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SERVICEABILITY OF LOW CREEP FLY ASH GEOPOLYMER CONCRETE BEAMS

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In reinforced concrete construction, deflection control is an important performance criterion for their serviceability. The aim of the research described in this paper is to assess the deformation of cracked reinforced geopolymer concrete beams under long term service loading. The geopolymer binder is Portland cement free, using 85% of low calcium fly ash, 15% of GGBFS (Ground Granulated Blast Furnace Slag) and a sodium silicate/sodium hydroxide based activator. Firstly, geopolymer concrete drying shrinkage and creep were measured. Different curing conditions at elevated temperature were used. All experimental results are compared to predictions made using the Eurocode 2. Secondly, geopolymer concrete beams were subjected to short time bending tests leading to concrete cracking (pre-cracking tests). Beams were then stored under sustained loading for a period of four months. Both deflection and cracks were monitored versus time. Results show that, providing an appropriate heat curing regime, geopolymer concrete creep is much lower than that observed for OPC concrete and predicted by the Eurocode 2. As a result, the time-dependent deflection of geopolymer concrete beams measured after 4 months under sustained loading was always significantly lower than that of traditional OPC concrete beams. All results are showing that the crack widths of geopolymer concrete beams are significantly smaller than those expected for OPC concrete beams according to fib model code 2010 for both short and long terms tests. It is concluded that low calcium fly ash-based geopolymer concrete is a promising option for precast applications.

Keywords: Alkali-activated, Reinforced concrete, Deflection, Time-dependent, Cracking, Shrinkage.

1 INTRODUCTION

Over the last two decades, geopolymer concretes (GPC) have emerged as novel engineering materials with the potential to become a substantial element in an environmentally sustainable construction and building products industry Davidovits (2011). GPC is the result of the reaction of materials containing aluminosilicates with an alkaline solution to produce an inorganic polymer binder. Industrial by-products such as fly ash and blast furnace slag are commonly used as the source of aluminosilicate for the manufacture of GPC due to the low cost and wide availability of these materials. Geopolymer binder can provide reduction of embodied CO_2 of up to 80% compared to OPC by the efficient use of precursors. In reinforced concrete construction, deflection control is an important performance criterion for their serviceability. Short term structural performance of geopolymer beams have been investigated by several authors (Dattatreya *et al.* 2011, Madheswaran *et al.* 2014). All authors agree that the short term response of geopolymer concrete beams is similar to OPC concrete beams. The aim of the research described in this paper is to assess the deformation of cracked reinforced geopolymer concrete beams under long term service loading by monitoring both time-dependent deflection increase and cracks widening. The geopolymer binder is Portland cement free, using 85% of low calcium fly ash, 15% of GGBFS (Ground Granulated Blast Furnace Slag) and a sodium silicate/sodium hydroxide based activator.

2 EXPERIMENTAL PROGRAM

Experiments aim to assess the time-dependent deflection increase and cracking widening of geopolymer concrete beams under sustained loading. The results obtained from tests on five beams are reported in this paper and compared to test results obtained on OPC concrete beams as well as fib model code 2010 predictions.

2.1 Geopolymer Concrete Mix Design and Precursors

Based on the outcomes of a previous study (Ng and Foster 2012), three different sources of aluminosilicate precursors have been used: fly ash (FA) from Eraring Power Station (New South Wales, Australia), an Ultra-fine FA branded as Kaolite high-performance ash (HPA) sourced from Callide Power Station (Queensland, Australia) and ground granulated blast-furnace slag (GGBFS) supplied by Blue Circle Southern Cement Australia. Both fly ashes are low calcium class F fly ash (ASTM C 618 Class F). The alkaline solution used was a mixture of 12 molar (M) sodium hydroxide (NaOH) solution and sodium silicate (Na2SiO3) solution.

Mix proportioning of the raw material ingredients, as shown in Table 1, was carried out by mass. About 85% of the blend is composed of low calcium class F fly ash. Sydney sand was used as fine aggregate and the coarse aggregate was ten mm nominal size crushed basalt. The aggregate's mass shown in Table 1 is in the saturated surface dry (SSD) condition. The triple aluminosilicate blend was mixed in the dry condition for about three minutes together with all aggregates. The alkaline solution was then gradually added, followed by the free water. Both concrete cylinders used to measure the concrete characteristics and beams were compacted by using a poker vibration. The workability of the fresh concrete was assessed using the standard slump test. The slump obtained was 130 mm.

Table 1. Geopolymer concrete mix.

Material	**(kg/m^3)**
Coarse aggregate	1138
Fine aggregate	730
FA	200
Kaolite HPA	55
GGBFS	45
Sodium hydroxide solution(NaOH)	45.7
Sodium silicate solution (Na_2SiO_3)	114.3
Free water	31

2.2 Curing Procedures

The compressive strength of the geopolymer concrete was found to be poor (< 20MPa) when cured in ambient condition (23℃ and 50% relative humidity), which is typical of low calcium fly ash geopolymer binders. Three types of heat curing conditions were adopted for the beams:

- 1D-Curing: cured in an 80°C water bath for one day.
- 2D-Curing: cured in an 80°C water bath for two days.
- 7D-Curing: cured in an 80°C water bath for seven days.

After casting, both concrete cylinders and beams were sealed to prevent excessive loss of moisture and stored in a curing room at 40°C. After 24h, all specimens were demolded and transferred to the 80°C water bath for heat curing. At the end of the heat curing period, all specimens were stored in the Laboratory atmosphere.

2.3 Testing Program

The properties of the hardened concrete (compressive strength, tensile strength and instantaneous elastic modulus) were measured at 28 days on concrete cylinders (diameter = 100 mm, height = 200 mm). Uniaxial compressive strength was measured according to ASTM C39/C39M-12a requirements. The modulus of elasticity was measured based on ASTM C469 standard test method. The tensile strength was obtained using the splitting test.

All beams are 2450 mm long, with a 2250 mm span between the supports and with 250x120 mm cross-section. The reinforcement layout of the beams is shown in Figure 1. The main longitudinal steel bars in each specimen are standard Australian deformed bars of 16 mm diameter (N16's). The concrete cover to the reinforcement is equal to 14 mm for all the beams. Stirrups were placed all along the beams with 200 mm spacing. The characteristic yield stress of the steel bars (the elastic limit) is fy = 500MPa.

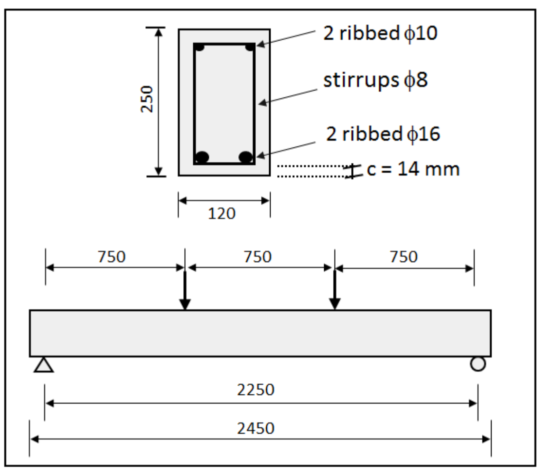

Figure 1. Layout of the reinforcement and loading arrangement (stirrups spacing: 200 mm).

The load tests commenced at age 28 days. For all beams, drying commenced after the heat curing period (two, three, or eight days) and then significant shrinkage developed prior to first loading. All beams were tested in four point bending (Figure 1), both for the sustained load tests and the short term tests. The experiments consisted of:

- Pre-cracking test: 28 days after casting, all beams were pre-cracked. The beams were loaded up to either 50 kN or 70 kN (Table 2). Loading and mid-span deflection were measured and concrete cracking was accurately recorded.

- Long term (sustained load) test: After the specimens were initially cracked under a short-term peak load, they were subjected to a sustained load for a period of 120 days. An appropriate spring loading device was used in order to ensure that the load remained constant for the duration of the tests in spite of creep, time-dependent loss in stiffness due to cracking and gradual reduction of tension stiffening with time. The sustained load adopted for four of the beams was 40 kN. This value was selected to represent a typical dead load for a reinforced concrete beam. One beam was kept unloaded (except for its self-weight) in order to assess the effect of concrete shrinkage with only a minor effect due to loading. The development of cracking and the increase in deflection were monitored over time in order to assess the time-dependent effects of concrete creep and shrinkage.

Table 2. Beam designations and values of the pre-cracking and sustained loads (P_{cr} is the cracking load).

Beam	Pre-cracking load	Cured	Sustained load
B1	70 kN ($2P_{cr}$)	7D80	40 kN
B2	50 kN ($1.8P_{cr}$)	7D80	40 kN
B3	50 kN ($2P_{cr}$)	2D80	Self-weight loading
B4	50 kN ($2P_{cr}$)	2D80	40 kN
B5	50 kN ($2.5P_{cr}$)	1D80	40 kN

The drying shrinkage tests were performed on 75x75x300 mm prisms in accordance with Australia Standard AS1012.13 (1992). During the tests the specimens were kept in a controlled temperature environment. The temperature and the relative humidity were maintained at about 23°C and 50% respectively. Standard creep tests were performed on 100 mm diameter cylinders with 200 mm height in accordance with Australian Standard AS1012.16 (1996). All creep tests were started 28 days after casting and the sustained load applied was 40 % of the 28 days compressive strength. Three specimens were tested for each curing condition for about 90 days. Both shrinkage and creep results were compared to the values calculated for an equivalent OPC based concrete using the Eurocode 2 (EN 1992-1-1, 2004).

3 EXPERIMENTAL RESULTS

Table 3 shows the average compressive strength, elastic modulus and tensile strength after 28 days obtained for all heat curing regimes. Results show that heat curing is required for low calcium fly ash geopolymer concrete to achieve structural concrete grade.

Table 3. Average compressive strength, elastic modulus and tensile strength versus heat curing duration.

	Ambient	1D80	2D80	7D80
f_{cm28} (MPa)	18.7	43.5	48.0	54.5
E_{cm28} (GPa)	18.0	20.3	23.7	22.0
f_{tm28} (MPa)	2.3	3.6	3.9	4.5

Standard shrinkage test results are presented in Figure 2a in comparison with Eurocode 2 predictions. Shrinkage stains at 90 days are overall lower than the ones predicted by the

Eurocode 2 regardless the curing regime. Increasing the heat curing duration does not lead to any consistent reduction in shrinkage. Minimum shrinkage at 90 days is obtained with only 24 hours heat curing.

Standard creep test results are presented in Figure 2b in comparison with Eurocode 2 predictions. Results show that the creep coefficient of all geopolymer concretes is greatly lower than the ones predicted by the Eurocode 2 for OPC concrete. Increasing the heat curing duration allows reducing creep but only marginally. Considering the energy consumption and carbon created by increasing the heat curing duration, 24 hours heat curing appears to be suitable to achieve both structural concrete grade compressive strength and low creep.

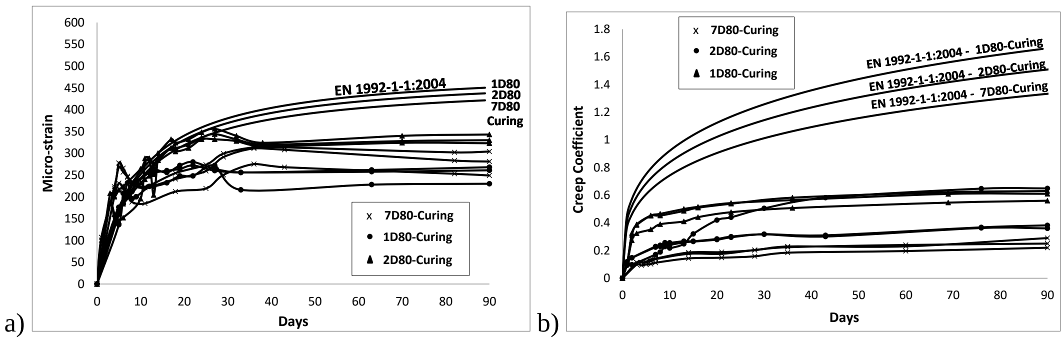

Figure 2. a) Shrinkage strain b) creep coefficient obtained for all curing conditions and all concrete specimens.

Figure 3 shows the percentage in time-dependent deflection increase relative to instantaneous deflection measured when applying the 40kN sustained loading. Results are compared to the ones obtained on OPC beams tested in similar conditions (Castel *et al.* 2014). Results show that the time-dependent increase in geopolymer beams deflection is very low and greatly smaller than that observed on OPC beams. The time-dependent performance of geopolymer beams in term of serviceability appears to be way better than that of OPC concrete beams due to the very low creep coefficient of the heat cured low calcium fly ash geopolymer concretes. In accordance with standard creep test results, increasing the heat curing duration seems to have only a marginal effect on geopolymer concrete beams time-dependent deflection increase.

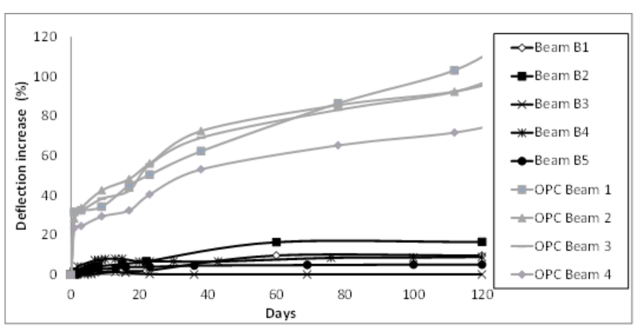

Figure 3. Comparison between the time-dependent deflection increase under sustained loading observed on Geopolymer and OPC concrete beams.

Finally, Figure 4 shows the average crack width measured after the pre-cracking tests (short term) and after 120 days under sustained loading (long term), compared to fib 2010 model code predictions. All results are showing that the crack widths of geopolymer concrete beams are significantly smaller those expected for OPC concrete beams according to fib model code 2010.

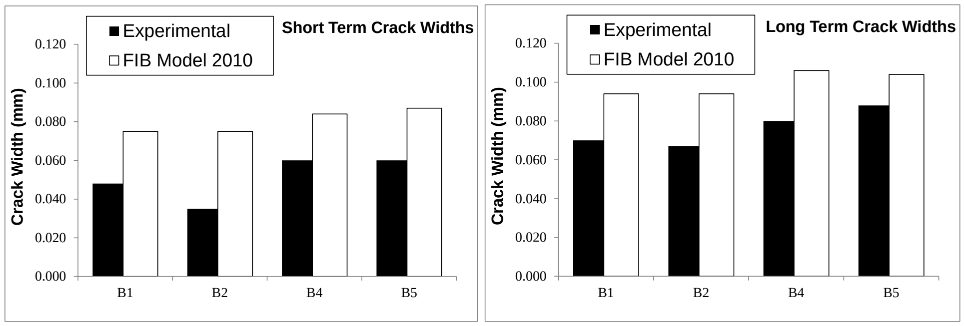

Figure 4. Comparison between the average instantaneous crack widths measured under 40kN loading and fib2010 predictions for both short term and long term tests.

4 CONCLUSIONS

Heat curing is required for low calcium fly ash geopolymer concrete and results show that 24h at 80^{o}C is suitable to achieve both structural concrete grade strength and low creep. The time-dependent performance of geopolymer beams in term of serviceability appears to be way better than that of OPC concrete beams due to the very low creep coefficient of heat cured geopolymer concrete. The time-dependent increase in geopolymer concrete beams deflection is very low and greatly smaller than that observed on OPC beams. All results are showing that the crack widths of geopolymer concrete beams are significantly smaller than those expected for OPC concrete beams according to fib model code 2010 for both short and long terms tests. It is concluded that low calcium fly ash-based geopolymer concrete is a promising option for precast applications.

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