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Dual-functional natural-fiber reinforced composites by incorporating magnetite

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ABSTRACT

Natural fiber reinforced composites with dual-functional properties, including electromagnetic shielding and paramagnetic functions, as well as improved water-resistant property, were fabricated using vacuum assisted resin transfer molding (VARTM) process. Magnetite particles were firstly mixed with kenaf fibers to form a mat, followed by resin intrusion and compression for the composite fabrication. The obtained kenaf fiber/magnetite/polyester composites were endowed with electromagnetic shielding and paramagnetic properties, without compromising the mechanical properties. When 35.2% magnetite was incorporated into the composites, the electromagnetic interference shielding effectiveness reached 79.2% with the range 8–12 GHz, and the saturation magnetization was 29.2 emu g^{-1}. The 24-h thickness swelling and water absorption of the composites after introducing magnetite were drastically reduced from 19.7% to 2.4% and 18.3% to 2.6%, counting as the decreases of 87.6% and 73.4%, respectively. It was indicated that the water resistance of the composite was improved significantly.

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1. Introduction

Lignocellulosic fibers have attracted arising interest in composite manufacturing, because of the excellent characteristics such as low density, low cost, ready availability, complete biodegradability, low accumulation in the environment, and successful waste management performance. As one of the lignocellulosic fibers, the application of kenaf (*Hibiscus cannabinus*, *L.* Malvaceae) bast fiber was widely investigated due to its lightness, low cost and high specific strength [1–5]. As well known, kenaf is a cellulosic source with both economic and ecological advantages, including the uses of core for natural plywood binder [6] and the bast for soda-AQ pulp [7]. Compared to the energy consumption of the glass fiber, it takes 15 MJ energy to produce 1 kg kenaf fiber, while, 54 MJ to produce 1 kg of glass fiber [8]. Furthermore, through the life cycle assessment (LCA), less negative environmental impacts were found in 'cradle to gate' consideration of kenaf fiber compared with the glass fiber [9]. To improve the properties of kenaf composites, many modification efforts were conducted, such as, alkaline treatment [10], rice-washed water treatment [11], using fiber/high-density polyethylene [12], etc. Utilizing an optimal kenaf fiber ratio to achieve the highest tensile property of the composites [13]. The natural fibers, hemp yarn, were used to make tubes [14].

Electromagnetic pollution becomes worldwide preoccupation because of the potentially harmful to human health [15]. Driven by the proliferation of electronics and instrumentation in commercial and industrial applications, electromagnetic interference (EMI) shielding has received arising interest in many areas. In order to reduce or avoid the electromagnetic pollution, the development of EMI shielding material from fully sustainable and eco-friendly materials have become an urgent issue for researchers in the composite industry. Generally, the most commonly used method is to block the field with barriers made of conductive or magnetic materials, so that the energy of electromagnetic wave was reduced to avoid the interference to the working electronic components [16,17]. At the present time, abundant EMI shielding materials and

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technologies have been produced and designed to reduce the interferences caused by electromagnetic signs [15,18–24]. Among them, metal is the most common EMI shielding material and extensively used in EMI shielding applications [18,19] because of the great electromagnetic reflection. However, the disadvantages of metal are also apparent, such as corrosive action, high density, electric conduction, and uneconomic processing [25]. These drawbacks deter it from the practical applications in the EMI shielding field. To avoid the problems mentioned above, the EMI shielding composites based on the lignocellulosic fibers are considered as the potential candidates [26–30], which are light, corrosion resistant, easily manufactured, economical, and environmentally friendly. Recently, the graphene nanoribbon [31], nano-carbon [22], magnetron sputtering [32] and powdered activated carbon [33] were used to enhance the EMI shielding.

The magnetic composites based on lignocellulosic fibers with both natural fiber properties and magnetic properties were usually prepared by loading magnetic fluids to wood fiber boards using impregnation [34]. The magnetite has been proposed for this application with the advantages of its biocompatibility and easy synthetic process [35]. The fabrication and characterization of magnetic composites based on wood were reported [36–38], which showed that the magnetic wood offered excellent performances such as easy to be heated, electromagnetic wave absorption, paramagnetic, wooden texture, easy to be processed, and humidity control functions. Therefore, magnetic treatment endowed the lignocellulosic fiber based composites with new functions and expands their applications. The composites were filled using the graphene oxide-deposited carbon fibers and applied for building materials with high electromagnetic interference shielding [39]. The magnetic wood with electromagnetic wave absorption application as a building material was reported [36].

The magnetite was used to fabricate composites because of the electromagnetic absorbing and paramagnetic properties [29,40,41]. The most magnetite was formed *in situ* from ferric ion and base solution [29,42], which might cause chemical pollution and not be convenient for the industrial production. However, the pollution can be avoided by directly using the magnetite particles. To fabricate the kenaf fiber based composites with electromagnetic shielding and paramagnetic properties, magnetite particles were physically mixed with kenaf fibers. The mixture was fabricated into composite through the vacuum assisted resin transfer molding (VARTM) process, which was expected to improve the mechanical property of composites [43].

In this study, the magnetite-introduced kenaf fiber reinforced composites were manufactured through the VARTM process. The effect of the magnetite contents on the mechanical, dynamic mechanical, water-resistant, electromagnetic shielding, and magnetic properties were investigated.

2. Materials and methods

Sourced from Kengro Corp., USA, the kenaf bast was chopped into approximately 50.8 mm in length. The sodium hydroxide (NaOH) solution (5%, w/v) was prepared using NaOH beads (≥97%, Acros Organics) and deionized (DI) water from the Millipore Milli-Q Integral Water Purification System. The magnetite particles (Fe_3O_4) were obtained from Beijing Chemical Reagents Co., China, and used as received. The unsaturated polyester resin (AROPOL Q 6585, 30% styrene, Ashland Chemicals) and tert-butyl peroxybenzoate (t-BP, 98%, Acros Organics) were used for fabricating the composites.

2.1. Preparation of magnetite loaded fibers

The kenaf fibers were obtained through the alkali retting process from the kenaf bast. Briefly, a mixture of 120 g kenaf bast (9.1% moisture content measured by Mettler-Toledo HB43-S Moisture Analyzer) and 1.8 L NaOH solution were added into a hermetical reactor (251 M, Parr Instrument Company, USA). This alkali retting process was carried out at 160 °C for 1 h with the mechanical stirring. The saturated vapor pressure remained at 0.60 MPa in the hermetical reactor. After cooling, the retted fibers were washed using running water and then dried. The fiber yield was measured as 38.5 ± 1.0%.

The magnetite loaded fibers were prepared by mixing the retted fibers (after being washed, but not dried) and magnetite. Prior to the mixing, the magnetite aqueous suspension was treated by a VCX 1500 ultrasonic (Sonics & Materials Inc., USA) for 5 min. The retted fibers were mixed into 1-L magnetite aqueous suspension, and mechanical stirred for 30 min. The mixture was formed a preform mat with a dimension of approximate 100 × 165 × 10 mm (width × length × thickness), and dried at 105 °C for 24 hours. The magnetite of 20 g (20 g L^{-1}), 30 g (30 g L^{-1}), or 40 g (40 g L^{-1}), was fed, and the resulting mats of magnetite loaded fibers were called as Kenaf/magnetite20, Kenaf/magnetite30, or Kenaf/magnetite40, respectively. The content of magnetite in each mat was calculated by the weight difference as shown below:

$$\text{Magnetite content} = \left(W_{\text{Kenaf/magnetite}} - W_{\text{Kenaf}}\right) \times \Big/ W_{\text{Kenaf/magnetite}} \times 100\% \quad (1)$$

where W_{Kenaf}/magnetite was the weight of Kenaf/magnetite and W_{Kenaf} was the weight of retted fiber. The magnetite loading efficiency was calculated as follows:

$$\text{Loading efficiency} = \left(W_{\text{Kenaf/magnetite}} - W_{\text{Kenaf}}\right) \times \Big/ W_{\text{Feeding magnetite}} \times 100\% \quad (2)$$

where $W_{\text{Feeding magnetite}}$ was the feeding magnetite, i.e. 20 g, 30 g, or 40 g.

2.2. Morphology analysis

The Quanta 200 environmental scanning electron microscope (SEM) with an accelerating voltage of 20 kV and a magnification of 2000× was used to observe the surfaces of the un-treated kenaf fibers and Kenaf/magnetite40. Prior to the SEM tests, the specimens were coated by a gold sputtering coater for 5 min to prevent the charging of the specimens by the SEM electron beam.

2.3. Determination of magnetite particle size

The particle-size distribution of magnetite was measured in accordance with dynamic light scattering (DLS) method by Beckman Coulter Delsa™ Nano C Particle Analyzer. Magnetite was dispersed into the DI-water with a concentration of 1 mg mL^{-1}. Prior to the particle-size measurement, magnetite aqueous dispersion was treated by a VCX 1500 ultrasonic (Sonics & Materials Inc., USA) for 5 min.

2.4. Fabrication of composites

The composites were fabricated using the un-treated kenaf fibers, Kenaf/magnetite20, Kenaf/magnetite30, and Kenaf/