Composites: Part B 54 (2013) 44–51

Contents lists available at SciVerse ScienceDirect

Composites: Part B

journal homepage: www.elsevier.com/locate/compositesb

Kenaf/polypropylene nonwoven composites: The influence of manufacturing conditions on mechanical, thermal, and acoustical performance

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ARTICLE INFO

Article history:
Received 8 February 2013
Accepted 23 April 2013
Available online 7 May 2013

Keywords:
A. Fabrics/textiles
B. Mechanical properties
B. Thermal properties
E. Compression molding

ABSTRACT

The kenaf/polypropylene nonwoven composites (KPNCs), with 50/50 blend ratio by weight, were produced by carding and needle-punching techniques, followed by a compression molding with 6-mm thick gauge. The uniaxial tensile, three-point bending, in-plane shearing, and Izod impact tests were performed to evaluate the composite mechanical properties. The thermal properties were evaluated using thermogravimetric analysis (TGA), differential scanning calorimetry (DSC) and dynamic mechanical analysis (DMA). The performance of sound absorption and sound insulation was also investigated. An adhesive-free sandwich structure was found to have excellent sound absorption and insulation performance. Based on the evaluation of end-use performance, the best processing condition combination of 230 °C and 120 s was determined, and the correlation between mechanical properties and acoustical behavior was also verified by the panel resonance theory.

1. Introduction

Industrial uses of natural fibers increasingly gain attention from various manufacturing sectors due to the public concern for energy security and environmental protection. The use of natural fibers for polymer composites is growing rapidly to meet diverse end uses in transportation, geotextiles, low cost building, and other construction industries [1,2]. Natural fibers play an important role in developing biodegradable composites to substitute glass or carbon fiber and inorganic-filler-reinforced plastics because of the growing concerns of global warming and the rising price of petroleum-based products [3,4]. Natural fibers from renewable natural resources offer several advantages such as high specific strength and modulus [5], low cost, low density [6], renewable nature [7], biodegradability, no health hazards, and low CO_2 emission in production [8]. Kenaf fiber is the bast of kenaf plant. It contains cellulose (44–57%), hemi-cellulose (22–23%), lignin (15–19%) ash (2–5%), and other elements (~6%) [9]. It is estimated that the output of kenaf fiber is 0.33 million tons worldwide per year [10]. Composites based on kenaf and matrices of thermosets such as epoxy [11] and polyester resin [12], and thermoplastics such as polypropylene [13], polylactic acid (PLA) [14], and polyvinyl alcohol (PVA) [15] have been reported.

The mechanical properties of natural fiber reinforced polymer matrix composites (PMCs) have been investigated over the past few decades. Herrera-Franco and Valadez-González [16] evaluated the mechanical properties of short and continuous henequen fiber reinforced high density polyethylene composites after silane coupling agent treatment. Jacobs et al. [17] concluded that the alkali treated sisal/oil palm hybrid fiber reinforced rubber composites exhibited better tensile properties than untreated composites. Because the interface modification methods can improve the fiber–matrix adhesion, composite strength is increased ultimately. A similar comparative study was also done on kenaf, jute, sunn-hemp and alkaline treated sunn-hemp fibers in terms of physical structure and thermal stability [18].

However, the interface modification process will cost extra time, energy and money. Comparing to the non-significant improvement, it is not cost-effective and practical for industrial mass production. In addition, all the literature mentioned above is studies on PMCs. PMCs are normally processed using injection molding or resin transfer molding technique [19,20]. The nonwoven fabrication and compression molding technique for producing KPNCs used in this research has not been paid much attention so far. The fiber content in PMCs is usually up to 30% by weight, meaning that the polymer matrix takes up a higher fraction of

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http://dx.doi.org/10.1016/j.compositesb.2013.04.065

the composite. In contrast, the fiber content of KPNCs is 50–70% by weight [21]. With such a high fiber fraction, kenaf fiber is therefore the dominant material and most load-bearing component in KPNCs. The melt PP fiber works like glue that bonds the intersected kenaf fiber. Besides, the higher the natural fiber content, the more environmental friendly is the composite.

Due to the nature of nonwoven fabrication, natural fibers are randomly distributed in-plane. In this nonwoven web structure, natural fiber and polymer bonding fiber are intersected with overlap points. This makes KPNCs feature a porous structure, instead of a continuous polymer matrix structure. Therefore, this nonwoven fabrication followed by the manufacturing method of composite compression molding allows KPNCs have a higher natural fiber content that tends to improve composite biodegradability. Recent research progress also includes the evaluation of notch and strain-rate effects on the mechanical property of 3-mm KPNC panels [13,22]. In this study, we focused on investigating the influence of manufacturing conditions on the end-use performance of 6-mm KPNCs. These findings could be useful information for industrial practice in fiber composite production.

The objective of this paper is to explore the manufacturing conditions that affect end-use performance of natural fiber polymer composites in terms of mechanical properties, thermal stability, and acoustical behavior. It is very attractive to produce more quiet personal vehicles and resident houses in today's rushed daily life. Sound absorption and insulation are the main factors for noise control. Traditionally, acoustical materials used to control vehicle and building noise are of the expensive non-biodegradable materials such as glass wool, polymer foams, fabric filler, and polymer fibers. In the present work, an alternative acoustical material made from KPNC is investigated. Nonwoven felts are good sound absorbers especially at high frequencies. However, they are less effective to sound insulation because of their porous structure. On the other hand, rigid composite panels are good sound barriers but poor sound absorbents because of their compressed structure.

In this paper, an adhesive-free sandwich structure was found to be excellent in both sound absorption and sound insulation performance. Parikh et al. [23] concluded that natural fiber nonwoven composites, stacked with an underlay of polyurethane, provided efficient noise absorption. Mueller and Krobjilowski [24] conducted acoustical tests on sound adsorption and insulation in cotton-based composite materials in both thermoset and thermoplastic matrices. Those composite materials showed remarkable acoustical behavior. Chen et al. [25] recently studied the acoustical and fogging performance of flax/PP composites produced by spunlaced technology. The nonwovens with a bulky and porous web structure were confirmed to provide better sound absorption performance. Similarly, there are no comprehensive studies on the influence of manufacturing conditions on the acoustic performance of those composites so far.

2. Materials and methods

2.1. Materials

The kenaf fiber was supplied by Engage Resources (Thailand), Ltd. Co. Polypropylene (PP) staple fiber, which was supplied by Fiber Science, Inc. with an average length of 50.8 mm and fineness of 7 denier was used for nonwoven formation and bonding. Kenaf and PP fibers were conditioned at 22 ± 1 °C and 49 ± 3% relative humidity for 48 h before processing. No chemical treatment on kenaf and PP fibers was applied. Major mechanical properties of kenaf and PP fibers in comparison with *E*-glass fiber are listed in Table 1. This data is provided by the manufacturer or is from literature.

2.2. Nonwoven composite fabrication

The manufacture of KPNCs involves three steps: carding, needle-punching, and thermal compression. The kenaf fiber, which acts as the reinforcement, was manually opened and mixed with PP fibers in 50/50 weight ratio. The mixture was then fed into an F015D Universal Laboratory Carding Machine to produce a fiber web. During carding, the mixture was further opened and individual fibers were combed to be parallel. The fiber web was carded once again in the perpendicular direction to improve web isotropy. Subsequently, these fibrous felts were transferred to a Morisson Benkshire needle-punching machine in order to produce nonwoven felts. The feeding speed is 1.6 m/min and the punching rate is 228 strokes/min. By applying the mechanical needling technology, the fiber blends were greatly entangled and interacted in the out-of-plane direction. After needle-punching the nonwoven felts are much denser and stronger than the fiber web. Next, the felts were cut into 0.3 m × 0.3 m size of segments and machine gauge length was set to 6.35 mm (1/4 in.) for composite thickness control. Samples were compression molded by the MEYER® Transfer Printing and Labority Press System (Type APV 3530/16). The pressing conditions are listed in Table 2. After compression molding, samples were transferred to a pair of cold plates and cold pressed at 5×10^5 Pa for 30 s to obtain a sleek surface. The 6-mm KPNC panels were then cut into specific sizes for instrumental characterization.

2.3. Mechanical properties

The tensile strength and modulus of the nonwoven composites were evaluated using a MTS QT/5 Universal Tester in accordance with the ASTM D 3039 for polymer matrix composite materials. Material flexibility was measured according to ASTM D 790 for reinforced plastics (three-point bending method). The in-plane shear properties of composite panels were tested using ASTM D 4255 (two-rail shear method). Composites impact strength was evaluated by a Tinius Olsen model 92T impact tester in accordance with the ASTM D 256 method A for determining the Izod pendulum impact resistance. It measures the energy required to fracture a notched specimen at relatively high rate bending conditions. Ten specimens were tested for each sample and average values were reported for the evaluation of tensile, flexural, shear and impact properties. All tests were under the condition of 22 ± 1 °C and relative humidity of 49 ± 3%.

2.4. Thermal analysis

Thermogravimetry (TG) technique was employed to analyze the thermal stability of fibers. Scans were carried out at a heating rate of 10 °C/min in nitrogen atmosphere with a gas flow of 20 ml/min from 30 °C to 800 °C. The measurements were performed using a SHIMADZU TGA-50 thermo analyzer. Sample weights were maintained within 8–10 mg. The heat resistant properties of kenaf and PP fibers were also characterized by TG technique in air atmosphere with a gas flow of 20 ml/min from 30 °C to 800 °C. Four heating rates of 5, 10, 20 and 40 °C/min were used.

The Differential Scanning Calorimetric (DSC) measurements were performed on a SHIMADZU DSC-60 at a heating rate of 5 °C/min in nitrogen atmosphere with a gas flow of 40 ml/min. Each thermogram was recorded from 20 °C to 200 °C. In order to erase the previous thermal history of PP fiber and to study the recrystallization of kenaf and PP fibers, temperature was then cooled to 20 °C at 10 °C/min. For PP fibers, samples were subsequently heated to 200 °C at 5 °C/min in the second scan. The glass transition point (T_g) of kenaf and PP fibers and the melting point (T_m) of PP fiber were evaluated from the maximum point of the