolymer Concrete (Hardjito and Rangan, 2005)

FIGURE 4: Dry Materials of Geopolymer Concrete (Hardjito and Rangan, 2005)

**FIGURE 5: Addition of Liquid Component (Hardjito and Rangan, 2005)**

FIGURE 6: Fresh Geopolymer Concrete Ready for Placing (Hardjito and Rangan, 2005)

FIGURE 7: Slump Measurement of Fresh Geopolymer Concrete (Hardjito and Rangan, 2005)

The compressive strength of geopolymer concrete is influenced by the wet-mixing time, as illustrated by the test data plotted in Figure 8. The test specimens were 100x200 mm cylinders, steam-cured at 60°C for 24 hours and tested in compression at an age of 21 days. Figure 8 shows that the compressive strength significantly increased as the wet-mixing time increased. The slump values of fresh concrete were also measured. These results showed that the slump values decreased from 240 mm for two minutes of wet-mixing time to 210 mm when the wet-mixing time increased to sixteen minutes.
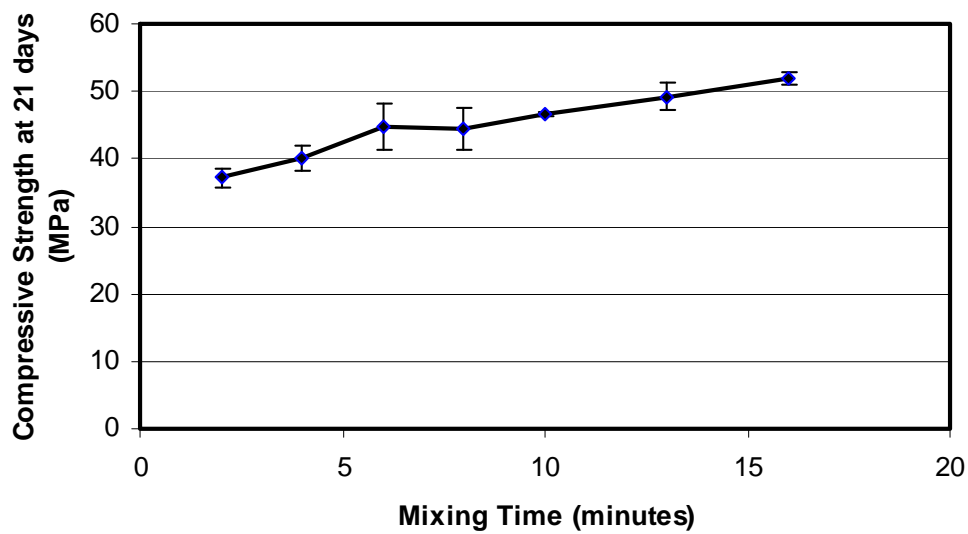
FIGURE 8: **Effect of Wet-Mixing Time on Compressive Strength of Geopolymer Concrete (Hardjito and Rangan, 2005)**

6. Curing of Geopolymer Concrete

Heat-curing of low-calcium fly ash-based geopolymer concrete is generally recommended. Heat-curing substantially assists the chemical reaction that occurs in the geopolymer paste.

Both curing time and curing temperature influence the compressive strength of geopolymer concrete. The effect of curing time is illustrated in Figure 9 (Hardjito and Rangan, 2005). The test specimens were 100x200 mm cylinders heat-cured at 60°C in an oven. The curing time varied from 4 hours to 96 hours (4 days). Longer curing time improved the polymerization process resulting in higher compressive strength. The rate of increase in strength was rapid up to 24 hours of curing time; beyond

24 hours, the gain in strength is only moderate. Therefore, heat-curing time need not be more than 24 hours in practical applications.
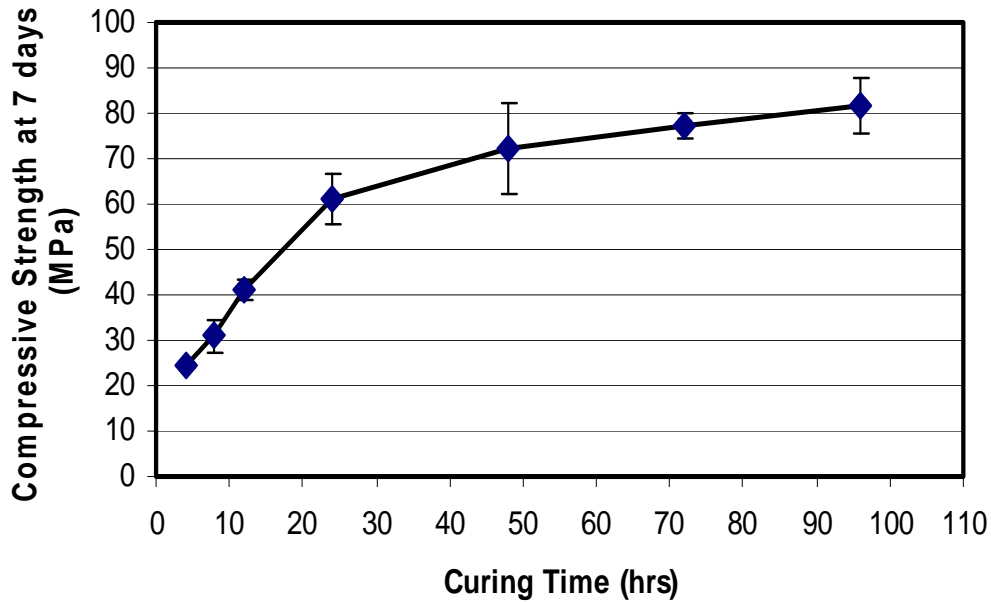
FIGURE 9: Effect of Curing Time on Compressive Strength of Geopolymer Concrete (Hardjito and Rangan, 2005)

Figure 2 shows the effect of curing temperature on the compressive strength of geopolymer concrete (Hardjito and Rangan, 2005). Higher curing temperature resulted in larger compressive strength.

Heat-curing can be achieved by either steam-curing or dry-curing. Test data show that the compressive strength of dry-cured geopolymer concrete is approximately 15% larger than that of steam-cured geopolymer concrete (Hardjito and Rangan, 2005). The temperature required for heat-curing can be as low as 30 degrees C (Figure 2). In tropical climates, this range of temperature can be provided by the ambient conditions.

The required heat-curing regime can be manipulated to fit the needs of practical applications. In laboratory trials (Hardjito and Rangan, 2005), precast products were manufactured using geopolymer concrete; the design specifications required steam-curing at 60°C for 24 hours. In order to optimize the usage of formwork, the products were cast and steam-cured initially for about 4 hours. The steam-

curing was then stopped for some time to allow the release of the products from the formwork. The steam-curing of the products then continued for another 21 hours. This two-stage steam-curing regime did not produce any degradation in the strength of the products.

A two-stage steam-curing regime was also used by Siddiqui (2007) in the manufacture of prototype reinforced geopolymer concrete box culverts. It was found that steam curing at 80 ˚C for a period of 4 hours provided enough strength for de-moulding of the culverts; this was then followed by steam curing further for another 20 hours at 80 ˚C to attain the required design compressive strength.

Also, the start of heat-curing of geopolymer concrete can be delayed for several days. Tests have shown that a delay in the start of heat-curing up to five days did not produce any degradation in the compressive strength. In fact, such a delay in the start of heat-curing substantially increased the compressive strength of geopolymer concrete (Hardjito and Rangan, 2005). This may be due to the geopolymerisation that occurs prior to the start of heat-curing.

The above flexibilities in the heat-curing regime of geopolymer concrete can be exploited in practical applications and prototype products can be manufactured ready for use within 24 hours after casting.

7. Design of Geopolymer Concrete Mixtures

Concrete mixture design process is vast and generally based on performance criteria. Based on the information given in Sections 3 to 6 above, some simple guidelines for the design of heat-cured low-calcium fly ash-based geopolymer concrete are proposed.

The role and the influence of aggregates are considered to be the same as in the case of Portland cement concrete. The mass of combined aggregates may be taken to be between 75% and 80% of the mass of geopolymer concrete.

The performance criteria of a geopolymer concrete mixture depend on the application. For simplicity, the compressive strength of hardened concrete and the workability of fresh concrete are selected as the performance criteria. In order to meet these performance criteria, the alkaline liquid-to-fly ash ratio by

mass, **water-to-geopolymer solids ratio** (*see Section 4 for definition*) by mass, the wet-mixing time, the heat-curing temperature, and the heat-curing time are selected as parameters.

With regard to alkaline liquid-to-fly ash ratio by mass, values in the range of 0.30 and 0.45 are recommended. Based on the results obtained from numerous mixtures made in the laboratory over a period of four years, the data given in Table 3 are proposed for the design of low-calcium fly ash-based geopolymer concrete. Note that wet-mixing time of 4 minutes, and steam-curing at 60°C for 24 hours after casting are proposed. The data given in Figures 2, 8, and 9 may be used as guides to choose other curing temperatures, wet-mixing times, and curing times.

Sodium silicate solution is cheaper than sodium hydroxide solids. Commercially available sodium silicate solution A53 with SiO_2-to-Na_2O ratio by mass of approximately 2, i.e., Na_2O = 14.7%, SiO_2 = 29.4%, and water = 55.9% by mass, and sodium hydroxide solids (NaOH) with 97-98% purity are recommended. Laboratory experience suggests that the ratio of sodium silicate solution-to-sodium hydroxide solution by mass may be taken approximately as 2.5 (Hardjito and Rangan, 2005).

The design data given in Table 3 assumes that the aggregates are in saturated-surface-dry (SSD) condition. In other words, the coarse and fine aggregates in a geopolymer concrete mixture must neither be too dry to absorb water from the mixture nor too wet to add water to the mixture. In practical applications, aggregates may contain water over and above the SSD condition. Therefore, the extra water in the aggregates above the SSD condition must be included in the calculation of water-to-geopolymer solids ratio given in Table 3.

TABLE 3: **Data for Design of Low-Calcium Fly Ash-Based Geopolymer Concrete Mixtures (Rangan, 2008, 2009)**

Water-to-geopolymer solids ratio, by mass	Workability	Design compressive strength (wet-mixing time of 4 minutes, steam curing at 60°C for 24 hours after casting), MPa
0.16	Very Stiff	60
0.18	Stiff	50
0.20	Moderate	40
0.22	High	35
0.24	High	30

Notes:

- The fineness modulus of combined aggregates is taken to be in the range of 4.5 and 5.0.

- When cured in dry-heat, the compressive strength may be about 15% larger than the above given values.

- When the wet-mixing time is increased from 4 minutes to 16 minutes, the above compressive strength values may increase by about 30%.

- Standard deviation of compressive strength is about 10% of the above given values.

The mixture design process is illustrated by the following Example:

Mixture proportion of heat-cured low-calcium fly ash-based geopolymer concrete with design compressive strength of 45 MPa is needed for precast concrete products.

Assume that normal-density aggregates in SSD condition are to be used and the unit-weight of concrete is 2400 kg/m^3. Take the mass of combined aggregates as 77% of the mass of concrete, i.e. 0.77x2400= 1848 kg/m^3. The combined aggregates may be selected to match the standard grading curves used in the design of Portland cement concrete mixtures. For instance, the aggregates may comprise 277 kg/m^3 (15%) of 20mm aggregates, 370 kg/m^3 (20%) of 14 mm aggregates, 647 kg/m^3 (35%) of 7 mm aggregates, and 554 kg/m^3 (30%) of fine sand to meet the requirements of standard grading curves. The fineness modulus of the combined aggregates is approximately 5.0.

The mass of low-calcium fly ash and the alkaline liquid = 2400 – 1848 = 552 kg/m^3. Take the alkaline liquid-to-fly ash ratio by mass as 0.35; the mass of fly ash = 552/ (1+0.35) = 408 kg/m^3 and the mass of alkaline liquid = 552 – 408 = 144 kg/m^3. Take the ratio of sodium silicate solution-to-sodium hydroxide solution by mass as 2.5; the mass of sodium hydroxide solution = 144/ (1+2.5) = 41 kg/m^3; the mass of sodium silicate solution = 144 – 41 =103 kg/m^3.

Therefore, the trial mixture proportion is as follow: combined aggregates = 1848 kg/m^3, low-calcium fly ash = 408 kg/m^3, sodium silicate solution = 103 kg /m^3, and sodium hydroxide solution = 41 kg/m^3.

To manufacture the geopolymer concrete mixture, commercially available sodium silicate solution A53 with SiO_2-to-Na_2O ratio by mass of approximately 2, i.e., Na_2O = 14.7%, SiO_2 = 29.4%, and water = 55.9% by mass, is selected. The sodium hydroxide solids (NaOH) with 97-98% purity is purchased from commercial sources, and mixed with water to make a solution with a concentration of 8 Molar. This solution comprises 26.2% of NaOH solids and 73.8% water, by mass (*see Section 3*).

For the trial mixture, **water-to-geopolymer solids ratio** by mass is calculated as follows: In sodium silicate solution, water = 0.559x103 = 58 kg, and solids = 103 – 58 = 45 kg. In sodium hydroxide solution, solids = 0.262x41 = 11 kg, and water = 41 – 11 = 30 kg. Therefore, total mass of water = 58+30 = 88 kg, and the mass of geopolymer solids = 408 (i.e. mass of fly ash) +45+11 = 464 kg. Hence the water-to-geopolymer solids ratio by mass = 88/464 = 0.19.

Using the data given in Table 3, for water-to-geopolymer solids ratio by mass of 0.19, the design compressive strength is approximately 45 MPa, as needed. The geopolymer concrete mixture proportion is therefore as follows:

20 mm aggregates = 277 kg/m^3, 14 mm aggregates = 370 kg/m^3, 7 mm aggregates = 647 kg/m^3, fine sand = 554 kg/m^3, low-calcium fly ash (ASTM Class F) = 408 kg/m^3, sodium silicate solution (Na_2O = 14.7%, SiO_2 = 29.4%, and water = 55.9% by mass) = 103 kg/m^3, and sodium hydroxide solution (8 Molar) = 41 kg/m^3(Note that the 8 Molar sodium hydroxide solution is made by mixing 11 kg of sodium hydroxide solids with 97-98% purity in 30 kg of water).

The geopolymer concrete must be wet-mixed at least for four minutes and steam-cured at 60°C for 24 hours after casting.

The workability of fresh geopolymer concrete is expected to be moderate. If needed, commercially available super plasticizer of about 1.5% of mass of fly ash, i.e. 408x (1.5/100) = 6 kg/m^3 may be added to the mixture to facilitate ease of placement of fresh concrete.

Numerous batches of the Example geopolymer concrete mixture have been manufactured and tested in the laboratory over a period of four years. These test results have shown that the mean 7th day compressive strength was 56 MPa with a standard deviation of 3 MPa *(see Mixture-1 in Table 2 and Table 6)*. The mean slump of the fresh geopolymer concrete was about 100 mm.

The above Example is used to illustrate the effect of alkaline liquid-to-fly ash ratio by mass on the compressive strength and workability of geopolymer concrete. When the Example is reworked with different values of alkaline liquid-to-fly ash ratio by mass, and using the data given in Table 3, the following results are obtained:

| Alkaline liquid/fly ash, by mass	Water/geopolymer solids, by mass	Workability	Compressive strength, MPa
0.30	0.165	Stiff	58
0.35	0.190	Moderate	45
0.40	0.210	Moderate	37
0.45	0.230	High	32

8. Short-Term Properties of Geopolymer Concrete

8.1. Behavior in Compression

The behavior and failure mode of fly ash-based geopolymer concrete in compression is similar to that of Portland cement concrete. Figure 10 shows a typical stress-strain curve of geopolymer concrete. Test data show that the strain at peak stress is in the range of 0.0024 to 0.0026 (Hardjito and Rangan, 2005). Collins et al (1993) have proposed that the stress-strain relation of Portland cement concrete in compression can be predicted using the following expression:

$$\sigma_c = f_{cm} \frac{\varepsilon_c}{\varepsilon_{cm}} \frac{n}{n-1+(\varepsilon_c / \varepsilon_{cm})^{nk}}$$

(3)

where f_{cm} = peak stress, ε_{cm} = strain at peak stress, n = 0.8 + (f_{cm}/17), and k = 0.67 + (f_{cm}/62) when $\varepsilon_c/\varepsilon_{cm}$>1 or equal to 1.0 when $\varepsilon_c/\varepsilon_{cm}$≤1. Figure 10 shows that the measured stress-strain curve correlates well with that calculated using Equation 3.
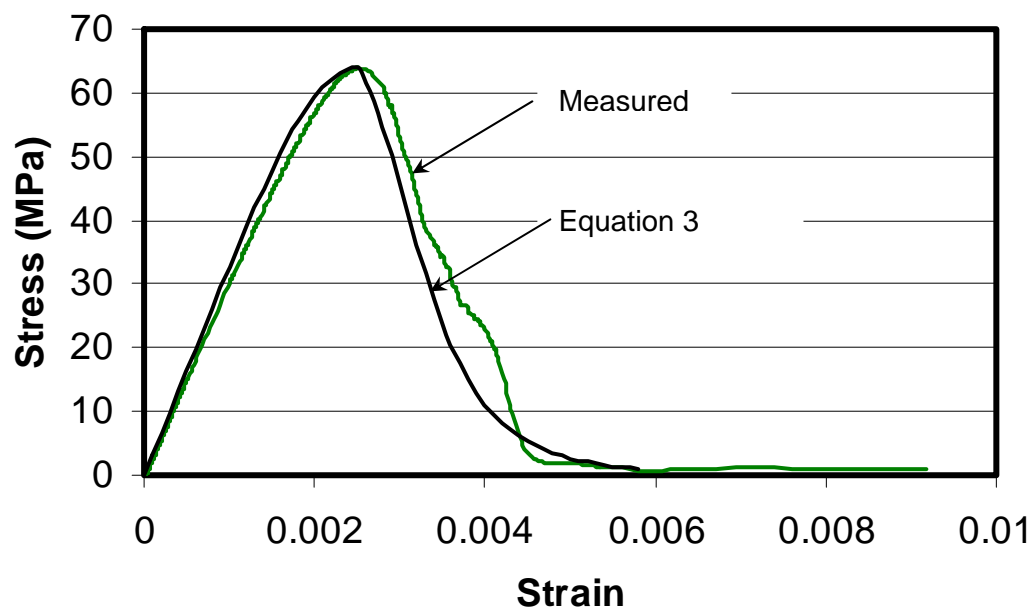
FIGURE 10: **Stress-Strain Relation of Geopolymer Concrete in Compression (Hardjito and Rangan, 2005)**

Table 4 gives the measured values of modulus of elasticity (E_c) of geopolymer concrete in compression.   As expected, the modulus of elasticity increased as the compressive strength of geopolymer concrete increased (Hardjito and Rangan, 2005).

For Portland cement concrete, the draft Australian Standard AS3600 (2005) recommends the following expression to calculate the value of the modulus of elasticity within an error of plus or minus 20 %:

$$E_c = \rho^{1.5} (0.024 \sqrt{f_{cm}} + 0.12) \qquad \text{(MPa)} \qquad (4)$$

where ρ is the unit-weight of concrete in kg/m^3, and f_{cm} is the mean compressive strength in MPa.

American Concrete Institute (ACI) Committee 363 (1992) has recommended the following expression to calculate the modulus of elasticity.:

$$E_c = 3320 \sqrt{f_{cm}} + 6900 \qquad \text{(MPa)} \qquad (5)$$

The average unit-weight of fly ash-based geopolymer concrete was 2350 kg/m^3. Table 4 shows the comparison between the measured values of modulus of elasticity of fly ash-based geopolymer concrete with the values calculated using Equation 4 and Equation 5.

It can be seen from Table 4 that the measured values were consistently lower than the values calculated using Equation 4 and Equation 5. This is due to the type of coarse aggregates used in the manufacture of geopolymer concrete.

The type of the coarse aggregate used in the test programme was of granite-type. Even in the case of specimens made of mixture with f_{cm}=44 MPa, the failure surface of test cylinders cut across the coarse aggregates, thus resulting in a smooth failure surface. This indicates that the coarse aggregates were weaker than the geopolymer matrix and the matrix-aggregate interface (Hardjito and Rangan, 2005).

TABLE 4: Modulus of Elasticity of Geopolymer Concrete in Compression (Hardjito and Rangan, 2005)

f_{cm}	E_c(measured) (GPa)	E_c(Eq.4) (GPa)	E_c(Eq.5) (GPa)
89	30.8	39.5 ± 7.9	38.2
68	27.3	36.2 ± 7.2	34.3
55	26.1	33.9 ± 6.8	31.5
44	23.0	31.8 ± 6.4	28.9

For Portland cement concrete using granite-type coarse aggregate, Aitcin and Mehta (1990) reported modulus of elasticity values of 31.7 GPa and 33.8 GPa when f_{cm}=84.8 MPa and 88.6 MPa, respectively. These values are similar to those measured for geopolymer concrete given in Table 4.

Sofi et al (2007a) used low-calcium fly ash from three different sources to manufacture geopolymer mortar and concrete specimens. The measured values of modulus of elasticity reported in that study showed a trend similar to that observed in the results given in Table 4.

Experimental studies have shown that the aggregate-binder interfaces are stronger in geopolymers than in the case of Portland cement (Lee and van Deventer, 2004). This may lead to superior mechanical properties and long-term durability of geopolymer concretes (Provis et al, 2007).

The Poisson's ratio of fly ash-based geopolymer concrete with compressive strength in the range of 40 to 90 MPa falls between 0.12 and 0.16. These values are similar to those of Portland cement concrete.

8.2. Indirect Tensile Strength

The tensile strength of fly ash-based geopolymer concrete was measured by performing the cylinder splitting test on 150x300 mm concrete cylinders. The test results are given in Table 5. These test results show that the tensile splitting strength of geopolymer concrete is only a fraction of the compressive strength, as in the case of Portland cement concrete (Hardjito and Rangan, 2005).

The draft Australian Standards for Concrete Structures AS3600 (2005) recommends the following design expression to determine the characteristic principal tensile strength (f_{ct}) of Portland cement concrete:

$$f_{ct} = 0.4 \sqrt{f_{cm}} \qquad \text{(MPa)} \tag{6}$$

Neville (2000) recommended that the relation between the tensile splitting strength and the compressive strength of Portland cement concrete may be expressed as:

$$f_{ct} = 0.3 \, (f_{cm})^{2/3} \qquad \text{(MPa)} \tag{7}$$

The calculated values of f_{ct} using Equations 6 and 7, given in Table 5, show that the measured indirect tensile strength of fly ash-based geopolymer concrete is larger than the values recommends by the draft Australian Standard AS3600 (2005) and Neville (2000) for Portland cement concrete.

Sofi et al (2007a) also performed indirect tensile tests on geopolymer mortar and concrete specimens made using three different sources of low-calcium fly ash. The trend test results observed in that study is similar to that observed in the results given in Table 5.

TABLE 5: Indirect Tensile Splitting Strength of Geopolymer Concrete (Hardjito and Rangan, 2005)

Mean compressive Strength (MPa)	Mean indirect tensile Strength (MPa)	Characteristic principal tensile strength, Equation (6) (MPa)	Splitting strength, Equation (7) (MPa)
89	7.43	3.77	5.98
68	5.52	3.30	5.00
55	5.45	3.00	4.34
44	4.43	2.65	3.74

8.3. Unit-weight

The unit-weight of concrete primarily depends on the unit mass of aggregates used in the mixture. Tests show that the unit-weight of the low-calcium fly ash-based geopolymer concrete is similar to that of Portland cement concrete. When granite-type coarse aggregates were used, the unit-weight varied between 2330 and 2430 kg/m^3 (Hardjito and Rangan, 2005).

9. Long-Term Properties of Geopolymer Concrete

9.1. Compressive Strength

Two geopolymer concrete mixture proportions used in laboratory studies are given in Table 2 (Wallah and Rangan, 2006). Numerous batches of these mixtures were manufactured during a period of four years. For each batch of geopolymer concrete made, 100x200 mm cylinders specimens were prepared. At least three of these cylinders were tested for compressive strength at an age of seven days after casting. The unit-weight of specimens was also determined at the same time. For these numerous specimens made from Mixture-1 and Mixture-2 and heat-cured at 60°C for 24 hours after casting, the average results are presented in Table 6 (Wallah and Rangan, 2006).

TABLE 6: **Mean Compressive Strength and Unit-weight of Geopolymer Concrete (Wallah and Rangan, 2006)**

Mixture	Curing type	7th Day compressive strength (heat-curing at 60°C for 24 hours), MPa		Unit-weight, kg/m³	
		Mean	Standard deviation	Mean	Standard deviation
Mixture-1	Dry curing (oven)	58	6	2379	17
	Steam curing	56	3	2388	15
Mixture-2	Dry curing (oven)	45	7	2302	52
	Steam curing	36	8	2302	49

In order to observe the effect of age on compressive strength of heat-cured geopolymer concrete, 100x200 mm cylinders were made from several batches of Mixture-1 given in Table 2. The specimens were heat-cured in the oven for 24 hours at 60°C. Figure 11 presents the ratio of the compressive strength of specimens at a particular age as compared to the compressive strength of specimens from the same batch of geopolymer concrete tested on the 7th day after casting (Wallah and Rangan, 2006). These test data show that the compressive strength increased with age in the order of 10 to 20 percent when compared to the 7th day compressive strength.
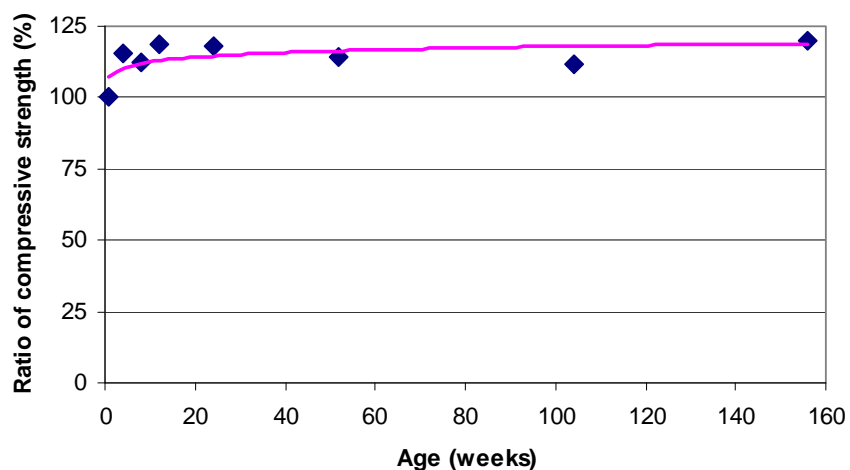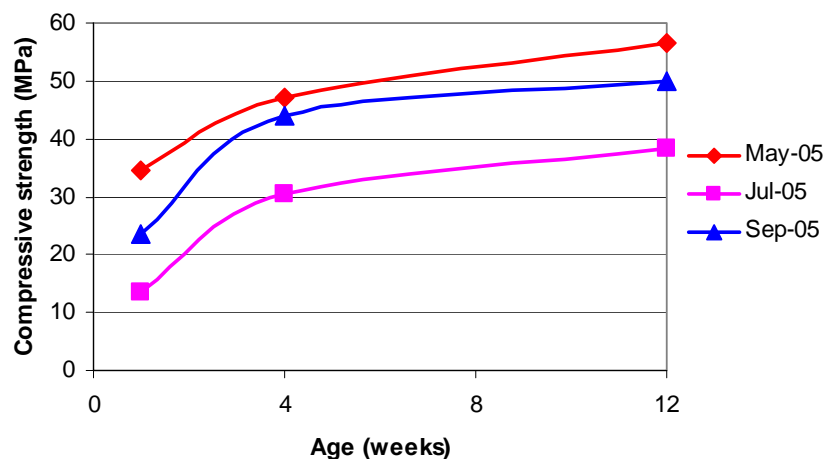

FIGURE 11: Change in Compressive Strength of Heat-cured Geopolymer Concrete with Age (Wallah and Rangan, 2006)

The test data shown in Table 6 and Figure 11 demonstrate the consistent quality, reproducibility, and long-term stability of low-calcium fly ash-based geopolymer concrete.

In order to study the effect of age on the compressive strength of fly ash-based geopolymer concrete cured in laboratory ambient conditions, three batches of geopolymer concrete were made using Mixture-1 given in Table 2. The test specimens were 100x200 mm cylinders.   The first batch, called May 05, was cast in the month of May 2005, while the second batch (July 05) was cast in the month of July 2005 and the third batch (September 05) in September 2005. The ambient temperature in May 2005 during the first week after casting the concrete ranged from about 18 to 25°C, while this temperature was around 8 to 18°C in July 2005 and 12 to 22°C in September 2005. The average humidity in the laboratory during those months was between 40% and 60%. The test cylinders were removed from the moulds one day after casting and left in laboratory ambient conditions until the day of test.

The test results plotted in Figure 12 show that the compressive strength of ambient-cured geopolymer concrete significantly increased with the age (Wallah and Rangan, 2006). This test trend is in contrast to the effect of age on the compressive strength of heat-cured geopolymer concrete (Figure 11).


FIGURE 12: Compressive Strength of Geopolymer Concrete Cured in Ambient Condition (Wallah and Rangan, 2006)

9.2. Creep and Drying Shrinkage

The creep and drying shrinkage behavior of heat-cured low-calcium fly ash-based geopolymer concrete was studied for a period of one year (Wallah and Rangan, 2006). The geopolymer concrete mixture proportions used in that study were Mixture-1 and Mixture-2, as given in Table 2. The test specimens were 150x300 mm cylinders, heat-cured at 60°C for 24 hours. The creep tests commenced on the 7th day after casting the test specimens and the sustained stress was 40% of the compressive strength on that day. The test results obtained for specimens made using Mixture-1 and heat-cured in an oven are shown in Figure 13 (Wallah and Rangan, 2006). The test trends were similar for both Mixture-1 and Mixture-2, heat-cured either in an oven or steam-cured.

Test results (Figure 13) show that heat-cured fly ash-based geopolymer concrete undergoes very little drying shrinkage in the order of about 100 micro strains after one year. This value is significantly smaller than the range of values of 500 to 800 micro strains experienced by Portland cement concrete.
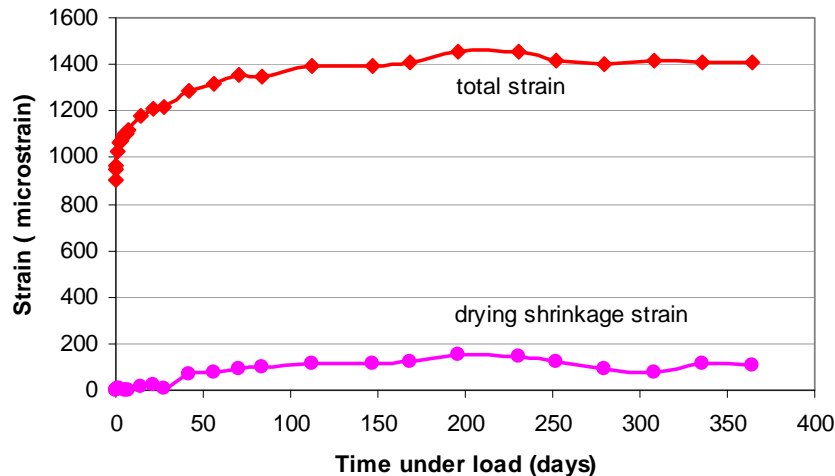
FIGURE 13: **Total Strain and Drying Shrinkage Strain of Heat-Cured Geopolymer Concrete (Wallah and Rangan, 2006)**

The creep coefficient, defined as the ratio of creep strain-to-elastic strain, after one year of loading for heat-cured geopolymer concrete with compressive strength of 40, 47 and 57 MPa is between 0.6 and 0.7, while for geopolymer concrete with compressive strength of 67 MPa this value is between 0.4 and 0.5. The specific creep, defined as the creep strain per unit of sustained stress, data are shown in Figure

14; the specific creep values after one year of loading are given in Table 7 (Wallah and Rangan, 2006). These values are about 50% of the values recommended by the draft Australian Standard AS3600 for Portland cement concrete.
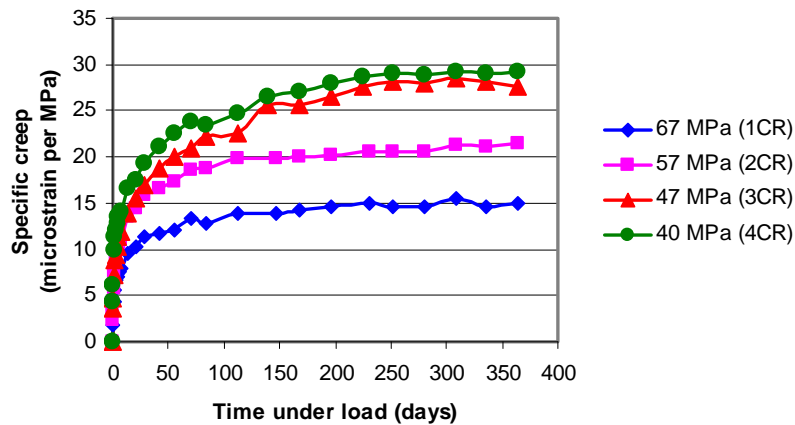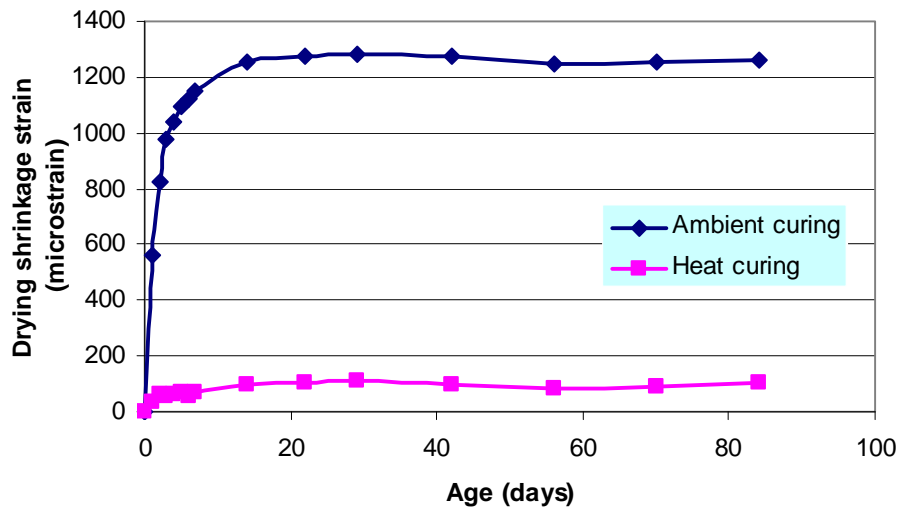

FIGURE 14: **Effect of Compressive Strength on Creep of Heat-Cured Geopolymer Concrete (Wallah and Rangan, 2006)**

TABLE 7: **Specific Creep of Heat-cured Geopolymer Concrete (Wallah and Rangan, 2006)**

Designation	Compressive strength (MPa)	Specific creep after one year loading $(x10^{-6}/MPa)$
1CR	67	15
2CR	57	22
3CR	47	28
4CR	40	29

The low drying shrinkage and the low creep of heat-cured geopolymer concrete offer benefits to the long-term performance of geopolymer concrete members.

The drying shrinkage strains of geopolymer concrete cured in ambient conditions are many folds larger than those experienced by the heat-cured specimens (Figure 15). As indicated by Equation 2, water is released during the chemical reaction process of geopolymers. In the specimens cured in ambient conditions, this water may evaporate over a period of time causing significantly large drying shrinkage strains especially in first two weeks as can be seen in Figure 15 (Wallah and Rangan, 2006).

FIGURE 15: **Drying Shrinkage of Heat-cured and Ambient-cured Geopolymer Concrete (Wallah and Rangan, 2006)**

9.3. Sulfate Resistance

Tests were performed to study the sulfate resistance of heat-cured low-calcium fly ash-based geopolymer concrete. The test specimens were made using Mixture-1 (Table 2) and heat-cured at 60°C for 24 hours after casting; they were immersed in 5% sodium sulfate solution for various periods of exposure up to one year. The sulfate resistance was evaluated based on the change in mass, change in length, and change in compressive strength of the specimens after sulfate exposure. The test specimens were 100x200 mm cylinders for change in mass and change in compressive strength tests and 75x75x285 mm prisms for change in length test (Wallah and Rangan, 2006).

Test results showed that heat-cured low-calcium fly ash-based geopolymer concrete has an excellent resistance to sulfate attack. There was no damage to the surface of test specimens after exposure to sodium sulfate solution up to one year. The visual appearances of test specimens after different exposures are shown in Figure 16. It can be seen that the visual appearance of the test specimens after soaking in sodium sulfate solution up to one year revealed that there was no change in the appearance

of the specimens compared to the condition before they were exposed. There was no sign of surface erosion, cracking or spalling on the specimens. The specimens soaked in tap water also showed no change in the visual appearance (Figure 16).

| Soaked in 5% sodium sulfate solution | Soaked in water | Left in ambient condition |
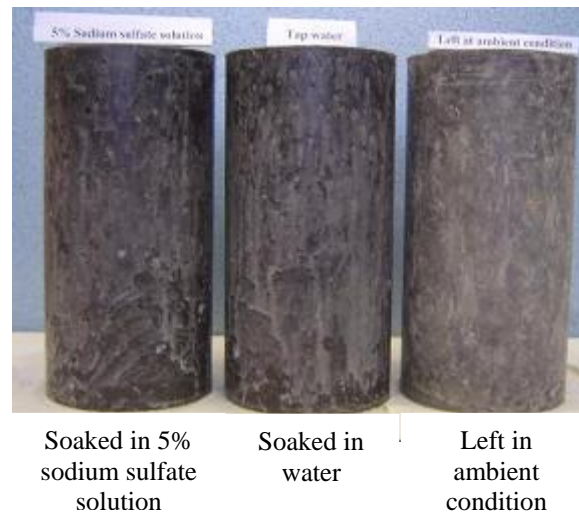
FIGURE 16: **Visual Appearance of Heat-cured Geopolymer Concrete Specimens after One Year of Exposure (Wallah and Rangan, 2006)**

There were no significant changes in the mass and the compressive strength of test specimens after various periods of exposure up to one year. The change in length was extremely small and less than 0.015% (Wallah and Rangan, 2006).

The deterioration of Portland cement concrete due to sulfate attack is attributed to the formation of expansive gypsum and ettringite which causes expansion, cracking, and spalling in the concrete. Low-calcium fly ash-based geopolymer concrete undergoes a different mechanism to that of Portland cement concrete and the geopolymerisation products are also different from hydration products. The main product of geopolymerisation, as given by Equation 2, is not susceptible to sulfate attack like the hydration products. Because there is generally no gypsum or ettringite formation in the main products of geopolymerisation, there is no mechanism of sulfate attack in heat-cured low-calcium fly ash-based geopolymer concrete. However, presence of high calcium either in the fly ash or in the aggregates could cause the formation of gypsum and ettringite in geopolymer concrete.

9.4. Sulfuric Acid Resistance

Tests were performed to study the sulfuric acid resistance of heat-cured low-calcium fly ash-based geopolymer concrete. The concentration of sulfuric acid solution was 2%, 1% and 0.5%. The sulfuric acid resistance of geopolymer concrete was evaluated based on the mass loss and the residual compressive strength of the test specimens after acid exposure up to one year. The test specimens, 100x200 mm cylinders, were made using Mixture-1 (Table 2) and heat-cured at 60°C for 24 hours after casting (Wallah and Rangan, 2006).

The visual appearance of specimens after exposure to sulfuric acid solution showed that acid attack slightly damaged the surface of the specimens. Figure 17 compares the visual appearance of the geopolymer concrete specimens after soaking in various concentrations of sulfuric acid solution for a period of one year with the specimen without acid exposure and left in ambient conditions of the laboratory. It can be seen that the specimens exposed to sulfuric acid undergoes erosion of the surface. The damage to the surface of the specimens increased as the concentration of the acid solution increased (Wallah and Rangan, 2006).

| 2% sulfuric acid solution | 1% sulfuric acid solution | 0.5% sulfuric acid solution | Left in ambient condition |
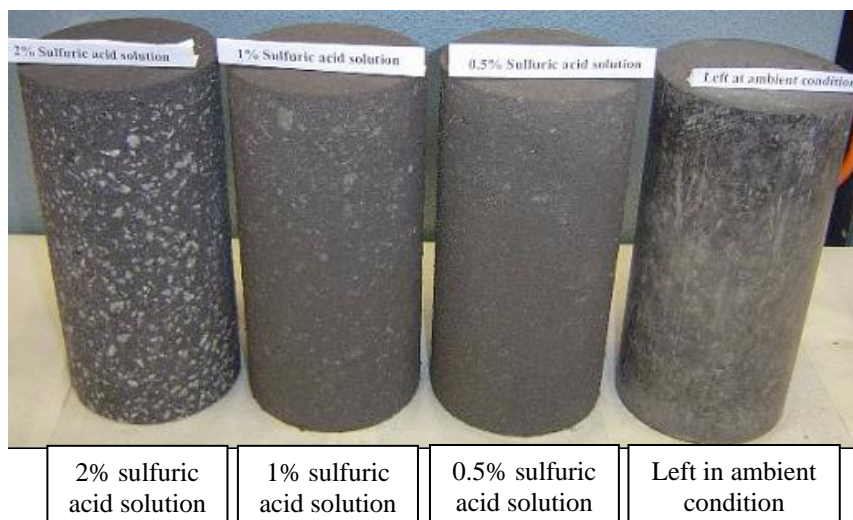
FIGURE 17: Visual Appearance of Heat-cured Geopolymer Concrete after One Year Exposure in Sulfuric Acid Solution (Wallah and Rangan, 2006)

The maximum mass loss of test specimens of about 3% after one year of exposure is relatively small compared to that for Portland cement concrete as reported in other studies. As shown in Figure 18,

exposure to sulfuric acid caused degradation in the compressive strength; the extent of degradation depended on the concentration of the acid solution and the period of exposure (Wallah and Rangan, 2006).
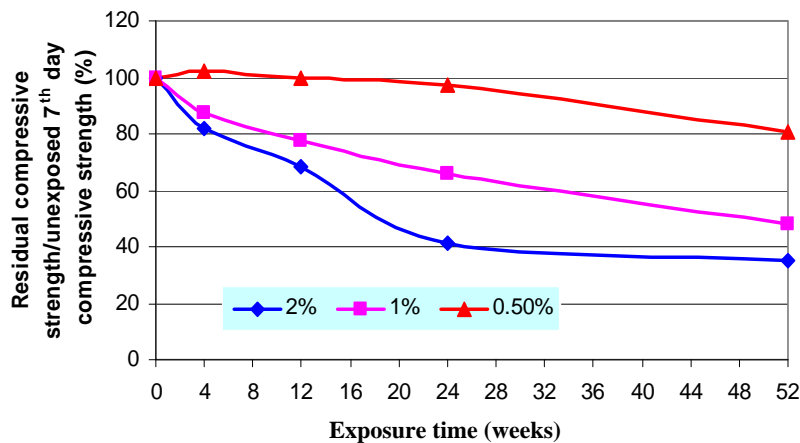
FIGURE 18: **Acid Resistance of Heat-cured Geopolymer Concrete (Wallah and Rangan, 2006)**

The acid resistance of geopolymer concrete must be considered in relation to the performance of Portland cement concrete in a similar environment. Past research data have shown that geopolymeric materials performed significantly better in acid resistance compared to Portland cement (Davidovits, 1994; Gourley and Johnson, 2005). The superior performance of geopolymeric materials in acidic environment is attributed to the lower calcium content of the source material.

10. Reinforced Geopolymer Concrete Columns and Beams

In order to demonstrate the application of heat-cured low-calcium fly ash-based geopolymer concrete, twelve reinforced columns and twelve reinforced beams were manufactured and tested (Sumajouw and Rangan, 2006).

In the column test program, the primary parameters were longitudinal reinforcement ratio, load eccentricity, and compressive strength of geopolymer concrete. The longitudinal reinforcement ratio was 1.47% and 2.95%. The column cross-section was 175 mm square. The average yield strength of longitudinal steel was 519 MPa. Closed ties made of 6mm diameter hard-drawn wires at 100 mm

spacing were used as lateral reinforcement. The concrete cover was 15 mm. The columns were subjected to eccentric compression and bent in single curvature bending. The columns were pin-ended with an effective length of 1684 mm.

The mixture proportions of geopolymer concrete used in the manufacture column specimens are given in Table 8. The average slump of fresh concrete varied between 210 mm and 240 mm. The nominal compressive strength of geopolymer concrete was 40 MPa for GCI and GCII series and, 60 MPa for GCIII and GCIV series. These target compressive strengths were achieved by using the mixtures given in Table 8 and by exploiting the flexibilities of heat-curing regime of geopolymer concrete. Accordingly, in the case of GC-I and GC-II column series, the test specimens were steam-cured at a temperature of 60°C for 24 hours after casting; on the other hand, the specimens of GC-III and GC-IV series were kept in laboratory ambient conditions for three days and then steam-cured at a temperature of 60°C for 24 hours.

The mixture proportions of geopolymer concrete used in the manufacture of beam specimens are also given in Table 8. The average slump of the fresh concrete varied from 175 mm for GBIII series to 255 mm for GBI series. The target compressive strength of geopolymer concrete was 40 MPa for GBI series, 50 MPa for GBII series, and 70 MPa for GBIII series. The specimens were kept in laboratory ambient conditions for three days after casting, and then steam-cured at 60°C for 24 hours to achieve the target strengths.

The beam cross-section was 200mm wide by 300mm deep, and 3300mm in length. The test parameters were concrete compressive strength and longitudinal tensile reinforcement ratio. All beams contained two 12mm diameter deformed bars as compression reinforcement, and two-legged vertical stirrups made of 12 mm diameter deformed bars at 150 mm spacing as shear reinforcement. The longitudinal tensile reinforcement ratios were 0.64, 1.18, 1.84, and 2.69%. The average yield strength of tensile steel bars varied between 550 and 560 MPa. The concrete cover was 25 mm. The beams were simply supported over a span of 3000mm, and subjected to two concentrated loads placed symmetrically on the span. The distance between the loads was 1000mm.

TABLE 8: **Geopolymer Concrete Mixture Proportions for Reinforced Columns and Beams (Sumajouw and Rangan, 2006)**

Materials	Columns		Beams
	Mass (kg/m^3)		
10mm aggregates	555	550	550
7mm aggregates	647	640	640
Fine sand	647	640	640
Fly ash	408	404	404
Sodium hydroxide solution	41 (16Molar)	41 (14Molar)	41 (14 Molar)
Sodium silicate solution	103	102	102
Super plasticizer	6	6	6
Extra added water	26 (GCI and GCII)	16.5 (GCIII and GCIV)	25.5 (GBI) 17.0 (GBII) 13.5(GBIII)

The behavior and failure modes of reinforced geopolymer concrete columns were similar to those observed in the case of reinforced Portland cement concrete columns. Typical failure modes of geopolymer concrete columns are shown in Figure 19 (Sumajouw and Rangan, 2006). As expected, the load capacity of columns was influenced by the load-eccentricity, the concrete compressive strength, and the longitudinal reinforcement ratio. When the load eccentricity decreased, the load capacity of columns increased. The load capacity also increased when the compressive strength of concrete and the longitudinal reinforcement ratio increased.

The load-carrying capacity of reinforced geopolymer concrete columns was calculated using both a simplified stability analysis proposed by Rangan (1990) and the moment-magnifier method incorporated in the daft Australian Standard for Concrete Structures AS 3600 (2005) and the American Concrete Institute Building Code ACI 318-02 (2002). As shown in Table 9, the calculated failure loads correlate well with the test values. These results demonstrate that the methods of calculations used in

the case of reinforced Portland cement concrete columns are applicable for reinforced geopolymer concrete columns.
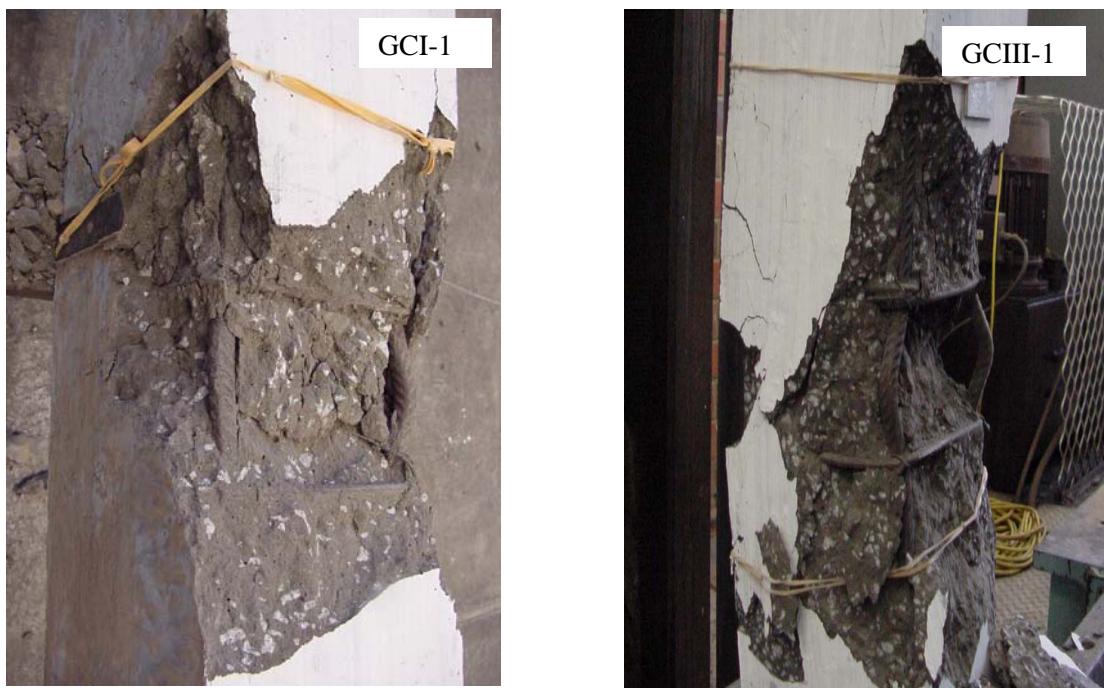
FIGURE 19: **Failure Mode of Reinforced Geopolymer Concrete Columns (Sumajouw and Rangan, 2006)**
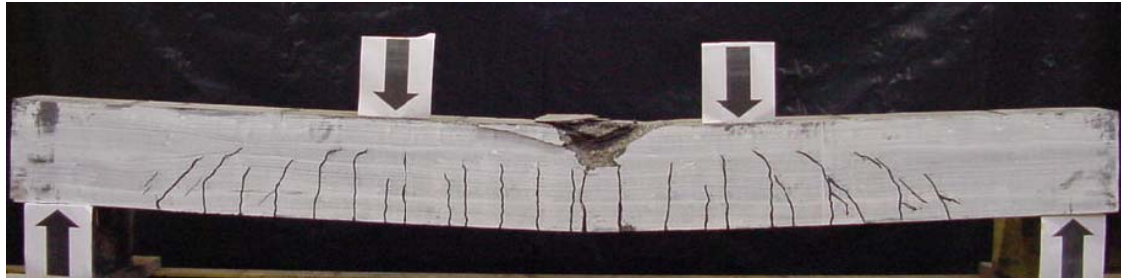
TABLE 9: Correlation of Test and Calculated Failure Loads of Reinforced Geopolymer Concrete Columns (Sumajouw and Rangan, 2006)

Column	$f_c^{'}$ (MPa)	e (mm)	p (%)	Test failure load (kN)	Calculated failure load (kN)			Failure load ratio*		
					Rangan	AS 3600	ACI 318-02	1	2	3
GCI-1	42	15	1.47	940	988	962	926	0.95	0.98	1.01
GCI-2	42	35	1.47	674	752	719	678	0.90	0.94	0.99
GCI-3	42	50	1.47	555	588	573	541	0.94	0.97	1.03
GCII-1	43	15	2.95	1237	1149	1120	1050	1.08	1.10	1.18
GCII-2	43	35	2.95	852	866	832	758	0.98	1.02	1.12
GCII-3	43	50	2.95	666	673	665	604	0.99	1.00	1.10
GCIII-1	66	15	1.47	1455	1336	1352	1272	1.09	1.08	1.14
GCIII-2	66	35	1.47	1030	1025	1010	917	1.00	1.02	1.12
GCIII-3	66	50	1.47	827	773	760	738	1.07	1.09	1.12
GCIV-1	59	15	2.95	1559	1395	1372	1267	1.11	1.14	1.23
GCIV-2	59	35	2.95	1057	1064	1021	911	0.99	1.04	1.16
GCIV-3	59	50	2.95	810	815	800	723	0.99	1.01	1.12
							Mean	1.01	1.03	1.11
							Standard deviation	0.07	0.06	0.08

*1 = Test/ Rangan; 2 = Test/AS3600; 3 = Test/ACI318-02; $f_c^{'}$ = concrete compressive strength, e = load eccentricity, and p = longitudinal reinforcement ratio.

The behavior and failure mode of reinforced geopolymer concrete beams were similar to those observed in the case of reinforced Portland cement concrete beams. Figure 20 shows the crack pattern and failure mode of a reinforced geopolymer concrete beam. The flexural capacity of beams was influenced by the concrete compressive strength and the tensile reinforcement ratio. The flexural strength of reinforced geopolymer concrete beams was calculated using the conventional flexural strength theory of reinforced concrete beams as described in standards and building codes such as the draft Australian Standard, AS 3600 (2005) and the ACI Building Code, ACI 318-02 (2002). The results are given in Table 10 (Sumajouw and Rangan, 2006). For beams with tensile reinforcement ratio of 1.18%, 1.84%, and 2.69%, the test and calculated values agreed well. In the case of beams with tensile

steel ratio of 0.64%, as expected, the calculated values were conservative due to the neglect of the effect of strain hardening of tensile steel bars on the ultimate bending moment.

FIGURE 20: **Crack Pattern and Failure Mode of Reinforced Geopolymer Concrete Beam (Sumajouw and Rangan, 2006)**

TABLE 10: Correlation of Test and Calculated Ultimate Moment of Reinforced Geopolymer Concrete Beams (Sumajouw and Rangan, 2006)

Beam	Tensile reinforce-ment ratio (%)	Concrete compressive strength (MPa)	Mid-span deflection at failure load (mm)	Ultimate moment (kNm)		Ratio: Test/Calc.
				Test	Calc.	
GBI-1	0.64	37	56.63	56.30	45.17	1.24
GBI-2	1.18	42	46.01	87.65	80.56	1.09
GBI-3	1.84	42	27.87	116.85	119.81	0.98
GBI-4	2.69	37	29.22	160.50	155.31	1.03
GBII-1	0.64	46	54.27	58.35	42.40	1.28
GBII-2	1.18	53	47.20	90.55	81.50	1.11
GBII-3	1.84	53	30.01	119.0	122.40	0.97
GBII-4	2.69	46	27.47	168.7	162.31	1.04
GBIII-1	0.64	76	69.75	64.90	45.69	1.42
GBIII-2	1.18	72	40.69	92.90	82.05	1.13
GBIII-3	1.84	72	34.02	126.80	124.17	1.02
GBIII-4	2.69	76	35.85	179.95	170.59	1.05
					Average	1.11
					Standard Deviation	0.14

Mid-span deflection at service load of reinforced geopolymer concrete beams was calculated using the elastic bending theory and the serviceability design provisions given in the draft Australian Standard,

AS 3600 (2005). According to AS3600, the calculation of short-term deflection of reinforced concrete beams should include the effects of cracking, tension stiffening, and shrinkage properties of the concrete. In these calculations, the service load was taken as the test failure load divided by 1.5; measured values of modulus of elasticity and drying shrinkage strain of geopolymer concrete were used. Good correlation of test and calculated deflections at service load is seen in Table 11 (Sumajouw and Rangan, 2006).

In all, the results given in Table 9, Table 10, and Table 11 demonstrate that reinforced low-calcium (ASTM Class F) fly ash-based geopolymer concrete structural members can be designed using the design provisions currently used in the case of reinforced Portland cement concrete members.

TABLE 11: Correlation of Test and Calculated Service Load Deflections of Reinforced Geopolymer Concrete Beams (Sumajouw and Rangan, 2006)

Beam	Service load (kN)	Deflection (Test) (mm)	Deflection (Calc.) (mm)	Ratio: Test/Calc.
GBI-1	75	13.49	11.88	1.17
GBI-2	117	15.27	12.49	1.25
GBI-3	156	13.71	12.41	1.14
GBI-4	217	15.60	14.21	1.14
GBII-1	78	14.25	11.91	1.21
GBII-2	121	14.38	12.58	1.20
GBII-3	159	13.33	12.36	1.14
GBII-4	225	16.16	14.18	1.17
GBIII-1	87	14.10	12.07	1.21
GBIII-2	124	12.55	12.41	1.08
GBIII-3	169	12.38	12.59	1.05
GBIII-4	240	14.88	14.16	1.10
			Mean	1.15
			Standard deviation	0.06

The studies carried out by Chang, et al (2007), Sarker, et al (2007a, 2007b), and Sofi, et al (2007b) also demonstrate the application of fly ash-based geopolymer concrete.

11. Geopolymer Precast Concrete Products

Gourley and Johnson (2005) have reported the details of geopolymer precast concrete products on a commercial scale. The products included sewer pipes, railway sleepers, and wall panels. Reinforced geopolymer concrete sewer pipes with diameters in the range from 375 mm to 1800 mm have been manufactured using the facilities currently available to make similar pipes using Portland cement concrete. Tests performed in a simulated aggressive sewer environment have shown that geopolymer concrete sewer pipes outperformed comparable Portland cement concrete pipes by many folds. Gourley and Johnson (2005) also reported the good performance of reinforced geopolymer concrete railway sleepers in mainline tracks and excellent resistance of geopolymer mortar wall panels to fire.

Siddiqui (2007) demonstrated the manufacture of reinforced geopolymer concrete culverts on a commercial scale. Tests have shown that the culverts performed well and met the specification requirements of such products.

12. Economic Benefits of Geopolymer Concrete

Heat-cured low-calcium fly ash-based geopolymer concrete offers several economic benefits over Portland cement concrete. The price of one ton of fly ash is only a small fraction of the price of one ton of Portland cement. Therefore, after allowing for the price of alkaline liquids needed to the make the geopolymer concrete, the price of fly ash-based geopolymer concrete is estimated to be about 10 to 30 percent cheaper than that of Portland cement concrete.

In addition, the appropriate usage of one ton of fly ash earns approximately one carbon-credit that has a redemption value of about 10 to 20 Euros. Based on the information given in this Report, one ton low-calcium fly ash can be utilized to manufacture approximately 2.5 cubic meters of high quality fly ash-based geopolymer concrete, and hence earn monetary benefits through carbon-credit trade.

Furthermore, the very little drying shrinkage, the low creep, the excellent resistance to sulfate attack, and good acid resistance offered by the heat-cured low-calcium fly ash-based geopolymer concrete may yield additional economic benefits when it is utilized in infrastructure applications.

13. Concluding Remarks

The Report presented information on heat-cured fly ash-based geopolymer concrete. Low-calcium fly ash (ASTM Class F) is used as the source material, instead of the Portland cement, to make concrete.

Low-calcium fly ash-based geopolymer concrete has excellent compressive strength and is suitable for structural applications. The salient factors that influence the properties of the fresh concrete and the hardened concrete have been identified. Data for the design of mixture proportions are included and illustrated by an example.

The elastic properties of hardened geopolymer concrete and the behavior and strength of reinforced geopolymer concrete structural members are similar to those observed in the case of Portland cement concrete. Therefore, the design provisions contained in the current standards and codes can be used to design reinforced low-calcium fly ash-based geopolymer concrete structural members.

Heat-cured low-calcium fly ash-based geopolymer concrete also shows excellent resistance to sulfate attack, good acid resistance, undergoes low creep, and suffers very little drying shrinkage. The Report has identified several economic benefits of using geopolymer concrete.

14. References

ACI Committee 318 (2002), *Building Code Requirements for Structural Concrete*, American Concrete Institute, Farmington Hills, MI.

ACI Committee 363 (1992), *State of the Art Report on High-Strength Concrete*, American Concrete Institute, Detroit, USA.

Aitcin, P. C. and P. K. Mehta (1990), "Effect of Coarse-Aggregate Characteristics on Mechanical Properties of High-Strength Concrete", *ACI Materials Journal* 87(2): 103-107.

Chang, E. H. , Sarker, P, Lloyd, N and Rangan, B.V. (2007), "Shear behaviour of reinforced fly ash-based geopolymer concrete beams", *Proceedings of the23rd Biennial Conference of the Concrete Institute of Australia*, Adelaide, Australia, pp 679 – 688.

Collins, M. P., D. Mitchell, J.G MacGregor (1993), "Structural Design Considerations for High Strength Concrete", *ACI Concrete International* 15(5): 27-34.

Committee BD-002 Standards Australia (2005), *Concrete Structures: Draft Australian Standard AS3600-200x,* Standards Australia.

Davidovits, J (1988) "Soft Mineralogy and Geopolymers", *Proceedings of the of Geopolymer 88 International Conference*, the Université de Technologie, Compiègne, France.

Davidovits, J (1994) "High-Alkali Cements for 21st Century Concretes. in Concrete Technology, Past, Present and Future", *Proceedings of V. Mohan Malhotra Symposium*, Editor: P. Kumar Metha, ACI SP- 144, 383-397.

Duxson P, Provis J L, Lukey G C and van Deventer J S J (2007), "The Role of Inorganic Polymer Technology in the Development of Green Concrete", *Cement and Concrete Research*, 37(12), 1590-1597.

Fernández-Jiménez A M, Palomo A, and López-Hombrados C (2006a), "Engineering Properties of Alkali-activated Fly Ash Concrete", *ACI Materials Journal*, 103(2), 106-112.

Fernández-Jiménez A M, de la Torre A G, Palomo A, López-Olmo G, Alonso M M, and Aranda M A G (2006b), "Quantitative Determination of Phases in the Alkali Activation of Fly Ash, Part I, Potential Ash Reactivity", *Fuel*, 85(5-6), 625-634.

Gartner E (2004), "Industrially Interesting Approaches to 'Low-CO_2' Cements", *Cement and Concrete Research,* 34(9), 1489-1498.

Gourley, J. T. (2003), "Geopolymers; Opportunities for Environmentally Friendly Construction Materials", Paper presented at the *Materials 2003 Conference: Adaptive Materials for a Modern Society,* Sydney.

Gourley, J. T., & Johnson, G. B. (2005), "Developments in Geopolymer Precast Concrete", Paper presented at the *International Workshop on Geopolymers and Geopolymer Concrete*, Perth, Australia.

Hardjito, D. and Rangan, B. V. (2005), *Development and Properties of Low-Calcium Fly Ash-based Geopolymer Concrete,* Research Report GC1, Faculty of Engineering, Curtin University of Technology, Perth, available at *espace@curtin* or *www.geopolymer.org*.

Lee W K W and van Deventer J S J (2004), "The Interface between Natural Siliceous Aggregates and Geopolymers", *Cement and Concrete Research*, 34(2) 195-206.

Malhotra, V. M. (1999), "Making concrete 'greener' with fly ash", *ACI Concrete International*, 21, 61-66.

Malhotra, V.M. (2006), "Reducing CO2 Emissions", *ACI Concrete International*, 28, 42-45.

McCaffrey, R. (2002), "Climate Change and the Cement Industry", *Global Cement and Lime Magazine (Environmental Special Issue)*, 15-19.

Neville, A. M. (2000), *Properties of Concrete*, Prentice Hall.

Provis J L, Muntingh Y, Lloyd R R, Xu H, Keyte L M, Lorenzen L, Krivenko P V,and J.S.J. van Deventer J S J (2007), "Will Geopolymers Stand the Test of Time?", *Ceramic Engineering and Science Proceedings*, 28(9), 235-248.

Rangan, B.V. (1990), "Strength of Reinforced Concrete Slender Columns", *ACI Structural Journal*, 87(1) 32-38.

Rangan, B.V. (2008) "*Low-Calcium Fly Ash-based Geopolymer Concrete*", Chapter 26 in Concrete Construction Engineering Handbook, Editor-in Chief: E.G. Nawy, Second Edition, CRC Press, New York.

Rangan, B.V. (2009), "*Engineering Properties of Geopolymer Concrete*", Chapter 13 in Geopolymers: Structures, Processing, Properties, and Applications, Editors: J.Provis and J. van Deventer, Woodhead Publishing Limited, London.

Sarker P.K., Grigg A, and Chang E.H. (2007a), "Bond Strength of Geopolymer Concrete with Reinforcing Steel", Proceedings of *Recent Developments in Structural Engineering, Mechanics and Computation*, CD ROM, Editor: A. Zingoni, Millpress, the Netherlands, 1315-1320.

Sarker P.K., and deMeillon T (2007b), "Residual Strength of Geopolymer Concrete After Exposure to High Temperature", Proceedings of *Recent Developments in Structural Engineering, Mechanics and Computation,* CD ROM, Editor: A. Zingoni, Millpress, the Netherlands, 1566-1571.

Siddiqui, K.S. (2007),"Strength and Durability of Low-Calcium Fly Ash-based Geopolymer Concrete", *Final Year Honours Dissertation*, The University of Western Australia, Perth.

Sofi M, van Deventer J S J, Mendis P A and Lukey G C (2007a), "Engineering Properties of Inorganic Polymer Concretes (IPCs)", *Cement and Concrete Research*, 37(2), 251-257.

Sofi M, van Deventer J S J, Mendis P A and Lukey G C (2007b), "Bond Performance of Reinforcing Bars in Inorganic Polymer Concrete (IPC)", *Journal of Materials Science*, 42(9), 3007-3016.

Sumajouw, M.D.J. and Rangan, B.V. (2006), *Low-Calcium Fly Ash-Based Geopolymer Concrete: Reinforced Beams and Columns,* Research Report GC3, Faculty of Engineering, Curtin University of Technology, Perth, available at *espace@curtin* or *www.geopolymer.org*.

Wallah, S.E. and Rangan, B.V. (2006), *Low-Calcium Fly Ash-Based Geopolymer Concrete: Long-Term Properties*, Research Report GC2, Faculty of Engineering, Curtin University of Technology, Perth, available at *espace@curtin* or *www.geopolymer.org*.

van Jaarsveld, J. G. S., J. S. J. van Deventer, L. Lorenzen (1997), "The Potential Use of Geopolymeric Materials to Immobilise Toxic Metals: Part I. Theory and Applications", *Minerals Engineering* 10(7), 659-669.