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Compressive stress-strain model for low-calcium fly ash-based geopolymer and heat-cured Portland cement concrete

Amin Noushini [a,*], Farhad Aslani [a,b], Arnaud Castel [a], Raymond Ian Gilbert [a], Brian Uy [a], Stephen Foster [a]

[a] Centre for Infrastructure Engineering and Safety, School of Civil and Environmental Engineering, University of New South Wales, Sydney, NSW 2052, Australia
[b] School of Civil Environmental and Mining Engineering, The University of Western Australia, Perth, WA 6009, Australia

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ABSTRACT

This research focuses on elucidating the present knowledge gaps in geopolymer concrete's engineering properties, specifically its stress-strain behaviour. Geopolymer concrete (GPC) is an emerging alternative to ordinary Portland cement concrete (OPCC), and is produced via a polycondensation reaction between aluminosilicate source materials and an alkaline solution. As a relatively new material, many engineering properties of geopolymer concrete are still undetermined. In this paper, the compressive strength, modulus of elasticity and stress-strain behaviour of ambient and heat-cured GPC and OPCC have been studied experimentally. A total of 195 geopolymer concrete cylinders and 210 Portland cement concrete cylinders were tested for the above mentioned characteristics. Based on the experimental results, constitutive models describing the complete stress–strain behaviour in uniaxial compression have been developed for the low-calcium fly ash-based geopolymer concrete and the heat-cured Portland cement concrete.

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1. Introduction

A precise evaluation of the mechanical properties of a material is essential in order to use it for structural engineering applications. Broad knowledge of the deformability of concrete is necessary, for instance, to calculate deflections of structures, to compute stresses from observed strains or to establish the constitutive laws for numerical simulations (e.g. input for finite element modelling, FEM, programs). Due to the intrinsic properties and compositions, any material can behave differently under different loading conditions. It is therefore crucial to study the stress-strain behaviour of new emerging materials to fully characterize their performance for the purpose of design and field implementation. Geopolymer concrete (GPC) is a new class of inorganic (polymer) material, first introduced in 1975 by Davidovits [1]. Geopolymer (GP) is made by mixing aluminosilicate source materials such as fly ash (FA), ground granulated blast-furnace slag (GGBFS), metakaolin (MK) or selected rock-forming minerals with an alkaline solution to form alkali silicon-oxo-aluminate chains and networks [2].

The stress-strain behaviour of ordinary Portland cement concrete (OPCC) under uniaxial compression is relatively well understood [3,4]. However, to this point, there has been relatively little investigation related to the constitutive behaviour and stress-strain modelling of geopolymer concrete. Hardjito et al. [5] investigated the stress-strain behaviour of fly ash based geopolymer concrete. Three sodium silicate fly ash based geopolymer mixes with FA content of 408 kg/m^3 and 28-day compressive strength of 41–64 MPa were studied. The stress-strain results reported by Hardjito et al. [5] for heat-cured (60–90 °C) geopolymer concretes fit well with the constitutive model proposed by Collins et al. [6] for Portland cement concrete and shown in Eqs. (1)–(3) with the strain at peak stress in the range of 2400–2600 micro-strain (με).

$$\sigma_c = f_{cm}\frac{\varepsilon_c}{\varepsilon_c'} \times \frac{n}{n-1+\left(\frac{\varepsilon_c}{\varepsilon_c'}\right)^{nk}} \quad (1)$$

* Corresponding author.
E-mail addresses: a.noushini@unsw.edu.au, a.noushini@gmail.com (A. Noushini).

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Notation

f_{cm}	concrete compressive strength (mean)
σ_c	concrete stress
E_c	concrete modulus of elasticity
E_{sec}	secant modulus of elasticity
ε_c	concrete strain
$\varepsilon'_{c,}$	concrete strain at peak stress
ε_{cu}	ultimate concrete strain
ε_{ic}	concrete strain at point of inflection
n	material parameter that depends on the shape of the stress-strain curve
n_1	modified material parameter for the ascending branch
n_2	modified material parameter for the descending branch
C	curing parameter

$$n = 0.8 + \left(\frac{f_{cm}}{17}\right) \quad (2)$$

$$k = 0.067 + \left(\frac{f_{cm}}{62}\right) \text{ when } \frac{\sigma_c}{f_{cm}} > 1 \text{ and } k = 1 \text{when } \frac{\sigma_c}{f_{cm}} \le 1 \quad (3)$$

Thomas and Peethamparan [7] investigated the stress-strain behaviour of heat-cured (48 h at 50 °C) fly ash and slag based geopolymer concretes. They used a high FA/GGBFS content of 570–620 kg/m^3 with a Na-silicate solution having a modulus within 0.75 < M_s < 1.5. Results obtained showed a more brittle failure for geopolymer concretes compared with those of the Portland cement concrete. The FA and GGBFS based geopolymer concretes showed similar stress-strain behaviour to the conventional concrete up to the peak stress, however, a rapid decline in stress during the post-peak softening was observed (less toughness). This was more pronounced for slag-based GPC presenting a brittle fracture immediately following the peak stress. The fly ash-based geopolymer concrete investigated by Thomas and Peethamparan [7] demonstrated a slightly lower strain at the ultimate stress compared with OPCC.

Some researchers were also focused on the stress-strain behaviour of confined geopolymer concretes and pastes. Haider et al. [8] studied experimentally the stress-strain curves for sodium silicate fly ash-based geopolymer paste under constant levels of confinement. Their study showed that geopolymer paste exhibits less deformation in the axial direction than Portland cement concrete under confinement. Ganesan et al. [9] compared the stress-strain behaviour of confined sodium silicate fly ash-based geopolymer concrete and Portland cement concrete. The GPC samples were initially cured at ambient temperature for 24 h and then placed in a 60 °C oven for another 24 h. Their study showed that the stress-strain model proposed in the literature [10] for confined Portland cement concrete can be applied for GPC by modifying the curve fitting factor.

Diaz-Loya et al. [11,12], studied the correlation between selected mechanical properties of GPCs synthesised from various high and low calcium type fly ashes. They found that the mechanical behaviour of the studied GPC is similar to that of Portland cement concrete, suggesting that ACI 318-08 models could be applied for GPC to determine its flexural strength and static elastic modulus. Diaz-Loya et al. also reported the stress-strain curves of the low and high calcium fly ash based GPCs. However, they were unable to plot the post-peak behaviour (descending branch) of the materials either due to the brittle nature of their GPCs at failure or lack of suitable post-crack measuring devices.

The curing methods applied by Diaz-Loya et al. [11] and Ganesan et al. [9] are different to the common curing method suggested by many researchers [5,13–16] for fly ash based GPCs. Diaz-Loya et al. stripped the GPC samples from the moulds after 24 h and then cured the hardened samples at 60 °C for 72 h. Ganesan et al. [9] initially cured the GPC samples at ambient temperature for 24 h and then placed them in a 60 °C oven for another 24 h.

It has been proved in many research works [13–15] that the initial curing condition significantly affects the degree of geopolymerization. The low initial temperature curing followed by a prolonged elevated temperature curing used by Diaz-Loya et al. [11] and Ganesan et al. [9] may lead to the formation of a more complex and dissimilar geopolymer structure compared to the one investigated in the present paper and also in many other fly ash based geopolymer studies. Therefore, the results reported by Diaz-Loya et al. [11] and Ganesan et al. [9] may not be directly comparable to the results reported in the current study.

The aim of this paper is to use a comprehensive experimental data set to develop a constitutive model to represent the complete stress-strain curves for ambient and heat-cured low-calcium fly ash-based geopolymer concretes. The study defines a novel constitutive relationship for heat cured geopolymer concrete, which appropriately predicts the complete stress-strain curve of the material. Since the compressive strength and stress-strain relationship of geopolymer concrete appear to be strongly dependent on the curing temperature and heat-curing duration, the effect of these parameters has also been addressed in the proposed stress-strain relationship.

Furthermore, a Portland cement concrete mix has been prepared as a reference point for the sake of comparison. The OPCC mix has the same amount of aggregate and binder as the geopolymer concrete. This mix has been cured under standard ambient curing conditions, as well as, heat curing conditions. The mechanical properties and stress-strain behaviour of the OPC concrete is also investigated and a stress-strain model for heat-cured conventional concrete is then proposed.

2. Experimental program

2.1. Materials

Three different sources of aluminosilicate materials have been used in this study for synthesising the geopolymeric binder. A low-calcium type (ASTM C 618 Class F) fly ash, sourced from Eraring Power Station in New South Wales, Australia has been used. The fineness of FA by 45 μm sieve was determined to be 87% passing (tested in accordance with AS 3583.1 [17]). A special grade (ultra-fine) fly ash branded as Kaolite High Performance Ash (HPA) by Cement Australia has also been used as the second aluminosilicate source. The Kaolite HPA was obtained from Callide Power Station in Queensland, Australia. And finally, ground granulated blast furnace slag (GGBFS) supplied by Blue Circle Southern Cement Australia was used as the third aluminosilicate source of the geopolymer binding system. The chemical compositions of the binders determined by x-ray fluorescence (XRF) analysis are listed in Table 1. Scanning electron microscopy (SEM) images of the raw materials are given in Fig. 1. The particle size distribution of the binders was determined using the laser diffraction technique with a Malvern Mastersizer 2000 instrument, and the results are presented in Fig. 2.

The alkaline solution mixture consisted of 12 M sodium

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