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Synthesis and mechanical properties of cotton fabric reinforced geopolymer composites

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ABSTRACT

Geopolymer composites reinforced with different layers of woven cotton fabric are fabricated using lay-up technique. Mechanical properties, such as flexural strength, flexural modulus, impact strength and fracture toughness of geopolymer composites reinforced with 3.6, 4.5, 6.2 and 8.3 wt% cotton fibres are studied. The fracture surfaces of the composites are also examined using scanning electron microscopy. The results show that all the mechanical properties of the composites are improved by increasing the cotton fibre contents. It is found that the mechanical properties of cotton fabric reinforced geopolymer composites are superior to pure geopolymer matrix.

1. Introduction

Geopolymers are inorganic compounds that can be cured and hardened at near-ambient temperatures to form materials that are effectively low-temperature ceramics with typical temperature resistance and strength [1]. In recent years, geopolymers have emerged as an alternative to cements [2,3]. However, despite their many desirable attributes, such as relatively high strength, elastic modulus and low shrinkage, geopolymers suffer from brittle failure like most ceramics. Nevertheless, this limitation can be overcome by the introduction of reinforcing materials, including short fibres or unidirectional long fibres into the geopolymer matrix. For this purpose, various inorganic fibres have been previously used as reinforcement in geopolymer composites [4–7].

However, contemporary concerns over environment and climate change have given rise to an increasing interest in natural materials to produce environmentally friendly composite materials for construction. Natural fibres are very attractive for composite materials as they have several useful characteristics, such as low cost, low density, availability, recyclability, and renewability. In addition, they possess excellent mechanical properties like high values of toughness, flexibility, specific modulus and specific strength [8,9].

For these reasons, natural fibres are more attractive to researchers and scientists as an alternative source of reinforcement to develop organic polymer composites. As an illustration, cellulose fibres have been used to reinforce various organic matrices like polyester, vinyl ester, and epoxy matrices [10–13]. However, at present there has been limited published research on the use of natural fibres to reinforce inorganic matrices despite the advantages they offer in terms of low cost, ready availability, low toxicity and good mechanical strength [14]. In a previous report, the authors studied the mechanical properties of short cotton fibre-reinforced geopolymer composites. Results showed that further increases in short cotton fibre content beyond 0.5 wt% caused a reduction in the mechanical properties due to poor workability which led to formation of voids and fibre agglomerations [15,16]. In a follow-up work by the same authors [17], similar behaviour has been reported in cotton fabric-reinforced geopolymer composites, with the exception that the mechanical properties decreased beyond 2.1 wt% cotton fibres. This decrease was attributed to poor bonding between the cotton fibre and matrix due to insufficient amount of geopolymer matrix in the composites containing more than 2.1 wt% cotton fibres.

In the present study, woven cotton fabrics (CF) have been impregnated (wet out) with geopolymer paste, stacked, and compressed by a roller to force the paste to penetrate the fabric and to remove most of the trapped air. The aim was to investigate the possibility of applying the above technique to manufacture geopolymer composites with cotton fabrics for structural applications, and to examine the basic mechanical properties through experimental testing. Useful results have been gathered for composites with various cotton fibre contents (0, 3.6, 4.5, 6.2 and

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8.3 wt%) under three-point bending tests. The results show that the addition of cotton fibres improves the mechanical properties of geopolymer composites such as flexural strength, flexural modulus, impact strength and fracture toughness. Synchrotron radiation diffraction (SRD) and scanning electron microscopy (SEM) were used to characterise the phase composition, microstructure, and failure mechanisms of woven cotton fibre reinforced geopolymer composites.

2. Experimental investigation

2.1. Materials

Cotton fabric (CF) of 30 cm × 7.5 cm was used to reinforce the geopolymer. This fabric is made up of yarns with a density of 1.54 g/cm^3, tensile strength of 400 MPa, and Young's modulus of 4.8 GPa. Low calcium fly-ash (ASTM class F), collected from Collie power station in Western Australia, was used as the source material of the geopolymer matrix. The chemical composition of fly-ash (FA) is shown in Table 1. The alkaline activator for geopolymerisation was a combination of sodium hydroxide solution and sodium silicate grade D solution. Sodium hydroxide flakes with 98% purity were used to prepare the solution. The chemical composition of sodium silicate used was 14.7% Na_2O, 29.4% SiO_2 and 55.9% water by mass.

2.2. Preparation of geopolymer composites

To cast the composite samples, five wooden moulds with open tops were prepared and greased to avoid the samples sticking during de-moulding. The fabrics were pre-dried for 60 min at 70 °C. An 8 M concentration of sodium hydroxide solution was prepared and combined with the sodium silicate solution one day before mixing. The fly ash and alkaline solution were mixed in a Hobart mixer to form a homogeneous paste. A thin layer of geopolymer paste was first spread in the wooden mould and the first layer of woven fabric was carefully laid on that layer. The fabric was then fully impregnated (wet out) with geopolymer paste by a roller and the process repeated for the desired number of cotton fibre layers. Each specimen contained different layers of cotton fabric (see Table 2) with final layer being geopolymer paste. The alkaline solution to fly ash ratio was fixed at 0.35 whereas the ratio of sodium silicate solution to sodium hydroxide solution was maintained at 2.5. The composite specimens were placed on a vibration table in order to ensure better penetration of the matrix between the fabric openings and to remove the entrapped air voids. Then, the composite specimens were pressed under 25 kg load for 3 h. Subsequently, the specimens were covered with plastic film and cured at 80 °C in an oven for 24 h. The samples were de-moulded and kept in room condition for 28 days before testing. The mechanical properties of unreinforced geopolymer used in this study were measured and used for comparison purpose. Typically, the compressive strength of the geopolymer paste is 21 MPa with density of 1.9 g/cm^3.

2.3. Characterisation

2.3.1. Synchrotron radiation diffraction (SRD)

The Powder Diffraction beamline at the Australian Synchrotron was used to collect the diffraction patterns of fly-ash and the geopolymer composites. The diffraction pattern of each sample was collected using a wavelength of 0.825 Å over the 2θ range of 5–45°.

Table 1
Chemical composition of fly ash.

SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K_2O	LOI
50%	28.25%	13.5%	1.78%	0.89%	0.38%	0.32%	0.46%	1.64%

Table 2
Formulations of samples.

Sample	Fabric layers	Fibre content (wt%)
Composite 0	0	0
Composites 1	5	3.6
Composites 2	10	4.5
Composites 3	20	6.2
Composites 4	40	8.3

2.3.2. Scanning electron microscopy (SEM)

The microstructures of geopolymer composites were examined using a Zeiss Evo 40XVP scanning electron microscope. The specimens were mounted on aluminium stubs using carbon tape and then coated with a thin layer of platinum to prevent charging before the observation.

2.4. Mechanical properties

2.4.1. Flexural strength

Rectangular bars with a length of 60 mm were cut from the fully cured samples and subjected to three-point bend tests to evaluate their flexural strength. The tests were performed in a LLOYD Material Testing Machine (50 kN capacity) with a displacement rate of 0.5 mm/min. Five specimens of each composition were tested. The flexural strength (σ_F) was determined using the following equation [9]:

$$\sigma_F = \frac{3}{2}\frac{P_m S}{BW^2} \tag{1}$$

where P_m is the maximum load at crack extension, S is the span of the sample, B is the specimen width and W is the specimen thickness (depth).

Values of the flexural modulus (E_F) were computed using the initial slope of the load–displacement curve, $\Delta P/\Delta X$, using the following formula [9]:

$$E_F = \frac{S^3}{4BW^3}\left(\frac{\Delta P}{\Delta X}\right) \tag{2}$$

2.4.2. Impact strength

The impact strength was determined using a Zwick Charpy impact tester with a 7.5 J pendulum hammer. Five bars of 60 mm long were utilised. The impact strength (σ_i) was calculated using the following equation [18]:

$$\sigma_i = \frac{E}{A} \tag{3}$$

where E is the impact energy required to break a sample with a ligament of area A.

2.4.3. Fracture toughness

Rectangular bars of 60 mm long and cross-sectional dimension of 20 × 20 mm were used in the fracture toughness measurements. A crack with a length to thickness (depth) (a/W) ratio of 0.4 was introduced into the specimen using a 0.4 mm diamond blade to evaluate the fracture toughness. The fracture toughness K_{IC} was calculated using the following equation:

$$K_{IC} = \frac{p_m S}{BW^{3/2}} f\left(\frac{a}{W}\right) \tag{4a}$$

where P_m is the maximum load at crack extension, S is the span of the sample, B is the specimen width, W is the specimen thickness