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A new approach to "Greening" plastic composites using pineapple leaf waste for performance and cost effectiveness

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ABSTRACT

The work described in this paper is the first detailed study aimed to demonstrate the important opportunity available in using all parts of a single renewable source, i.e. pineapple leaf waste, as filler for the preparation of green plastic composite with a wide range of adjustable properties. This will not only provide the product designer an opportunity to lower the material cost, but also offer an opportunity to adjust the price-performance ratio and make use of every part of the waste leaf. Fresh pineapple leaves, which contain about 85% water, are chopped into small pieces and ground into paste. This is called whole ground pineapple leaf (WGL) and contains approximately 2.8% by weight of high quality dry fiber, called pineapple leaf fiber (PALF) as well as a large fraction of non-fibrous material (NFM) of approximately 10% by weight. WGL, PALF and NFM are examined as fillers for polypropylene reinforcement. It was found that PALF provided the highest improvement in all mechanical properties tested (tensile, flexural and impact tests) and also heat distortion temperature, followed by WGL and NFM, respectively. NFM, although it provided only slightly improved tensile and flexural properties, could maintain or even improve impact strength. Brief consideration of environmental issues suggests that using pineapple leaf waste can be beneficial in terms of both lower embodied energy and also lower overall emissions.

1. Introduction

The use of bio-based substances in preference to petroleum-based equivalents in order to produce green materials is now very important, is becoming very attractive and widely practiced due to the problems of global warming and oil depletion. This can range from part substitution to complete replacement. One example of this is the use of cheap and naturally abundant materials, such as ligno-cellulosic substances like wood flour, to produce wood polymer composites (WPC) [1,2]. WPC, although having improved stiffness, still possess some disadvantages such as reduced strength and impact properties [3,4]. So in this paper we report the first detailed study aimed to demonstrate the important opportunity available in using all parts of a single renewable source, i.e. pineapple leaf waste,

One of the recent trends, especially for the automotive industry [5,6], is to use natural fiber to produce natural fiber reinforced composites (NFRC) where plastic composites with superior properties, over the unreinforced and particulated filled counterparts, are required [7,8]. In addition to just replacing materials from different sources, it is also important to consider the sustainability of the practice in terms of carbon footprint. It has been shown that there is a clear advantage in using natural fiber reinforced polymer composite [9,10]. However, for some type of fiber, there is still a debate over the carbon footprint benefit of using natural fiber from cultivated plants [11]. The benefit will be more obvious if natural fibers are obtained from agricultural wastes such as pineapple leaf, coir, banana, rice husk and bagasse. In fabricating a material, industrial or product designers should be aware of these important points.

Thailand, like many agricultural countries, has access to various kinds of natural fiber. Any kind of natural fiber can be used to produce NFRC, and indeed almost everything has been studied. However, for widespread use, the fiber availability and its properties are the main factors determining selection. A fiber that is abundantly available and is used very little is pineapple leaf fiber (PALF). Thailand is currently the world's largest pineapple producer [12] with about 240,000 acres under cultivation [13]. After harvesting, a large amount of pineapple leaf waste approximately 20,000–25,000 tons/acre, remains causing various problems for farmers. Pineapple is also grown in many other countries worldwide, such as Brazil, Philippines, Costa Rica, Malaysia, Indonesia and Hawaii, in total on about 2.1 million acres. In addition to its availability, PALF is also attractive in terms of its mechanical properties, which should be good for plastic reinforcement. Indeed, a number of published research works [14,15] have demonstrated the use of PALF in plastic or polymer reinforcement. However none has studied

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the use of other non-fibrous parts of the leaf. These non-fibrous parts constitute as high as 10% of fresh pineapple leaf while PALF constitutes only 2–3%. So a large low value fraction of the leaf is left unused and, being discarded, may pose environmental problems. Recently, we have presented a simple and novel method to extract PALF fiber in the form suitable for plastic reinforcement [16]. In the research reported in this paper it is shown that, with the same method, all parts of pineapple leaf can be used for plastic reinforcement enabling maximum utilization of the pineapple waste. The study encompasses mechanically ground whole leaf (WGL). In some studies the component parts were separated into PALF and non-fibrous material (NFM). So WGL, PALF and NFM are compared as fillers for polypropylene. It is shown that a wide spectrum of composite properties can be obtained. This will not only lower the material cost but also offer an opportunity to adjust the price-performance ratio and make the utilization of pineapple leaf waste more attractive for industrial applications.

Many workers have discussed the theoretical aspects of fiber reinforcement and the application of these to natural fibers. The most relevant of these theories are mentioned against the background of this work in Section 3.6 (theoretical considerations) below.

2. Materials and methods

2.1. Polymer matrix

Isotactic polypropylene (extrusion grade, Moplen400H, Thailand) with a density of 0.9 g/cm^3 and melt flow index of 2.4 g/10 min from Basell polyolefin was used as the polymer matrix.

2.2. PALF

Pineapple leaves were collected from cultivation areas in Kok Kwai District, Ban Rai, Uthai Thani Province, Thailand. The leaves were washed to remove soil and dirt. Whole fresh pineapple leaves, which contain approximately 85% water, were then cut to a length of 5 mm and milled with a locally made disc mill. It had two circular plates of 150 mm diameter, one revolving and one stationary. The revolution speed was about 7700 rpm. The discs were separated by projecting teeth, between which the substances are ground. Milling was carried out by feeding chopped pineapple leaf into the hopper at the top of the mill and continued for 10 s. The milled materials were cleaned with water and air dried at room temperature for 3 days. The resulting dried crumb was ground with a high speed grinder consisting of a stainless steel bowl and a rotating blade similar to that in a food processor. The grinder (Hao Peng, China) was operated at a rotating speed of 25,000 rpm for 30 s and yielded a loose powder. The material at this stage is designated whole ground leaf or WGL. WGL is composed of fibrous and non-fibrous materials. The former is designated PALF and the latter NFM. PALF and NFM were separated from WGL by sieving with steel wire mesh number 60.

2.3. Preparation of composites

PP composites of different compositions were prepared in two steps. First, PP and the filler, namely WGL, PALF or NFM, were melt mixed on a two roll mill for 15 min. The temperatures of the front and back rollers were 185 °C and 175 °C, respectively. The mixture was taken out with some stretching to form unidirectional prepreg. The prepreg was then compression molded to form a sheet of 1 and 3 mm thickness at a temperature of 195 °C under a pressure of 3.5 MPa for 5 min, followed by cooling under the pressure of 7.0 MPa for 3 min.

2.4. Characterization techniques

Morphology: The shape and size of ground leaf particles were observed with a scanning electron microscope (SEM) (Hitachi Tabletop Microscope; model TM 1000, Japan).

Thermal analyses: TGA was carried out with Mettler Toledo TGA instrument (Model SDTA851, Switzerland) in order to compare the thermal stability of different materials. The samples were heated from 40 to 800 °C at heating rate of 20 °C/min under a nitrogen atmosphere. In addition, heat distortion temperature (HDT) was also determined with a dynamic mechanical analyzer (Q800, TA Instruments, USA) using the three-point bending mode. The specimen dimensions used for this analysis were 50 mm (L) × 12 mm (W) × 3 mm (T). The following test conditions, adopted from ASTM: D648, were used [17]. The specimens were heated at the rate of 2 °C/min from 35 to 160 °C under a constant load of 0.455 MN/m^2 and the HDT was determined as the temperature at which the specimens reached 0.25 mm.

Mechanical properties: Tensile testing was carried out on a universal testing machine (Instron 4469, High Wycombe, UK) with a 1 kN load cell. The specimen was cut along the fiber direction to a strip of 10 mm wide with a scroll saw. The gauge length was 50 mm and the extension rate was 5 mm/min. Secant modulus at 1% strain and tensile strength (or yield strength in case of PP) were determined.

Flexural testing was carried out according to ASTM: D790 by using a universal testing machine (Instron 4469, High Wycombe, UK) at a strain rate of 1.28 mm/min with load cell at 1 kN. The specimens were 80 mm length, 10 mm width and 3 mm thickness. The span length was 48 mm. Flexural modulus and flexural strength were determined at 1% and 5% strain, respectively.

The impact strength, fracture initiation energy and fracture propagation energy were measured on a notched Izod impact testing machine (Radmana ITR-2000, McVan Instruments, Australia) following ASTM: D256. The impact specimens were 60 mm length, 12 mm width and 3 mm thickness. The samples were notched with a Davenport notch cutting apparatus to a depth of about 1.3 mm. The reported values of tensile properties, flexural properties and impact properties were averaged from five specimens.

Water absorption of PP composites was measured by immersion of composite specimens in distilled water at room temperature. Weight gain measurement was determined after 1 and 14 or 30 days, respectively. The percentage of water absorption was calculated using the following equation:

$$\%\text{Water absorption} = \frac{W_f - W_i}{W_i} \times 100 \qquad (1)$$

where W_i is the initial weight of the sample before immersion, and W_f is the final weight of the sample after immersion in water for a predetermined time.

3. Results and discussion

3.1. Total solid and fiber contents

Table 1 displays the compositions and content of ground pineapple leaf based on the shape of ground materials found in the present study. Total recoverable solid or WGL constituted approximately 12.85% weight of fresh leaf. Approximately 21% of WGL is PALF and the rest is NFM. Interestingly, the amounts of PALF and NFM compare very well to that of the two major components of plants, cell wall and cell content usually determined in forage analysis [18]. They are generally determined in terms of neutral detergent fiber (NDF) and neutral detergent soluble (NDS), respectively. Thai pineapple leaf has been reported to contain NDF and NDS as