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Evaluation of tension-stiffening, crack spacing and crack width of geopolymer concretes

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HIGHLIGHTS

- Tensile stress of concrete decreases with reducing the concrete volume.
- Concrete cross-section has a significant influence on the transverse tensile cracks.
- The tension-stiffening effect of GPC is slightly more significant than that of OPC concrete.

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ABSTRACT

This paper presents the results of an experimental study on the behavior of twenty geopolymer concrete prisms tested under uniaxial tension to investigate the tension-stiffening effect on the deformation and crack width of geopolymer concretes, prepared using either fly ash-based geopolymer concrete or granulated lead smelter slag (GLSS)-based geopolymer concrete. The test parameters included concrete type, concrete prism cross-section and steel bar diameter. The results suggest that the tensile stress of concrete decreases with an increase in the reinforcement ratio due to the reduction in concrete volume. Moreover, enlarging the concrete cross-section results in postponing the transverse tensile cracks. The results also suggest that geopolymer concretes exhibit slightly more significant tension-stiffening effect than that of OPC concrete. Furthermore, it has been shown that the tension-stiffening mechanisms of geopolymer and ordinary Portland cement (OPC) concretes are in agreement, suggesting that the provisions developed for OPC concrete can be modified to predict the behavior of geopolymer concrete.

1. Introduction

The worldwide demand for construction and building materials has increased and it will reach a major industrial concern in the foreseeable future. Ordinary Portland cement (OPC) has been used as the active constituent binder in concrete production for centuries. However, according to statistics, the production of OPC involves heating calcareous materials, such as limestone or chalk in a rotary kiln to a temperature of about 1300–1450 °C [1], resulting in an emission of one ton of carbon dioxide (CO_2) for every ton of OPC [2]. Moreover, it consumes approximately 2.5 tons of fossil fuels, calcining of limestone and raw and natural materials, such as sand, water and stone as aggregates [3]. For the conservation of natural resources, studies have recently focused on producing an environmentally friendly concrete as an alternative to OPC-based concrete in order to lower CO_2 emission, as well as to utilize recycled materials in construction industry. By-product waste materials, such as fly ash have the potential to replace OPC in which they provide comparable mechanical properties. The majority of existing studies on fly ash-based geopolymer have been concerned with material and mechanical properties [4,5], which demonstrate that GPCs exhibit comparable mechanical properties. As a result, the research attention has turned to study different aspects of GPCs, such as their possible use in structural application [6,7], and durability [8,9].

The tensile behavior and bond performance of geopolymer concrete were found to be comparable to that of conventional OPC concrete [10,11]. However, the ability of the intact geopolymer concrete with an embedded tension reinforcement to carry tensile stresses after the occurrence of cracks, which is manifested in the so-called tension-stiffening effect, is not well understood. Phenomenologically, the surrounding concrete increases the stiffness of the rebar, and hence the bond action between reinforcement and concrete is also increased [12,13]. Direct uniaxial tensile test reveals the tension softening behavior of concrete,

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which, in turn, reveals the resistance of concrete against crack extension [14]. As a result, knowledge of stress redistribution within a structural element and relevant material properties in both elastic and post-failure stage can be obtained by studying the tension-stiffening mechanism [15].

This paper presents an experimental study that was aimed at investigating the tension-stiffening mechanism and the key parameters that influence the uniaxial tension behavior of geopolymer concretes manufactured using fly ash and granulated lead smelter slag (GLSS). This is one of the first comprehensive study on the uniaxial tension behavior of prisms manufactured with geopolymer concretes, and the primary aims to determine crack width and crack spacing pattern. The paper initially summarizes the experimental program, including material and specimen properties and testing procedures. Subsequently, the results of the experimental program are presented followed by the discussions on the influences of the type of concrete and steel bar diameter. In the final part, empirical models to predict the crack width of geopolymer concrete are presented, which were based on mathematical regression analysis of the experimental data.

2. Experimental program

2.1. Test specimens and materials

A total of 20 reinforced concrete prisms were designed, manufactured, and tested under direct tension at the laboratory of Adelaide University. All specimens had a length of 650 mm and cross-sections of either 75 × 75 mm or 150 × 150 mm. A single reinforcing ribbed steel bar of either 12 mm or 16 mm diameter was placed longitudinally through the centroid of each specimen. The axial tension load was applied to the exposed reinforcement bar as shown in Fig. 1.

The specimens were manufactured using three different types of concrete: OPC, fly ash and GLSS as binders. To manufacture fly ash-based geopolymer concrete, low-calcium class-F fly ash produced at Port Augusta Power Station in South Australia was used. The GLSS-based geopolymer concrete was manufactured using 50% fly ash and 50% granulated lead smelter slag sourced from Nystar port Pirie in South Australia. The alkaline solution phase in both concrete types, fly ash and GLSS, consisted of a combination of sodium silicate (Na_2SiO_3) and 14 M sodium hydroxide (NaOH) premixed by a local supplier with distilled water. The proportions of the three components of the alkaline activator solution were 65.3% water, 20.8% Na_2SiO_3 and 13.9% NaOH by weight. The chemical compositions of OPC, fly ash and GLSS were determined by X-ray fluorescence (XRF) and are summarized in Table 1. The mixtures proportions of fly ash and GLSS concretes were developed by Albitar et al. [16,17] and are presented in Table 2, together with mixture proportion of OPC concrete, which was used for reference purpose.

2.2. Instrumentation and testing procedure

Two linear variable displacement transformers (LVDTs) were placed on opposite sides of the prism as shown in Fig. 1 to measure the average axial elongation of the concrete prism form which the average concrete strain was determined. To measure the average axial strain in the reinforcing steel bar, two 5 mm strain gauges were used, one on each end of the steel bar. In addition, two LVDTs were mounted on each edge of prisms to measure the slip of steel relative to concrete after deducting the strain of the steel, as shown in Fig. 2(a). This slip represents a half crack width at each end of the specimen.

All test specimens were subjected to short-term uniaxial tensile load at a rate of 0.1 mm/min in a 900 kN capacity universal testing machine using tension grips to hold the extended bars at each end, as shown in Fig. 2(b). The test continued until yielding of the steel bar for specimens with a 75 × 75 mm cross-section, whereas specimens with a 150 × 150 mm cross-section the test continued until near rupturing of steel bar. The location and width of cracks were measured at 10 kN interval, as well as at the formation of each new crack. It should be noted that the specimens are designated by letters FA, GLSS or OPC to describe the binder material followed by the number that corresponds to their series and then the diameter of the steel bar and finally the concrete cross-section (i.e., FA 1 – 12 – 75).

3. Experimental results

3.1. Failure mode

The typical failure mode and crack pattern of specimens are shown in Fig. 3, whereas the failure modes of all the test specimens are shown in Fig. S1, which is available in the Supplementary Data, together with the corresponding crack numbers and locations for each specimen. All the specimens sustained high elastic stiffness until the first transverse tensile crack was initiated, which led to a drop in the elastic stiffness. The formation of the first transverse crack (primary crack) generally appeared near the middle portion of the specimens, and as the applied load was increased, additional cracks appeared along with the widening of the first crack. In some specimens, two cracks appeared simultaneously in which each one occurred near the edge on the opposite side. An example of this can be seen in Fig. 3(d) where cracks 1 and 2 appeared at the same time. Longitudinal splitting cracks appeared on some specimens tested until near rupturing of the steel bar, and two specimens, OPC 1 – 12 – 150 and OPC 2 – 12 – 150, did not develop any cracks.

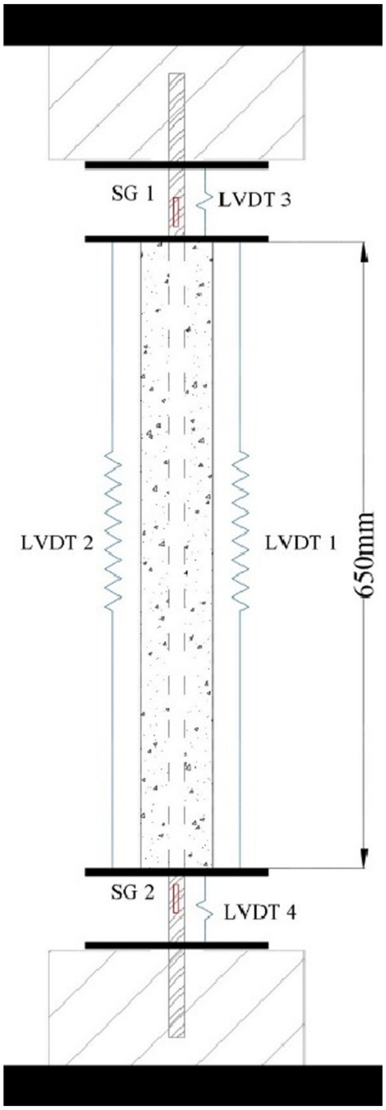

Fig. 1. Test set-up.

3.2. Material properties

The measured material properties of each concrete including compressive strength (f'_c), splitting tensile strength (f'_{ct}), flexural strength (f'_{cf}) and elastic modulus of concrete (E_c) are tabulated in Table 3. It should be noted that the mix designs listed in Table 2 were used to manufacture all the specimens, but prisms with a