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Factorial study of material and process parameters on the mechanical properties of extruded kenaf fibre/polypropylene composite sheets

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ABSTRACT

Thin kenaf/polypropylene (PP) composite sheets were manufactured via extrusion. The effects of kenaf and maleated PP (MAPP) proportions, fibre length, PP melt flow index (MFI) and die temperature on tensile, flexural, in-plane and out-of-plane shear properties were analysed by conducting experiments through 'design of experiments' methodology. Higher kenaf content and lower die/barrel temperatures resulted in composite sheets with higher average mechanical properties in various modes of testing. Matrix MFI appeared to significantly affect all mechanical properties. It is interesting to note that the properties of the very short-fibre composites produced are comparable to those reinforced with longer discontinuous fibres and long-fibre mats.

1. Introduction

Components of physical infrastructure are typically constructed using steel, aluminium and reinforced concrete, which are produced using finite resources. Statistics show that buildings alone consume 50% of the total resources used globally and 70% of global timber products [1]. Over-exploitation of such building materials has led to environmental damage and depletion of available natural resources. Furthermore, most conventional building materials are energy-intensive to produce, and construction and demolition remnants constitute a significant amount of landfill volume. Buildings are claimed to be responsible for 40% of the waste which ends up in landfills and 40% of greenhouse gas emissions [2]. An increase in the demand for civil structures (made from conventional materials) due to population growth will leave a large ecological footprint.

Current interest in long-term sustainability of material resources, which consequently results in new environmental regulations, and changing public and governmental attitudes, has stimulated considerable advancements in composite materials. In recent years, synthetic (petroleum-based) fibre-reinforced polymer composites (SRPC) have been slowly replacing conventional building materials due to a number of factors. In comparison to conventional materials, SRPCs have greater specific strength and stiffness, greater fatigue strength and impact absorption capacity, better resistance to corrosion, fire, acids and natural hazardous environments, longer service life and lower life-cycle costs, and non-toxicity [3]. The increasing use of polymeric composites reinforced using natural fibres (NFRC) instead of synthetic fibres may provide even greater long-term benefits to the overall infrastructure management. However, there are problems associated with variability in natural fibre properties and the resulting uncertainty of performance. This necessitates careful study of manufacturing these composites under controlled conditions and producing more reliable and superior design data.

There are various types of natural fibres which have been used as reinforcements in NFRCs and kenaf (Hibiscus Cannabinus) is a particularly attractive choice due to its rapid growth (e.g. 150–180 days for a mature crop) over a wide range of climate [4,5]. Furthermore, a comparison of the potential specific moduli and cost per length of fibres in resisting 100 kN load between natural fibres and glass fibres demonstrates how kenaf, among a few other fibres, is primed to compete with glass fibres [3]. In addition, government incentives, for example the Ninth Malaysia Plan (2006–2010), have encouraged further development of kenaf-based industries [6].

With regards to the matrix system, completely biodegradable materials, such as poly-lactic acid, are preferable to fully satisfy regulations around the use of environment-friendly and sustainable materials. However, the current high costs of these materials constitute a disadvantage in comparison to commodity polymers such as PP, which are cheap and can be recycled easily. Furthermore, the composites should be stable during their expected structural lifetime while being capable of controlled degradation.

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Kenaf/PP composites are, therefore, of considerable commercial interest.

1.1. Processability/manufacturability of kenaf reinforced polypropylene composites

There have been several publications on PP composites reinforced with kenaf fibres, focusing mainly on the fabrication of the composites using compression moulding methods [4,7–21], because they can process reinforcing fabric and fibres of any length without much damage. In addition, such methods preserve the isotropic properties of composites with minimal changes in physical properties due to molecular relaxation during usage [22]. Nevertheless, fabrication of composites consisting of loose natural fibres using conventional compression moulding methods typically results in a non-uniform fibre distribution, as reported by Zampaloni et al. [19] and Shibata et al. [23].

There are very few studies on kenaf/PP composites manufactured via extrusion [24,25] and injection moulding [26–29] processes. Extrusion and injection moulding machines are common in the industry and have the capability of dispersing fibres evenly throughout a matrix. However, feeding fibres of considerable length into these machines can pose problems such as poor feed regulation (e.g. bridging) and deficient funnel flow [30,31]. Longer fibres require more stringent compounding conditions if they are to be satisfactorily dispersed. Because of that, the final fibre lengths of composites are lower than those of the initial input lengths, as demonstrated by various authors [12,13,32,33]. It must be noted that both the flow of materials and the ramming/extrusion process are more consistent and steady with less fluctuation, and a higher extrusion throughput rate can be obtained, when short fibres with a narrow fibre-length distribution are used. This could be used for producing superior mechanical properties if the manufacturing parameters are controlled properly.

It is surprising to note that there is only one study in this area that focuses on secondary processing, in this case, thermoforming of kenaf/PP composite sheets [19]. Previous experience in forming and shaping oriented natural fibre-reinforced thermoplastics has shown that the formation of unidirectional continuous loose fibre-reinforced composites typically results in distortions and fibre wrinkling. In contrast, randomly oriented fibres are capable of providing good formability, but lack of the advantages of highly directional properties which are desired in composite parts [19]. Formable sheets consisting of aligned, discontinuous short fibres appear to be more successful than randomly oriented continuous fibres [34], provided that fibre–matrix adhesion is adequate. However, to date, the knowledge of processing kenaf/PP composites via extrusion and thermoforming processes is limited.

1.2. Characterisation of mechanical properties

Figs. 1 and 2 illustrate the tensile properties [4,7–14,19,21,25,28,35–45] while Figs. 3 and 4 illustrate the flexural properties [4,9,10,12–15,19,21,28,37,41,43–49] of kenaf/PP composites manufactured using various fibre contents, fibre surface treatments, fibre sizes/forms and manufacturing processes.

1.2.1. Manufacturing process

A strong relationship between preferred manufacturing processes and fibre sizes/forms can be observed. Extrusion employs very short fibres in particulate/powder form (referred to here as fibres of 53–540 μm in length) while injection moulding employs fibres of 2–51 mm in length (i.e. fibres which are not clearly continuous or powdery in nature). Studies which have employed compression moulding method cover a wide range of fibre sizes from continuous (unidirectional, long fibre of 178 mm and fibre mats) to short and very short fibres.

1.2.2. Fibre content and sizes/forms

The highest mechanical properties for the injection moulding process have been obtained at 40 wt% fibre content. The highest tensile strength and modulus of kenaf/PP composites produced via this process are 33.5 MPa (with MAPP) and 1.3 GPa (with ultrasonic treatment), respectively [28]. The highest reported flexural strength and modulus are 62.2 MPa [50] and 1.1 GPa (with MAPP and ultrasonic treatments), respectively [28].

Using the compression moulding process, the highest mechanical properties have been obtained at 50 wt% fibre content, with the fibre reinforcement mostly in continuous fibre and non-woven mat forms. Tensile strengths as high as 110–138 MPa can be achieved. The fibre reinforcement effect in these high-strength cases was found to be 238–329% over that of base PP [7,11,35]. Wambua et al. [43] reported that a tensile modulus as high as 7.2 GPa can be achieved, although details on the fibre sizes have not been described. Non-woven kenaf mat/PP composites have been reported to have flexural strengths up to 118 MPa and flexural moduli of 9.6 GPa at 50 wt% fibre content [47]. The fibre contents which appear as the most appropriate for achieving high tensile properties for short and very short fibres produced via compression moulding method range between 40 wt% to 50 wt% [13,14,44]. However, a low fibre content generally results in the highest flexural strength for composites with short (75 MPa) [13] and very short fibres (63 MPa) [44]. Conversely, higher flexural moduli for composites with short and very short fibres are obtained at higher fibre contents, 85 wt% [15] and 50 wt% [44], respectively.

It is interesting to note that when the mechanical properties of kenaf/PP composites are compared across the manufacturing processes, particulate and continuous kenaf/PP composites appear to have similar flexural strengths, flexural moduli and tensile moduli at fibre contents $\leqslant$ 40 wt% [4,12,21,44,45,47,50]. In some cases, short kenaf/PP composites appear to have superior flexural strengths than particulate- and long fibre-based composites at low fibre contents [13].

1.2.3. Fibre and matrix treatments

Composites made of untreated fibres and PP have poor tensile [8,11,13,35,36,44] and flexural properties [4,9,12,28,44,47,49] due to weak bonding between the hydrophilic fibres and hydrophobic matrix. There are also cases where a combination of various treatments have resulted in only a marginal effect on the mechanical properties of kenaf/PP composites. In one study, the reinforcement effect on tensile strength was merely 18%, despite the fact that the reinforcing kenaf fibres had been treated with both sodium hydroxide (NaOH) and electron beam irradiation (EBI), and the matrix had been treated with MAPP [38]. Interestingly, some MAPP-treated kenaf/PP composites made using very short kenaf fibres (of approximately 0.54 mm) seem to result in a similar increase (of 33–38%) in reinforcement as those reinforced using short kenaf fibres (approximately 20 mm) [12,19]. This is possibly because, in the case of very short kenaf fibres, there is a large increase in surface area for fibre–matrix wetting, and provided that there is good fibre–matrix interfacial bonding, the stresses can be transferred between fibres and matrix successfully. Furthermore, very short kenaf fibres can be compacted and dispersed within a matrix very well.

Due to the lack of data covering a wider range of composite preparation conditions (e.g. combinations of fibre surface treatment and fibre length for a given fibre content), the effectiveness of fibre surface treatment methods and the minimum length of reinforcement required to improve tensile and flexural properties