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Incorporation of glass fibre fabrics waste into geopolymer matrices: An eco-friendly solution for off-cuts coming from wind turbine blade production

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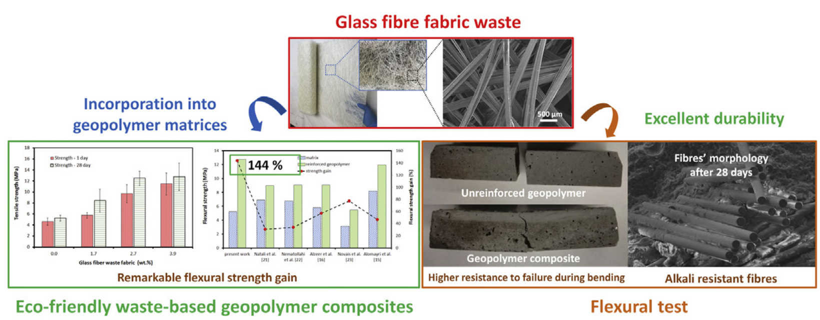
HIGHLIGHTS

- Glass fibre fabrics off-cuts coming from wind turbine blade production were reused.
- This waste was used for the first time to produce fibre reinforced geopolymers.
- The fabrics significantly increase geopolymers' flexural strength (up to 144%).
- This study provides a sustainable solution for glass fibre off-cuts.
- The fabrics reuse enhances the global sustainability of wind energy production.

GRAPHICAL ABSTRACT



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ABSTRACT

In this investigation, an innovative and sustainable solution for glass fibre off-cuts is proposed. For the first time, glass fibre fabrics (non-woven mat) produced during wind turbine blade manufacture were used to produce reinforced inorganic polymer composites. The influence of fabric amount on the composites' microstructure, water absorption, strength and apparent density was investigated. Results show that the fabrics exhibited an impressive flexural strength gain (up to 144%) at the 28th day, when compared to the non-reinforced geopolymer, while simultaneously increasing the composites' ductility. This feature may extend the application range of such geopolymers. Moreover, the fabric prevents the complete collapse of the composites upon failure, while the matrix alone fails catastrophically under load.

1. Introduction

In recent years, interest in the renewable production of energy using wind power has significantly increased. Installed wind power capacity has increased enormously from 23,900 MW in 2001 to 486,749 MW in 2016 [1]. Since 2005, Portugal's share of wind energy in total gross electricity generation has grown from 3 to 20% in 2016. This share is well above the EU average (10%), placing Portugal in the fourth position regarding wind energy production [2]. Over this period of time, a fivefold increase in wind energy generation was observed in the EU [2], due to the concerted European strategy to enhance the sustainability of energy production in Europe. Wind energy production is generally considered a sustainable and carbon-free process. However, some of the components (e.g. wind turbine blades) are not remotely sustainable. In fact, the blades, made of composite containing fibres (typically glass fibres) and epoxy resins, are currently regarded as unrecyclable [3]. The lifespan of wind turbines is assumed to range between 20 and 30 years [4], meaning that the first installed wind turbines are already approaching their end of life, and that their

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disposal will shortly become a serious issue. Recently, Liu et al. [3] estimated that there will be 43 million tons of blade waste in 2050, which demonstrates the urgency of developing new recycling strategies. The manufacturing process of the blades also generates a huge amount of waste materials (e.g. flow mesh with resin residue and cured composite off-cuts) that are detrimental to the global sustainability of wind energy production. Among the produced wastes, glass fibre off-cuts assume particular relevance, not only due to their very high volume, but also since they are currently disposed of in landfills. For the first time glass fibre fabrics waste was used to produce eco-friendly waste-based geopolymer composites.

Geopolymers are rapidly growing as a promising alternative to conventional Portland cement, because of environmental and performance benefits. Indeed, their lower carbon footprint [5] and the possibility of using distinct waste streams as raw materials, such as biomass [6] and coal [7] fly ash, waste glass from end-of-life fluorescent lamps [8], red mud [9] and geopolymer waste [10], are major advantages over Portland cement. Geopolymers (also known as inorganic polymers) are synthesised by mixing aluminosilicate precursors (e.g. fly ash, blast furnace slag) with alkaline activators. The geopolymerisation leads to a gel network consisting of SiO_4 and AlO_4 tetrahedral units, linked alternatively by shared oxygen atoms [11]. Despite their promising properties, geopolymers suffer brittle fracture, and for that reason numerous fibres (e.g. polymeric, natural and steel fibres) [12–14] have been considered as reinforcement agents. For obvious (environmental and economic) reasons, natural fibres such as cotton [15], wool [16] and flax [17] have been extensively considered, yet the durability of the composites produced is a major concern, limiting their widespread use. Indeed, natural fibres can be degraded in a highly alkaline medium which exists within geopolymers [18,19], leading to a reduction of the composite properties over time. Assaedi et al. [20] observed a 23% reduction in flexural strength for flax fabric reinforced geopolymers after 32 weeks, in comparison with the value measured at the fourth week. Glass fibre exhibits high flexural strength, which suggests the feasibility of it being used as a reinforcement agent. Nevertheless, the number of investigations considering its use in geopolymeric matrices is surprisingly low [21,22]. The reinforcement of geopolymers using glass fibres has been recently reported by the authors, but using short length fibres and metakaolin as an aluminosilicate source [23]. Here, a more eco-friendly strategy was implemented, in which glass fibre fabrics waste (reinforcement agent) and biomass fly ash (source of reactive silica and alumina) were used to produce eco-friendly geopolymer-fibre composites. The effect of the fabric amount on the composites' microstructure, apparent density, and mechanical strength was studied. This is the first ever investigation considering the use of glass fibre fabrics coming from wind turbine blade production in geopolymers production. This study provides a sustainable solution (production of reinforced geopolymers for structural applications) for the glass fibre off-cuts coming from wind turbine blade production, while it is expected that the proposed methodology can be applicable to glass fibre wastes coming from the recycling of wind turbine blades, or indeed any other sources. Furthermore, the combined use of two unexplored waste streams (glass fibre fabric and biomass fly ash) further reduces the environmental impact and production cost of the composites, while contributing towards a circular economy.

2. Experimental conditions

2.1. Materials

In this study biomass fly ash (FA), produced by a Portuguese pulp and paper industry, was used as the main aluminosilicate source (70 wt%), while metakaolin (MK) (Argical™ M1200S, Univar®) was used in lower amounts (30 wt%) to balance the composition's molar ratios. The reference composition was prepared using 35 wt% FA, 15 wt% MK, 37.5 wt% sodium silicate (SiO_2/Na_2O = 1.960; purchased from Quimialmel, Portugal) and 12.5 wt% sodium hydroxide solution (10 M). The sodium hydroxide was supplied by Sigma Aldrich (ACS reagent, 97%). Three other formulations were also prepared, using different quantities (one, two and three layers) of glass fibre fabric waste as reinforcement agent. This waste is generated during wind turbine blade production (*Riablades S.A.* (Aveiro, Portugal)). The glass fibre fabric (non-woven mat) waste was received as large mats of filaments (m scale mats, see Fig. 1), which were cut to 2 cm × 8 cm fabrics prior to their addition to a geopolymer slurry.

2.2. Geopolymer preparation

Four formulations were prepared in this study: one unreinforced (reference composition), plus three glass fibre fabric reinforced ones. In all compositions, the aluminosilicate sources (FA and MK) and the alkaline activators (sodium silicate and sodium hydroxide) were first mixed separately until homogenised. Then the solid precursors were mixed for 10 min with the alkaline activators using a mechanical mixer. After mixing, the geopolymer slurry was transferred to steel moulds (2 cm × 2 cm × 8 cm), and then the moulds were vibrated for 60 s to remove air bubbles entrapped into the mixture. The preparation of the reinforced composites required an additional step, in comparison with the unreinforced matrix, where the fabric (number of layers depending on the composition) was added to the slurry. For these compositions, a specific volume of slurry was initially added to the moulds. Then, a layer of the glass fibre fabric was added to the paste. At this stage, the moulds were vibrated for 60 s to ensure wetting of the fibres. Finally, a second layer of geopolymeric slurry was added to the mould. This last step was repeated for the composites containing two and three fabric layers (a schematic drawing of the specimens showing the position of the fabrics within the composites is presented in Fig. 2a–c). Afterwards, the moulds were covered with a plastic film and cured at 40 °C (65% relative humidity) for 24 h inside a climatic chamber (Fitoclima 300 EP10 from Aralab). After this period the samples were removed from the moulds, and cured at room temperature for 27 days till the mechanical characterisation.

The produced compositions contained 1.7 wt% (1 layer), 2.7 wt% (2 layers) and 3.9 wt% (3 layers) glass fibre fabric waste. The fibre weight fraction was calculated after demoulding the samples, and considering the fabric mass in each specimen.

2.3. Materials characterisation

X-ray powder diffraction (XRD) measurements were performed to assess the mineralogical composition of the precursors and the geopolymer samples using a Rigaku Geigerflex D/max-Series instrument (Cu Kα radiation, 10–80°, 0.02° 2θ step-scan and 10 s/step). The software PANalytical X'Pert HighScore Plus was used to identify the distinct phases.

The chemical composition of the raw materials (aluminosilicate precursors and fabric waste) was determined by X-ray fluorescence (Philips X'Pert PRO MPD spectrometer).

The loss on ignition (LOI) was also measured at 1000 °C.

Three-point bending strength tests of geopolymeric samples (2 cm × 2 cm × 8 cm) cured for 1 and 28 days were performed at room temperature using a Universal Testing Machine (Shimadzu, model AG-25 TA; displacement rate of 0.5 mm/min). Three specimens per composition were tested, and the arithmetic mean reported.

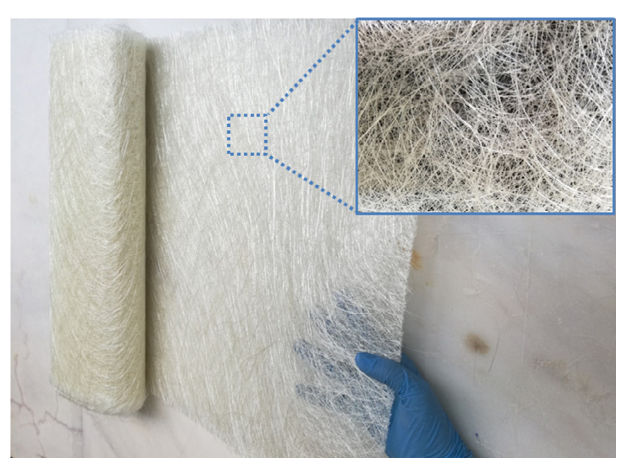

Fig. 1. Photograph of the large glass fibre mats coming from wind turbine production. The inset photograph illustrates the random orientation of the glass fibres.