Investigation of long-term behaviour of composite geopolymer concrete beams under sustained loads

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Publication details
INVESTIGATION OF LONG-TERM BEHAVIOUR OF COMPOSITE GEOPOLYMER CONCRETE BEAMS UNDER SUSTAINED LOADS

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ABSTRACT

The long term behaviour of steel composite beams constructed with geopolymer concrete is investigated. A sustained load of 1 kPa was applied on top of the beams at the age of 14 days. Creep tests on geopolymer concrete show higher creep in the specimens loaded at 14 days than those loaded at 28 days. Long term deflection calculations were performed by using the age-adjusted effective modulus method (AEMM) through input of properties of geopolymer concrete from experimental data including elastic modulus, modulus of rupture, creep and shrinkage. The estimated deflection by AEMM as applied to geopolymer concrete beams is compared with the experimental results, and the accuracy is discussed.

KEYWORDS

Geopolymer, alkali-activated, concrete beams, creep, age-adjusted effective modulus, deflection.

INTRODUCTION

The manufacturing of ordinary Portland cement (OPC) as the main binder in concrete releases almost 1 tonne of CO₂ per tonne of OPC resulting from the calcination of limestone. Activation of industry by-products and waste materials, such as fly ash and blast furnace slag, with an alkali can replace the OPC content in concrete and the resulting product is commonly known as alkali-activated concrete or geopolymer concrete (GPC) (Davidovits 1991). Utilisation of GPC reduces CO₂ emission and removes materials from landfill, and can lead to sustainable construction (Duxson et al. 2007). Research on GPC have shown that it is superior to ordinary Portland cement concrete (OPCC) in mechanical properties (Collins and Sanjayan 1999a) and in durability (Byfors et al. 1989). Although GPC is a potential alternative as a sustainable construction material, the current application of GPC in structural elements is limited due to lack of codes and standards for structural design (Duxson et al. 2007). The long-term mechanical properties of GPC are essential for serviceability limit state design but there has been little research on creep behaviour of GPC. These properties vary with the types of binder...
materials, mix proportion and curing method of GPC (Collins and Sanjayan 1999a; Hardjito et al. 2004).

The age-adjusted effective modulus method (AEMM) is believed to be accurate and simple, and it is widely used in structural design for serviceability. It was first developed by Trost (1967) and then improved by Bazant (1972). However, the AEMM was originally developed for concrete structures made with OPC. Research on AEMM and long-term behaviour of GPC structures is limited. Therefore, it is important to study the long-term behaviour of GPC structures before application in construction.

This paper shows the creep behaviour of GPC in the structural elements by monitoring two composite GPC beams under sustained loads and the comparison with prediction of deflection by AEMM.

**TEST PROCEDURES**

**Geopolymer Concrete (GPC)**

The formulation of GPC used in this research is shown in Table 1. Commercial sodium silicate was used as activator. Firstly, the aggregates and the binder were well mixed in the agitator drum on the concrete mixer truck. The activator was then added into the mixture on site and mixed for 5 minutes. Finally the water was added into the mixture and mixed for 5 minutes.

<table>
<thead>
<tr>
<th>GGBFS (kg/m$^3$)</th>
<th>FA (kg/m$^3$)</th>
<th>water-binder ratio</th>
<th>Aggregates (kg/m$^3$)</th>
<th>Activator concentration (wt.% binder)</th>
</tr>
</thead>
<tbody>
<tr>
<td>380</td>
<td>20</td>
<td>0.4</td>
<td>1150</td>
<td>630</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>10</td>
</tr>
</tbody>
</table>

**Experimental Program**

Flexural creep testing was carried out on two composite GPC beams which replicated the suspended floor systems in practice in full size (span, depth and reinforcements). Two composite steel formworks were elevated from the ground and supported on two permanent supports on both ends and two temporary supports spaced at 2 m. GPC was cast inside the laboratory so as to simulate cast in-situ construction. The temporary supports were removed at the age of 14 days, followed by the application of uniformly distributed load of 1 kPa on top of the beams with the use of 20 kg sandbags.

Detail of the beam setup is shown in Figure 1, and the reinforcement details of these two beams are listed in Table 2. Foil type strain gauges were attached to the top reinforcements with adhesive and covered with a number of coats for long term protection on each beam. Dial gauges with accuracy to 0.01 mm were placed at mid-span below the beams for measurement of deflection.

Besides, the properties of GPC were determined through a series of material tests. The compressive strength was determined from the mean value of two concrete cylinders of 100 mm dia. at 7 days, 14 days and 28 days. Compressive creep tests were done on concrete cylinders of 150 mm dia. according to AS 1012.16 (1996). Because there is no standardised curing process specified for GPC, the GPC specimens were cured according to the procedures for OPC specified in Australian Standards, in which, the specimens were moist cured in a lime saturated bath at 23°C until 7 days and then they were moved into the drying room, in which the temperature was kept at 23°C and the relative humidity (RH) at 50%. Two GPC cylinders were loaded at the age of 14 days, while another two were loaded at the age of 28 days to observe the effect of loading age. Flexural strength testing was carried out on the prism specimens of 100 mm × 100 mm × 400 mm according to AS 1012.11 (2000).
Table 2. Detail of reinforcement in two composite geopolymer concrete beams

<table>
<thead>
<tr>
<th>Beam types</th>
<th>B1</th>
<th>B2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top reinforcement</td>
<td>SL72 Mesh</td>
<td>SL92 Mesh</td>
</tr>
<tr>
<td>Bottom reinforcement</td>
<td>N12 @ 200mm centres</td>
<td>N12 @ 200mm centres</td>
</tr>
<tr>
<td>Composite steel formwork</td>
<td>KF57 1.00 BMT</td>
<td>KF57 1.00 BMT</td>
</tr>
</tbody>
</table>

**Analysis using AEMM**

AEMM was used to predict the long-term deflection of the GPC beams. Properties of GPC, obtained from the experimental results including elastic modulus, modulus of rupture, creep and shrinkage, and reinforcement details and load profile were input to AEMM. The age-adjusted effective modulus is given by:

$$ E_e(t, \tau_0) = \frac{E_e(\tau_0)}{1 + x(t, \tau_0)\phi(t, \tau_0)} \tag{1} $$

where $E_e(t, \tau_0)$ is the age-adjusted effective modulus at time $t$ in days, which is larger than the loading age at time $\tau_0$ in days, $E_e(\tau_0)$ is the elastic modulus at time $\tau_0$, $\phi(t, \tau_0)$ is the creep coefficient, and $x(t, \tau_0)$ is the age-adjusted coefficient.

Since there has been no creep function developed for GPC, the creep coefficient can only be obtained from the experimental data, and the age-adjusted coefficient was assumed to be 0.65 for all ages for sustained loads following the suggestion by Gilbert and Ranzi (2011).

The long-term strains and curvatures in the cross-sections of the beam can be calculated. Deflection of the beams was derived from the double integration of the curvatures from the sections in every 0.5 m along the beams. Because the beams were expected to crack under the applied loads, tension stiffening was taken into account to avoid overestimation of deflection. The effect of tension stiffening was calculated according to Eurocode 2 (2004):

$$ \delta(t) = \delta_{\text{cr}}(t) + (1 - \zeta)\delta_{\text{u}}(t) \tag{2} $$

$$ \zeta = 1 - \beta \left( \frac{M_c(t)}{M_s} \right)^2 \tag{3} $$

where $\delta(t)$ is the predicted deflection accounting for tension stiffening, $\delta_{\text{cr}}(t)$ is the predicted deflection for the fully cracked condition, $\delta_{\text{u}}(t)$ is the predicted deflection for the uncrack condition, $\zeta$ is the distribution coefficient, $\beta$ is the coefficient taking account of the influence of the duration of the loading in which it is equal to 1 for single short-term loading and 0.5 for sustained loading, $M_c(t)$ is the crack moment computed taking account of the long-term effects and $M_s$ is the service moment.
Assumptions

The thermal strain was assumed to remain uniform along the beams. The coefficient of thermal expansion of GPC in this analysis was assumed to be $11 \times 10^{-6} \, \text{K}^{-1}$, similar to that of OPCC and steel reinforcements. The raw strain data were then adjusted to exclude the effect of temperature.

Because drying shrinkage is influenced by the size of concrete element (Bissonnette et al. 1999), shrinkage strain on the beams was taken from the end section over the support measured by the strain gauges to reflect the real condition of the beams. This section of the beams was not loaded ($M^* = 0$), so it was assumed that no creep effect occurred.

RESULTS AND DISCUSSION

Concrete Properties

The slump of the fresh GPC was 150 mm. The uniaxial compressive strength and modulus of rupture at ages of 7 days, 14 days and 28 days under two conditions of curing are shown in Table 3. For specimens that were stored into the drying room after 7 days of bath curing, the compressive strength was generally lower than those with bath curing at all ages. This reduction in strength development was hypothesised to be due to microcracking induced by drying (Collins and Sanjayan 2001). The flexural strength development was affected more significantly by drying. This can be explained by the extra tensile stress at the drying surface induced by differential drying shrinkage as observed in OPCC (Gilbert 2001). Microcracking at the surface can also occur due to drying (de Sa et al. 2008). However, GPC exhibited higher tensile strength than OPCC in general (Collins and Sanjayan 1999b).

<table>
<thead>
<tr>
<th>Age (days)</th>
<th>Condition of curing</th>
<th>Uniaxial compressive strength (MPa)</th>
<th>Modulus of rupture (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>Bath cured</td>
<td>42.63</td>
<td>6.23</td>
</tr>
<tr>
<td>14</td>
<td>Bath cured</td>
<td>42.87</td>
<td>-</td>
</tr>
<tr>
<td>14</td>
<td>Bath cured until 7 day, then drying room</td>
<td>40.32</td>
<td>4.43</td>
</tr>
<tr>
<td>28</td>
<td>Bath cured</td>
<td>46.67</td>
<td>6.75</td>
</tr>
<tr>
<td>28</td>
<td>Bath cured until 7 day, then drying room</td>
<td>41.83</td>
<td>4.07</td>
</tr>
</tbody>
</table>

The test results from the creep test are illustrated in Figure 2. The creep strain of the specimens was measured up to 237 days. Specimens loaded at the age of 14 days exhibited more creep strain than those loaded at the age of 28 day. The elastic modulus of GPC was derived from creep testing, and the average value of two loaded specimens was taken as 28,970 MPa and 27,970 MPa at 14 days and 28 days, respectively.

![Figure 2. Creep coefficient of geopolymer concrete](image-url)
Prediction of Deflection by AEMM

The initial predicted deflections with the input properties of GPC obtained above were higher than the measurements by approximately 30%. This is because the actual flexural strength of the GPC beams is higher than that of the prism stored in the drying room. It is proved by the observation of flexural cracks on the beams at age of 35 days, which were found within 2 m in mid-span. The cracking region is smaller than the initial prediction of 4 m. It is noted that the tensile side on the beams is at the bottom side, which is covered by the composite steel formwork, hence the drying effect was expected to be minor. The curing type of such face was close to the sealed condition. Unfortunately, flexural test specimen was not carried out in such condition.

The type of curing had an influence on the strength development as drying induced microcracks on the exposed surfaces (Collins and Sanjayan 2001). The actual flexural tensile strength of the beams would be expected to be between drying and bath curing conditions, which is 4.43 - 6.07 MPa. The flexural tensile strength was then estimated to match the observation of crack locations. Values of 5.25 MPa and 4.85 MPa were computed for flexural tensile strength at the ages of 14 days and 28 days, respectively, via reversed calculation of cracked moment using AEMM.

Then the deflection of the beams was computed with the above flexural tensile strength as shown in Figure 3. The root mean square was 0.79 for beam B1 and 0.76 for beam B2 when first calculated taking account of tension stiffening. The results showed a good prediction on deflection in the later age but overestimation in the first two months period. This was because the coefficient $\beta$ in Eq. 3 was chosen as 0.5 for age after first loaded at 14 days and this underestimated the tension stiffening effect at the early age. Since GPC exhibits a generally higher tensile strength than OPCC, it was expected to benefit more from tension stiffening. When $\beta = 1$ was used for the age up to 56 days, the prediction of deflection was in agreement with the measurement (shown as revised tension stiffening in Figure 3), with the root mean square of 0.97 for beams B1 and B2.
CONCLUSIONS

This paper presents the long-term behaviour of GPC based on a series of standard material tests and the monitoring of two full scale composite GPC beams under sustained loads. The strength of GPC was influenced by the curing condition. Drying at early age caused more reduction in flexural tensile strength than in compressive strength, likely due to the differential drying shrinkage and microcracking at the drying surfaces. GPC loaded at early age showed higher creep than that loaded at later age. However, the ultimate creep cannot be observed in this testing period. A longer period is suggested to fully understand the creep behaviour of GPC.

The composite steel formwork used in this case provided a sealed condition and acted as extra bottom reinforcements to the GPC beams, thus the creep deflection would be reduced. When the correct input properties of GPC are available, AEMM is applicable to the structural design of GPC. Therefore, material tests should be done accordingly to improve the accuracy of the prediction of long-term behaviour. It is suggested that further work should be done to develop equations which can predict the properties of GPC, such as creep, shrinkage and tensile strength as a function of compressive strength or similar easily attainable parameter.

REFERENCES


