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Development, characterisation and Finite Element modelling of novel waste carpet composites for structural applications

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ABSTRACT

Carpets are composite materials and, like many composite materials, waste carpet is both difficult and expensive to recycle because of the complicated, multi-stage processes involved. Consequently, in the United Kingdom, approximately 400,000 tonnes of carpet waste are sent to landfill annually. However, the landfill option is becoming uneconomic due to increasing landfill charges, the reduction in landfill sites and changes in environmental legislation. This dual economic and environmental burden has led to research interest in the processing of waste carpets into useful feedstocks for use in manufacturing. This study describes the experimental characterisation of a novel structural composite material that has been fabricated from waste carpets, and which is intended for use in low grade structural applications such as agricultural fencing. Details of the manufacturing process for the composites are described, as are the results of tensile and three-point bending tests, and the observed failure modes post-testing. In addition, Finite Element (FE) analysis was used to simulate the structural behaviour of fencing posts and rails manufactured from the carpet-based composite, and these results are compared with commercially available timber and PVC equivalent designs. Finally, structural analysis and design optimisation of the composite fencing was undertaken and this is used to demonstrate that from a mechanical property standpoint, the novel waste carpet structural composite may offer potential as an alternative to the timber and PVC materials typically used in such applications. Therefore, this study has demonstrated a practical approach for recycling carpet waste, which could lead to a substantial reduction in the volume of carpet waste discarded to landfill and subsequently yield both economic and environmental benefits.

1. Introduction

Carpets, which are typically used as floor coverings, are composite materials that are difficult and costly to separate and reprocess at the end of their useful lives. This is because they are multilayer mixtures of different polymers and inorganic fillers. According to Carpet Recycling UK (Bird, 2014), 400,000 tonnes of carpets are sent to landfill in the UK annually. However, the landfill option is becoming increasingly impractical due to environmental impact considerations, reduced availability of sites, and increasing cost. More specifically, the landfill tax associated with the disposal of carpet waste to landfill was £24 per tonne in 2007 and increased to £84 per tonne in 2016 reflecting a 250% increase over nine years (Gardner, 2016). The UK Government (2016) have also stated that the landfill tax will increase to £89 in 2018 to meet environmental objectives aimed at reducing the amount of waste produced and increasing the use of alternative waste management options. It is expected that, by 2025, carpet waste will be banned from UK landfill sites, because it is non-biodegradable and reduces their availability of landfill for other uses (Bird, 2014). Therefore, effective waste management is vital in attaining a sustainable environment. Indeed, the European Union's seventh framework programme aims to find innovative ways of utilising waste as a resource (European Union, 2010). Furthermore, as one tonne of recycled carpet waste saves 4.2 tonnes of CO_2 emissions (Carpet Recycling UK, 2010, Department for Environment Food and Rural Affairs, 2011), annual estimated savings of 1,680,000 tonnes of CO_2 emissions (based on 400,000 tonnes being sent to landfill annually in the UK) could be achieved through the sustainable recycling of carpet waste in the UK.

A typical carpet consists of four layers: face fibre, primary backing, adhesive and secondary backing (see Fig. 1), with

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approximate component percentages of 46%, 6%, 4% and 44% by weight, respectively (Vaidyanathan et al., 2013). In addition, post-consumer waste carpets typically contain dirt, chemicals and other materials, which accumulate in-service and make them about 30% heavier than new carpets (Mihut et al., 2001).

The face fibre (top layer) can either be nylon, polypropylene, polyethylene terephthalate (PET), mixed synthetics or natural fibres such as wool, cotton and jute (Jain et al., 2012). The primary backing is the layer through which the yarns of the face fibres pass and elastomeric adhesive is applied to the underside of the primary backing to hold the face fibres in place (The Carpet and Rug Institute, 2003). The elastomeric adhesive is typically made of styrene butadiene rubber (SBR), which can be filled with inorganic materials such as calcium carbonate ($CaCO_3$) or barium sulphate ($BaSO_4$) (Mihut et al., 2001). The secondary backing is the layer bonded to the back of the carpet pile. The primary and secondary backings can be made of polypropylene, nylon, polyurethane or jute (Miraftab and Mirzababaei, 2009). According to Helms and Hervani (2006), nylon and polypropylene are the most commonly used materials for the backings and face fibres of carpets.

Recently, the authors carried out a review of different carpet waste processing options in the UK, and also reported on the fabrication and mechanical properties of carpet based composites (Sotayo et al., 2015). This review highlighted that there are studies (Zhang et al., 1999, Gowayed et al., 1995) that have shown the potential of carpet waste being used as a raw material in the fabrication of structural composites and thereby diverting them from landfill and incineration options. However, there are limitations with these different processing options, which have focussed mainly on carpets with synthetic/man-made face fibres and/or the utilisation of only a fraction/layer of the carpet (i.e. face fibres, backing layers). In addition, some of the processes involved the mechanical separation of the carpets' constituents, costly fibre reprocessing procedures (i.e. depolymerisation), and the addition of glass fibres, all of which increase manufacturing processes, and hence, increase production cost.

Given the challenges associated with carpet recycling reported in Sotayo et al. (2015), this paper forms part of the broader objective, namely to recycle carpet waste via the sustainable development and experimental characterisation of novel waste carpet structural composites for use in fencing and other structural applications. Hence, the paper explores a manufacturing process which excludes a second phase (i.e. addition of glass fibres), mechanical separation, and fibre reprocessing, but includes carpets with both synthetic and natural fibres. An aim of this approach is to explore the viability of replacing common fencing materials (timber and PVC) with such carpet derived composites. Through this, carpet recycling could lead to economic benefits and a significant positive impact on the environment by reducing greenhouse gas emissions, preserving natural resources (i.e. non-renewable fossil fuel), decreasing deforestation and diverting carpet waste from landfill and incineration.

This paper reports details of the manufacture and experimentally derived mechanical properties of waste carpet structural composites, and uses the measured properties to computationally model the expected load-deformation response of a fencing structure. Via structural analysis and design optimisation, a composite fence structure having similar load-deformation response to conventional PVC and timber fences is proposed. Details of the manufacturing process are described and statistical analyses and failure modes (via Scanning Electron Microscopy (SEM) analysis) of the composite test-pieces are reported. It is concluded that the results of the investigation provide useful insight and understanding of the mechanical properties of novel waste carpet structural composites, and their suitability for use as alternatives to timber and PVC fencing.

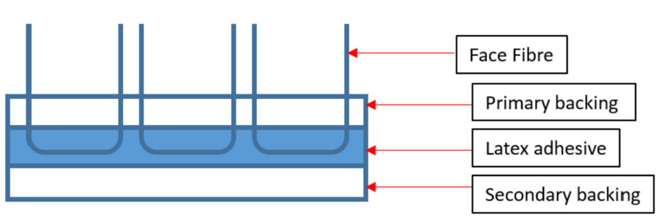

Fig. 1. Typical construction of carpet.

2. Manufacturing process for waste carpet structural composites

Post-consumer waste carpets were sorted according to their face fibres using a Thermo Scientific microPHAZIR PC handheld Near-Infrared (NIR) analyzer (Thermo Scientific, 2010) into three different categories: (a) Waste carpets with polypropylene face fibres; (b) Waste carpets with mixed synthetic face fibres (polypropylene, PET and nylon fibre blends); and (c) Waste carpets with wool face fibres. The waste carpets were then separately shredded in a UNTHA VR140 granulator with a 40 mm screen. From these granulated carpet feedstocks, four different formulations of carpet feedstock composites (Composite C_PP; C_PPW; C_SF and C_SFW) were fabricated, as detailed in Table 1.

A 1 kg batch size of shredded carpet waste was mixed in a Banbury mixer until the temperature in the barrel reached 150 °C. The blended mixture was then placed in a steel mould of size 300 mm × 150 mm × 10 mm, and the mould was subjected to a pressure of 14 MPa in a hydraulic press for five minutes at ambient temperature. Fig. 2 shows a flow diagram of the processes used for fabricating the waste carpet structural composites.

Once cool, rectangular test-pieces of size 39 mm × 11 mm × 293 mm were cut from the compression moulded composite slabs (see Fig. 3). After removing the sample from the hydraulic press, thickness expansion (i.e. springback of about 1 mm) occurred. The post-compression moulded samples demonstrated visible defects that included flow lines, voids and regions of surface profile irregularity (roughness), reflecting the inhomogeneous nature of the carpet feedstocks, and the broad range of melting temperatures of the constituent fibres. Such defects are common in materials made from recycled waste (Waghorn and Sapsford, 2017, Singh et al., 2017). Therefore, post-processing (i.e. machining) of the samples would be required for the production of a good surface finish.

Of note, Composite C_SFW was observed to contain a significant fraction of un-melted fibres/fibre-rich phase. At the processing temperature within the Banbury mixer of 150 °C, neither the wool fibres nor the thermosetting elastomeric adhesive (SBR) melted. In contrast, the melting temperature of the polypropylene fibres is about 160 °C, which is significantly lower than the melting temperatures of the other synthetic fibres, e.g. nylon (215–265 °C) and PET (256–268 °C) (Palenik, 1999). Hence, for all of the composites, the post-compression moulded form was that of a polypropylene matrix, within which was dispersed mixed second phases of elastomeric adhesive, inorganic fillers ($CaCO_3$ and $BaSO_4$), dirt particles and other carpet fibres (nylon, PET, wool).

3. Experimental characterisation

3.1. Experimental setup, instrumentation and test procedure for the three-point bending tests

Three-point bending tests were carried out on the moulded