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Mechanical, thermal and morphological properties of a bio-based composite derived from banana plant source

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ABSTRACT

This paper focuses on the synthesis and testing of a novel bio-based composite structure in which banana fibres was infused with resin made from banana sap. The mechanical, thermal, morphological and bio-degradation properties of the bio-composite were characterized and it was found that the material was suitable for general non-functional components. Mechanical tests indicated 15% increase in tensile strength, 12% improvement in tensile modulus and a 25% improvement in flexural modulus when compared to structures produced without banana sap. At elevated temperatures a decrease in the moduli was observed. The thermal stability of the biocomposite composite improved and this corresponded with an increase in the glass transition temperature. Morphological studies using scanning electron microscopy revealed improved compatibility between the fibre and banana sap matrix. This resulted in improved dynamic modulus values and low damping values. Finally, degradation tests revealed increased microbial activity on the banana sap composite. This was indicative of improved biodegradation rates.

1. Introduction

There is an urgency to address environmental and economic concerns in the production of new materials and hence in this regard these new materials must be bio-resourced and renewable. As is well known natural fibres and bio-resins are able to produce "green material" [1].

According to the European Union's directive on end-of-life vehicles, from 2015 onwards, all new vehicles should be 85% reusable and recyclable by weight; 10% can be used for energy recovery and only 5% can be used in landfills [2]. A few reports from the literature on bio-based polymer composites are summarized. The auto industry has used banana fibres for body parts, for instance the under floor protection trim of Mercedes A class has been made from banana fibre reinforced composite [3]. When the banana fruit is harvested, a large amount of bio-mass remains because each banana plant cannot be used for the next harvest [4]. Hence without any additional cost banana fibres can be used for industrial purposes and will benefit the environment significantly [5]. Since these bio-composite materials are environmentally friendly, the use of biodegradable bio-composites as replacements to non-biodegradable polymers has raised significant interest [6]. Although

extensive research has been done worldwide on banana fibres [4,7–10] as well as various synthetic resins systems [11–14], to the best of our knowledge banana sap has not been used for the manufacture of resins. Our earlier studies [15] has shown that banana sap can be effectively used in the manufacture of a bio-based resin. Natural fibres have already established a reputation as filler materials in industrial applications [16,17]. Jute, flax, hemp and coir are good reinforcement in polymer matrices and are used in automotive applications, construction and packaging industries [18–20]. Banana fibres is a waste product and without incurring much costs, the fibres can be used for industrial purposes [21,22]. Despite these advantages, natural fibres have a setback. They are hydrophilic have low impact strength, have non-uniformity, and have a low processing temperature and this hence this limits their applications. On the other hand natural fibres could lead to a weight reduction of 10–30% [23].

There is an abundance of banana plants in KwaZulu Natal, South Africa, and if the banana plant biocomposite can be used for industrial purpose, then a significant industry can emerge.

The advantage of the biocomposite is its compostibility and degradation rates. Biodegradation of a polymeric material is a chemical degradation brought about by the action of naturally occurring micro-organisms such as bacteria and fungi via enzymatic action into metabolic products of micro-organisms (for example H_2O, CO_2, CH_4 and biomass). This is an important

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characteristic for components that must be disposed of at the end of their life. Additionally, the mechanical, thermal and morphological properties are important aspects of structures of the composite material.

In this study the thermal, mechanical, morphological and biodegradable characteristics of a bio-composite manufactured from a bio-resin formulated from banana sap and banana fibres is addressed.

2. Experimental

2.1. Materials

The banana fibres were obtained from the pseudo-stem of the banana plant from a plantation in Durban, South Africa. The untreated fibres were converted into non-woven mat by needlepunching (CSIR, Port Elizabeth, SA).

The banana sap bio-resin, hereafter referred to as **BSM**, was synthesized with propylene glycol, maleic anhydride and banana sap containing 35% styrene. The resin blend was cured with an accelerator (0.03 wt%): cobalt naphthenate (Sigma Aldrich, SA) and a catalyst (1.2 wt%): methyl ethyl ketone peroxide (Sigma Aldrich, SA). Another resin without banana sap, hereafter referred to as the **control resin**, was synthesized in a similar manner. The details of BSM and control resin can be seen from our earlier work [15].

2.2. Preparation of bio-composite panels

Two types of composite panels were processed, one with BSM and the other with the control resin. In each of the panels two layers of the non-woven banana fibre mats (30 wt%) were infused with the resins by vacuum assisted resin infusion moulding (VARIM). The panels were left to cure overnight, and thereafter post cured at 80 °C for three hours. Thereafter specimens were CNC machined to size in accordance with ISO 14125 and ISO 527.

2.2.1. Tensile and flexural analysis

Tensile and flexural properties of the composite panels were determined using the Lloyd LR 30K universal testing machine under displacement mode fitted with a 1 kN load cell. The crosshead speed was set at 1 mm/min.

The BSM bio-composite material that will be used in the interior motor component was tested at ambient and at elevated temperatures. The panels were subjected to temperature soaking by ramping the oven temperature from 25 to 80 °C at 10 °C/min and immediately tested for tensile and flexural strength. In each case, five replicates samples of each type were tested.

Tensile and flexural strength tests of the BSM and control composites were tested at ambient and elevated temperatures. Descriptive statistics including the mean and standard deviation values were calculated for each test group. All procedures were done at 95% confidence intervals. The t-test: two-sample assuming unequal variances with $\alpha = 0.05$, $P(T \leqslant t)$ was used to determine if there was a significant difference between the two composite samples. All statistical analyses were performed using SPSS (Windows version 21, Chicago, Illinois, USA).

2.2.2. Scanning electron microscopy (SEM)

The fracture surface morphology of the tensile fractured specimens was examined with an environmental scanning electron microscope (EVO 15 HD, Carl Zeiss) at an accelerating voltage of 20 kV. The fractured surface was gold coated to avoid electrical charging during scanning.

2.2.3. Thermal analysis

Thermogravimetric analyses (TGA) and differential scanning calorimetry (DSC) were carried out using TA Instruments SDT Q600. 10 mg samples were scanned from 30 °C to 400 °C at a heating rate of 10 °C/min in a nitrogen atmosphere (50 ml/min). TGA and DSC of the control and the BSM bio-composite were studied.

2.2.4. Heat deflection temperature analysis

Heat deflection temperature (HDT) analysis was conducted using the dynamic mechanical analyser according to DIN EN ISO 75 method to determine the temperature at which the sample deforms. The samples (80 × 10 × 4 mm) were analysed using a three point bending mode at a loading of 1.8 MPa and with heating rate of 5 °C/min. HDT was measured at a fixed deflection of 2 mm.

2.2.5. Dynamic Mechanical Analysis (DMA)

DMA is an effective tool to study the effect of temperature on the mechanical properties of material. DMA is mainly used to evaluate the interfacial interactions in composite material. The storage modulus assesses the load bearing capacity of a composite material. Since the fibre-reinforced material undergoes various types of dynamic stressing during service, studies of viscoelastic behaviour of these materials are of great importance. Viscoelastic properties such as storage modulus (E'), loss modulus (E'') and damping parameter ($\tan \delta$) as a function of temperature were measured using a Dynamic Mechanical Analyser (TA Instruments DMA Q800). Samples of dimensions (25 × 10 × 3 mm) were mounted on the dual cantilever clamp. Flexural testing was done at temperatures from 25 to 350 °C range using a heating rate of 5 °C/min at a frequency of 10 Hz and amplitude of 50 μm.

2.2.6. Water absorption

The effect of water absorption on the bio-composite materials was investigated in accordance with ASTM D570 standard.

The percentage of water absorbed by the composite material was calculated by using weight difference between the samples immersed in water and the dry samples using Eq. (1).

$$\Delta M(t) = \frac{m_t - m_0}{m_0} \times 100 \tag{1}$$

where $\Delta M(t)$ is moisture uptake at time t, m_t and m_0 are the mass of the wet weight and dry weight at time t, respectively.

The diffusion of water in the composite medium is studied using Fick's steady state flow by applying Eq. (2):

$$\frac{M_t}{M_\infty} = \frac{4\sqrt{Dt}}{L\sqrt{\pi}} \tag{2}$$

where M_t is the weight of water content at time t, M_∞ is the equilibrium water content, L is the sample thickness and D is diffusion coefficient and $M_t/M_\infty \leqslant 0.6$ was maintained.

The movement of the solvent molecules in the polymer segments is characterized by the diffusion coefficient. The absorption of water by the natural fibre is related to the permeability of the water molecules through the biocomposite material. Therefore, the sorption coefficients that are related to the equilibrium sorption and is calculated by Eq. (3):

$$S = M_\infty/M_t \tag{3}$$

where M_∞ and M_t are the percentage of water uptake at infinite time and time t.

The permeability coefficient P, (mm²/s), which implies the net effect of sorption and diffusion and is given by Eq. (4):

$$P = D \times S \tag{4}$$