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Hemp fiber reinforced thermoplastic polyurethane composite: An investigation in mechanical properties

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ABSTRACT

In this study, the effect of fiber content, fiber length and alkali treatment on mechanical properties of hemp fiber and thermoplastic polyurethane (TPU) composite were investigated. It focused on the correlative effect of rigid hemp fiber and elastomeric polyurethane on tensile and flexural properties. Furthermore, the stress-strain behavior and the fracture analysis of the composite were discussed. To evaluate the influence of fiber length, three different lengths according to critical fiber length were chosen and examined. Interlaminar shear strength (ILSS) test, Fourier transfer infrared spectroscopy (FTIR) and X-ray diffraction (XRD) were conducted to understand the effect of fiber treatment on fiber-matrix interactions and fiber contents. Results presented that by increasing fiber volume content to 40%, flexural strength enhanced 193.24%. Additionally, 15 mm hemp fiber was found to be the optimum fiber length, where flexural strength at 40% fiber volume was further increased to 274.3%. ILSS tests of treated and untreated hemp fibers showed slight difference. However, FTIR spectra, XRD analysis and Scanning Electron Microscopy micrographs indicated the extraction of non-cellulosic materials from the surface in treated fibers, without altering the cellulose structure. It was found that, there are possibilities to balance the flexural properties and tensile properties by hemp fiber and TPU which is not achievable by glass fibers.

1. Introduction

Over the last decades, environmental issues and government restrictions have led industries to replace the petroleum-based material with agricultural-based to make eco-friendly products. In attempt to make green products, natural fibers were employed to reinforce polymers. Natural fibers such as hemp, flax, jute, sisal, etc. have some advantages over common inorganic or synthetic fibers, e.g. glass and carbon fibers. These are less density, less machine wear during processing, no health hazards and high degree of flexibility (Kabir et al., 2012; Mwaikambo et al., 2007). One of the important natural fibers in industry is hemp, which has relatively short cropping cycle and can be easily grown in a large array of environments. In addition, hemp with tensile strength of about (310–1110) MPa is one of the strongest fibers among all bast fibers (Müssig and Christian, 2010). Compounding hemp fibers with thermoplastics such as polypropylene, polyethylene and thermoset resins (e.g. polyester) had demonstrating improvements in tensile and flexural properties, which in some cases are comparable with glass fiber composites(Beckermann and Pickering, 2008; Lu and Oza, 2013a; Sawpan et al., 2012).

However, to develop a natural-fiber composite with appealing mechanical properties, careful choice of materials is necessary. Plant fibers being hydrophilic with polar characteristics of cellulose as the main component, are incompatible with non-polar polymers including polypropylene, polyethylene, etc. Therefore, a third material should be utilized to improve interface adhesion, i.e., coupling agent. Within this framework, polar polymers such as polylactic acid, polyurethane and natural polymers (e.g. Polyhydroxybutyrate or Euphorbia resin (Mwaikambo et al., 2007)) could be perfect choices.

Thermoplastic polyurethane (TPU) has been used in applications where strong mechanical characteristics are required. To make an eco-friendly, biodegradable, natural fiber composite, the polar cyanide groups on TPU backbone chain, along with its good mechanical properties, makes it a great choice as a matrix. Although thermoset polyurethane and PU foam have been reinforced with fibers of banana (Merlini et al., 2011), sugarcane bagasse, coir, sisal (Mothé and De Araújo, 2000; Otto et al., 2017), jute, flax (Bledzki et al., 2001; Kuranska and Prociak, 2012), pine wood (Aranguren et al., 2007), hemp fiber (Aranguren et al., 2007; Kuranska and Prociak, 2012), date palm fibers (Oushabi et al., 2017), oil palm empty fruit bunch, rice

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husk, hard wood (El-Shekeil et al., 2012) and microcrystalline cellulose (Głowińska and Datta, 2015) before, few studies on TPU-biocomposites have been conducted. In recent studies, kenaf (Datta and KopczyńSka, 2015; El-Shekeil et al., 2012), rice husk (Tayfun et al., 2014) and cocoa husk fibers (El-Shekeil et al., 2014) have been compounded with TPU. In all cases, due to strong nature of TPU, the tensile strength of composites was lower than matrix; however flexural properties indicated improvements. Comparing TPU reinforced with synthetic fibers such as glass (Arenz and Lausberg, 1990; Wilberforce and Hashemi, 2009), Kevlar (Kutty et al., 1992), carbon (Sánchez-Adsuar et al., 2003) which have very appealing mechanical properties; natural fiber-TPU composites have better flexibility and lower modulus. In addition, they have better process durability that prevents extreme breakage and helps in maintenance of fibers' aspect ratio (Beckermann and Pickering, 2008).

In spite of strong tensile properties, TPU suffers from weak flexural modulus ("TPU TDS-MSDS – INTERPLAST, SAFIC ALCAN," n.d.), making it inappropriate for applications undertaking flexural stresses. The aim of this work is to evaluate the reinforcing characteristics of hemp fibers to deliver improved flexural properties to composite, in balance with other properties in making a biodegradable composite without using any coupling agents.

The effect of alkali treatment on hemp fiber characteristics were studied through interlaminar shear stress (ILSS), FTIR spectra and SEM micrographs analysis. The crystalline structures of raw and treated fibers were observed by X-ray scattering and the crystallinity index was calculated. Also, flexural and tensile properties as the mechanical characteristics of prepared Hemp-TPU compounds were investigated regard to different fiber loadings, length and modification.

2. Materials and methods

2.1. Materials

Thermoplastic polyurethane from Epaflex (Epamould® 295A10) with a density of 1.19 g/cm^3 and hardness of 95 (shore A) was used. Dew retted hemp bast fibers with an initial length of 40 mm were obtained from HempFlax. The Fiber chemical contents are shown in Table 1.

2.2. Fiber preparation

First, hemp fibers were washed with boiling water to remove water-soluble minerals. For alkali treatment, fibers were soaked in 5 wt% sodium hydroxide solution with the fiber: solution weight ratio of 1:25, at 120 °C for 60 min. Sodium hydroxide concentration, temperature and immersion time were determined according to previous studies in order to have high extraction efficiency while preventing degradation of cellulose chain structure (Beckermann and Pickering, 2008; Kostic et al., 2008). Then, to boost alkalization efficiency, the process was repeated. After treatment, fibers were thoroughly washed with tap water to remove all remained sodium ions and then dried in oven at 80 °C for 48 h. Finally, bast fibers were separated from hurds manually. The Dried fibers were stored in a sealed plastic bag to avoid moisture absorption.

Table 1
Chemical composition of hemp fiber.

Fiber contents	(%)
Cellulose	66
Hemicellulose	16
Pectin	4
Lignin	9
Fat/Wax	1
Minerals	2
Ash	2

Fiber mass loss measurements were carried out by measuring dry fiber's mass before and after alkalization process to calculate the fiber's mass loss percentage. The initial humidity of hemp fibers was calculated by measuring fiber's mass before and after drying in oven.

2.3. Composite preparation

Composites with hemp contents ranging from 10 to 40 vol fraction were prepared in a Brabender plasti-corder internal mixer operating at an optimized temperature of 175 °C with the rotating speed of 30 rpm, respectively. Composite sheets were then made using Toyoseiki 35 MPa mini press.

3. Characterization

3.1. Mechanical characterization

Using a Santam tensile testing machine, tensile and three point bending flexural tests were carried out according to ASTM D 638 and ASTM D 790, respectively. Samples for tensile test were punched in dumbbell shaped from 1 mm thick composite sheets. Flexural specimens were cut with dimensions of 130 × 15 × 5 mm. The machine was run at a cross head speed of 5 mm/min and 23 mm/min for tensile and flexural tests, respectively. The short beam three point bending test (ILSS) were carried out according to ASTM D 2344 with cross head speed of 1 mm/min and span to depth ratio of 4:1. Samples were cut from 5 mm thick sheet.

3.2. Scanning electron microscopy (SEM) analysis

Hitachi S-4160 scanning electron microscopy (Hitachi, Japan) was used to study the fractured surfaces of tensile tested composite samples with hemp fibers before and after alkali treatment. Prior to analysis, the samples were coated with Au by means of DC Sputtering.

3.3. Fourier transform infrared (FTIR) spectroscopy

The FTIR analysis of the untreated and alkali treated hemp fibers were carried out using a Bomem MB-Series FTIR spectrometer. A total of 5 scans was taken for each sample with a resolution of 4 cm^{-1}.

3.4. X-ray scattering (XRD) analysis

Raw and treated fibers were cut and pressed into discussing a cylindrical steel mold in a laboratory press. Samples were analyzed using a Siemens D5000 system. The CuKα radiation was generated at 40 KV and 40 mA over a range of 2θ values from 5 to 60 at a scanning speed of 1.2°/min.

4. Results and discussions

4.1. Mechanical properties

The mechanical properties of composites mainly depend on properties of matrix and fibers, adhesion of fibers to matrix at interface and fiber distribution in matrix. However, as strong fiber-matrix bonds are required for effective transfer of stresses from matrix to fibers across the interface, fiber-matrix adhesion plays the most significant role (Datta and KopczyńSka, 2015; Husić et al., 2005; Luz et al., 2007; Rask et al., 2012).

4.1.1. Tensile properties

4.1.1. a Effect of fiber length on tensile properties. Fiber length is one of the main parameters that can affect composite mechanical properties (Joseph et al., 2002; Sathishkumar et al., 2012). When fibers are at least as long as their critical length (lc), stresses are transferred properly by