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Influence of natural fibre reinforcements on the flammability of bio-derived composite materials

M.W. Chai, S. Bickerton *, D. Bhattacharyya, R. Das

Centre for Advanced Composite Materials, University of Auckland, Private Bag 92019, Auckland, New Zealand

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ABSTRACT

Composite materials are increasingly being used in applications in which their fire response is a critical consideration. Environmental concerns motivate the use of natural fibres, but they represent an additional fuel source for combustion, and their composites will perform worse in flammability testing compared to synthetic alternatives. An experimental study is presented, comparing flax fibre reinforced epoxy samples to composites formed from glass fibre reinforcements of similar architecture, reinforcing the same resin system. The flax composites ignite earlier, release greater levels of heat, and their structure deforms significantly during combustion. Further studies are required to increase understanding of the combustion process, if efficient mechanisms are to be found to reduce flammability of natural fibre composites to acceptable levels.

1. Introduction

The application of advanced composite materials is continually increasing, particularly in structural applications in the marine, automotive, aerospace, building, and industrial sectors [1]. Flammability is a critical issue in many industrial applications, particularly in the area of transportation where confined spaces make fires a significant hazard. The term flammability takes into account a range of different issues, and therefore requires clear definition. Babrauskas and Peacock [2] define flammability as the reaction-to-fire processes of a material, breaking this down into the following sections: ignitability, flame spread, heat release, and the resulting products from combustion. Combustion is a catalytic exothermic reaction maintained by internally generated heat and free radicals [3]. Bourbigot and Duquesne [4] define flammability with similar factors: ignitability, burning rate (which includes heat release and mass loss parameters), spread rates, and combustion products. The latter definition provides a more comprehensive set of factors to define flammability.

The ignitability of a material incorporates the material's time to ignition, ignition temperature, and the critical heat flux for ignition to occur [2]. These are important elements to consider when looking at preventative measures against fire, as preventing ignition inherently prevents the fire itself. The spread rates defined by the term flammability are flame spread, pyrolysis, burn-out, and smoulder [2]. Understanding how fast a fire will spread across a structure is of vital importance, and one of the goals of fire retardancy is to slow down or completely stop this process. The burning rate takes into account the heat release rate and mass loss rate of the material [2]. The heat release rate is an important indication of flammability as it allows for the quantitative observation of the combustion process, and the amount of energy surrounding materials or people are being exposed to. The mass loss rate gives an indication of the effect on the structural integrity of the material.

The main combustion products examined are smoke and any toxic species being emitted by the material during thermal decomposition and combustion. Most deaths caused by fire derive from the inhalation of combustion gases and particulates (most commonly carbon monoxide) [3], and thus the monitoring and inhibition of their production need to be considered. However, the production of visible smoke in the early stages of fire can also provide an early warning mechanism for people or smoke alarms nearby.

Over the last two decades, natural fibre reinforced polymers (NFRPs) have become an increasingly popular alternative to synthetic fibre reinforced counterparts because natural fibres are renewable, biodegradable, and at least partially recyclable. They are increasingly being used in new material systems. The advantages and disadvantages of utilising natural fibres have been discussed by numerous authors [1,5–11]. The major drawback motivating the research presented here, is the relatively poor fire resistance of natural fibres, which hinders their use in highly regulated sectors such as the aerospace industry. The flammability of composites reinforced by natural fibres in comparison to synthetic fibre composites is the primary focus of this paper.

* Corresponding author. Tel.: +64 9 373 7599x89055/88194; fax: +64 9 373 7479.
E-mail address: s.bickerton@auckland.ac.nz (S. Bickerton).

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The majority of previous studies have investigated the flammability of natural fibres and synthetic fibres as separate entities, usually focusing on the production and testing of a particular material system (reinforcement + matrix + possible fire retardant). While both natural fibres and synthetic fibres have been considered, previous authors have compared two material systems directly, without taking fibre architecture into account. Helwig and Pauksta [12] considered the flammability of flax fibre reinforced polypropylene composites, and observed that the inclusion of less than 20% flax fibres by weight reduced the maximum heat release rate, but resulted in shorter ignition times. Alvarez et al. [13] investigated the thermal degradation and decomposition of jute fibre reinforced vinyl ester composites, and determined that the inclusion of jute fibres into the system at a 0.30 fibre volume fraction decreased the thermal stability of the composite. The flammability of wood-polypropylene composites was studied by Borysiak et al. [14], and it was determined that the introduction of wood particulates into the material system at a 0.50 volume fraction caused earlier ignition times, but significantly reduced peak heat release rates, average mass loss rates, and smoke/gas emissions.

In this study, the flammability characteristics of epoxy-based composite systems are explored experimentally. The performance of flax fibre reinforced composites is compared to glass fibre reinforced composites, while endeavouring to match the fibre architectures for the two systems. Three flax and glass fibre reinforcements are considered, the results from three types of fire tests being presented (horizontal burn, vertical burn, and cone calorimetry).

2. Materials

Three flax fibre reinforcements, supplied by Libeco-Lagae in Belgium, were used in this study; a unidirectional fabric and two different twill weaves. Flax (*Linum usitatissimum*) is an attractive natural fibre reinforcement because it is easy to handle, has good mechanical properties (particularly when modified to enhance bonding with polymer matrices), and high aspect ratios [15–19]. Three glass fibre reinforcements, supplied by SP-High Modulus in New Zealand, were used for the study; a unidirectional fabric, a twill weave, and a plain weave. Glass was selected as the synthetic fibre reinforcement because it is the fibre type used in the highest volumes in the composites manufacturing industry, and has been the focus of most previous flammability research.

Details of all six reinforcements and the resulting composite samples are provided in Table 1, and Fig. 1 presents close-up images of each. The goal was to select glass fibres that could replace the natural fibres in terms of fabric architecture, while maintaining the same fibre volume fraction in the resulting panels. However, natural fibre tows are typically more circular in shape than glass fibre tows, which are more ovular, leading to the need to compromise between matching areal weight and tow width. For the purposes of this study, fabrics with similar tow widths were selected. This meant that more layers were required for the glass fibre samples than for the flax fibre samples to achieve the same fibre volume fraction and laminate thickness. While this may have an effect on sample combustion due to phenomena such as layer nesting, it was decided that maintaining the out-of-plane tow distribution was more important to maintain a similarly tortuous path for pyrolysed gases permeating to the combusting surface. Weave type was also kept the same where possible. A plain weave was used instead of a twill weave for the lighter woven glass fabric, because glass fibre twill weaves were not available at the areal weight required.

Prime 20LV, an infusion grade epoxy resin, was supplied by SP-High Modulus for the matrix material in all laminates. A 10% fast / 90% slow hardener mixture was used, leading to a cure time of approximately 15 h at 25 °C. The resin system used was not a flame retarded version, since the objective of this study was not to develop a fire resistant material system but rather to provide the best possible comparative study between glass and flax fibre reinforced composites of the same composition.

3. Manufacturing of composite samples

The Resin Transfer Moulding (RTM) process was used to create composite panels. This method provided good control of panel thickness and fibre volume fraction (V_f). The RTM mould used in this study produces panels 450 mm × 300 mm, a selection of spacer plates being employed to adjust panel thickness. For this study, a 6 mm spacer plate was utilised, and the target fibre volume fraction for all samples was 0.40.

Prior to being infused, the flax fabrics were placed in a vacuum oven at 65–70 °C for at least 48 h in order to reduce the moisture content in the flax fibres as suggested by Umer [7]. No moisture content data was recorded for the purposes of this study. There was an unavoidable delay between removing fabrics from the vacuum oven and the initiation of the infusion process, because a 15–20 min set-up time was required once the fabrics were removed from the vacuum oven. This is unlikely to have a significant effect on the resulting fibre moisture content entrapped after resin infusion, as the majority of the setup time was spent under vacuum conditions inside the mould.

A Boe-Therm Temp 95–9-2–3 Vac heat exchanger was connected to the aluminium mould through a water piping system embedded in both the top and bottom halves of the mould, providing temperature control during the filling and resin cure phases of the process. Temperature control also provided for reduction of the time to cure the resin during the post-filling period. The heat exchanger's temperature output was set to 25 °C during the filling stage, and was increased to 65 °C for post-filling and resin cure. All panels remained in the mould at 65 °C for at least 12 h to post-cure the resin.

The filling time was controlled by a vacuum pump used in conjunction with a dual-vacuum device. The dual vacuum device provided control of two different vacuum levels at the inlet and vent of the mould. Full vacuum was drawn at the mould vent, while the inlet pressure was varied from 50 to 101 kPa depending on the fabric to be infused. Maintaining full vacuum at the vent served to minimise void creation in the parts.

Table 1
Description of manufactured sample panels.

Fibre type	Fabric type	Areal weight (g/m^2)	Panel thickness (mm)	V_f	No. of layers
Glass	UNI	450	6.3	0.39	14
	PW	125	6.2	0.37	48
	TW	300	6.2	0.38	20
Flax	UNI	305	6.3	0.38	11
	TW (1)	315	6.6	0.38	11
	TW (2)	550	6.2	0.39	6