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 to 12 GHz, and the saturation magnetization was 29.2 emu g⁻¹. The 24-hour thickness swelling and water absorption of the composites after introducing magnetite were drastically reduced from 19.7% and 18.3% to 2.4% and 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.

Keywords: A. Fibres; B. Magnetic properties; E. Resin transfer molding (RTM); Water resistance

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 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 ($\geq 97\%$, 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 one hour 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 $38.5 \pm 1.0\%$.

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 minutes. The retted fibers were mixed into 1-liter magnetite aqueous suspension, and mechanical stirred for 30 minutes. The mixture was formed a preform mat with a dimension of approximate $100 \times 165 \times 10$ mm (width $\times$ length $\times$ 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:

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

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

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

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 2,000 $\times$ 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 minutes 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 minutes.

2.4. Fabrication of composites

The composites were fabricated using the un-treated kenaf fibers, Kenaf/magnetite20, Kenaf/magnetite30, and Kenaf/magnetite40 through vacuum-assisted resin transfer molding (VARTM) process described in the previous research [43]. Briefly, the kenaf preform, with a dimension of 110 $\times$ 165 $\times$ 10 mm (width $\times$ length $\times$ thickness), was placed on the mold that was covered with a flexible polyethylene vacuum bag. The resin (unsaturated polyester resin with 1.5% of t-BP) was infused by a vacuum pump (Vacmobile 20/2 System with Becker U4.20) with a pressure of 1.3–1.6 kPa. The vacuum force pulled the resin along the distribution layer into the fiber reinforcement preform. The resin-infused preform was cured at 100 °C for 2 h, and then 150 °C for 2 h, in the hot press with a pressure of 13 MPa. Once the fabricated composite cooled down to room temperature, the vacuum bag and distribution layer were removed.

2.5. Mechanical property tests

From each composite, twelve specimens sized 25 $\times$ 160 $\times$ 3 mm (width $\times$ length $\times$ thickness) were cut by a 9-in Skil benchtop band saw (Robert Bosch Tool Corp., USA), for examining the modulus of elasticity (MOE), modulus of rupture (MOR), and bending elongation at break (BEB) of the composites using the Shimadzu AGS-X universal testing machine in accordance with the procedure described in ASTM D790 standard. Three-point bending set-up was used with a span of 50 mm and a crosshead

speed of 1.3 mm min⁻¹. The tensile modulus (TE), tensile strength (TS), and tensile elongation at break (TEB) of the specimens (twelve replicates) were tested in accordance with the procedures described in ASTM D638 standard by the Shimadzu AGS-X tester with an axial extensometer (Epsilon Technology Corp., USA) with a 50.8 mm (2 inch) gauge length. The specimen dimensions were 19 × 165 × 3 mm (width × length × thickness) and the cross section of the narrow section was 13 × 57 mm (width × length). A crosshead speed of 5 mm min⁻¹ was used.

2.6. Dynamic mechanical analysis

A TA instruments Q800 DMA tester was employed for the dynamic mechanical analysis (DMA). Each specimen sized 1 × 4 × 30 mm (thickness × width × length) was used for the DMA three-point bending tests with a gauge length of 25.4 mm. The temperature from 35 to 200 °C with a ramping speed of 5 °C min⁻¹ was performed, and the frequency of the oscillation was set to be 1 Hz. The storage modulus (E'), loss modulus (E'') and mechanical loss factor (tan δ) were plotted as a function of temperature.

2.7. Water-resistant tests

The composites made with un-treated and magnetite loaded fibers were used to determine their thickness swelling and water absorption. The specimens with a dimension of 25 × 25 × 3 mm (width × length × thickness) were cut using the 9-in Skil benchtop band saw. Five replicates were tested for each composite. Twenty four-hour water submersion tests were carried out in accordance with the ASTM D1037 standard for the determination of the thickness swelling and water absorption.

2.8. Electromagnetic interference shielding tests

The electromagnetic interference shielding effectiveness (EMI SE) measurement with both amplitude and phase properties was carried out using an E8363B PNA Network Analyzer (Agilent Technologies Inc., USA) in a frequency ranging from 8 GHz to 12 GHz, presenting the results of the shielding measurements in decibels (dB). All the specimens were machined to the same dimension (42 × 42 mm) with the corresponding WR90 SMA/F waveguides (Fairview Microwave Inc., USA), which led to the samples exactly fit the size of waveguides. The mode of measurement was a typical transmission measurement (scalar S₂₁ - measurement). The dB value described the level of the incident power or power-flux density decreased after it passed the device during the test. To calculate the dB value from the incident power P₁, respectively, from the arriving electrical field strength E₁ and the transmitted power P₂ or field strength E₂, the following equation was used:

$$SE_{dB} = 10 \log(P_1/P_2) = 20 \log(E_1/E_2) \quad (3)$$

The received dB values were then converted into percentage of EMI SE using the following equation:

$$SE = 1 - 10^{-SE_{dB}/10} \times 100\% \quad (4)$$

2.9. Magnetic tests

Magnetic hysteresis loops of the specimens were determined with a 7410 VSM meter (Lake Shore Cryotronics, Inc., USA) at 300 K in an external magnetic field from -20 to 20 kOe in 100 Oe steps and

an averaging time of 100 ms. The coercivity (H_c), saturation magnetization (M_s), and retentivity (M_r) were also evaluated. The dimensions of specimens for magnetic tests were $3 \times 7 \times 3$ mm (width $\times$ length $\times$ thickness). The specific M_s of the composites was calculated as following:

$$\text{Specific } M_s = M_s \text{Magnetite content} \quad (5)$$

3. Results and Discussion

3.1. Characterization of kenaf fibers

The components of the un-treated **Kenaf**, **Kenaf/magnetite20**, **Kenaf/magnetite30**, and **Kenaf/magnetite40**, are presented in Table 1. The magnetite loading efficiency was calculated according to Eq. (1). The results showed that, with the increase of feeding magnetite from 20 g to 30 g and 40 g, the composition of magnetite was increased from 31.0% to 39.5% and 44.3%, respectively. However, the loading efficiency, calculated by Eq. (2), was slightly reduced from 86.4% to 83.8% and 76.7%, respectively, with the increase of feeding magnetite.

Table 1. Components of un-treated and treated kenaf fibers.

Specimen	Magnetite		Components (wt.%)	
	Feeding (g)	Loading efficiency (%)	Fiber	Magnetite
Kenaf	-	-	100.0	-
Kenaf/magnetite20	20	86.4	69.0	31.0
Kenaf/magnetite30	30	83.8	60.5	39.5
Kenaf/magnetite40	40	76.7	55.7	44.3

The SEM images of the **Kenaf** and **Kenaf/magnetite40** are shown in Fig. 1 for comparison. The magnetite particles on the fiber surface were visible in **Kenaf/magnetite40** (Fig. 1b), compared with un-treated Fiber (Fig. 1a). The particle-size distribution of the magnetite is shown in Fig. 2. The **number-based** (Fig. 2a) and **volume-based** (Fig. 2b) **distributions** of magnetite particle size showed that the magnetite had peaks at 159.7 ± 51.3 nm, and 254.1 ± 180.5 nm, respectively.

Fig. 1. SEM observation of the **Kenaf** (a), **Kenaf/magnetite40** (b).

Fig. 2. Particle-size distribution of magnetite in differential number (a), and differential volume (b).

3.2. Mechanical properties of composites

The physical properties of the composites are summarized in Table 2. The resin content of **Kenaf**/polyester was 33.3%, which was reduced by 20.7 – 25.4% after the magnetite **loaded** fibers were used, and also the fiber content was reduced from 66.7% to 44.1 – 53.2%. The density was increased from 1,159.4 Kg m⁻³ (**Kenaf**/polyester), to 1,473.4 Kg m⁻³ (**Kenaf**/magnetite20/polyester), 1,600.1 Kg m⁻³ (**Kenaf**/magnetite30/polyester), and 1,609.2 Kg m⁻³ (**Kenaf**/magnetite40/polyester), respectively. Since the magnetite has a density between 4.8 to 5.1 g cm⁻³, the densities of the composites increased dramatically after the magnetite particles being introduced.

Table 2. Physical and water-resistant properties of the composites.

Composite	Density (Kg m ⁻³)	Components (wt. %)			24-hour water submission (%)	
		Resin	Fiber	Magnetite	Thickness swelling	Water absorption
Kenaf /polyester	1,159.4 (44.5) ^a	33.3	66.7	-	19.7 (3.8)	18.3 (2.3)
Kenaf /magnetite20/polyester	1,473.4 (61.3)	23.0	53.2	23.9	5.0 (1.4)	4.9 (0.7)
Kenaf /magnetite30/polyester	1,600.1 (42.0)	25.4	45.2	29.5	2.5 (0.6)	2.7 (0.2)
Kenaf /magnetite40/polyester	1,609.2 (79.5)	20.7	44.1	35.2	2.4 (0.3)	2.6 (0.2)

Note: ^a mean (standard deviation)

The results of 3-point bending tests (MOE, MOR and BEB) of the four types of composites are compared in Fig. 3. By adding the magnetite, the composite MOEs were increased by 50.1% (**Kenaf**/magnetite20/polyester composite), 52.9% (**Kenaf**/magnetite30/polyester composite), and 46.6% (**Kenaf**/magnetite40/polyester composite). The MORs of the **Kenaf**/magnetite20/polyester, **Kenaf**/magnetite30/polyester, and **Kenaf**/magnetite40/polyester composites were by 75.3%, 60.6%, and 43.6%, **respective**. In addition, BEBs of the **Kenaf**/magnetite20/polyester, **Kenaf**/magnetite30/polyester,

and **Kenaf**/magnetite40/polyester composites were slightly increased by 29.5%, 13.7%, and 2.5%, respectively. In summary, the addition of magnetite could help improving the anti-flexural properties. In a report [29] of magnetite loaded kenaf fiber reinforced composites fabricated using the traditional hot-pressing method, MOE was decreased from 2,875 MPa to 2,729 – 2,007 MPa after introducing magnetite particles. However, in this work the MOE was significantly increased. It might be contributed to the VARTM process, which could enhance MOE considerably compared with the traditional hot-pressing process [43].

Fig. 3. Modulus of elasticity (a), modulus of rupture (b) and bending elongation at break (c) from the 3-point bending tests of the four composites including **Kenaf**/polyester (A), **Kenaf**/magnetite20/polyester (B), **Kenaf**/magnetite30/polyester (C), and **Kenaf**/magnetite40/polyester (D).

TE, TS, and TEB of the four types of composites are compared in Fig. 4. The TE of **Kenaf**/magnetite20/polyester, **Kenaf**/magnetite30/polyester, and **Kenaf**/magnetite40/polyester composites were **increased by** 37.7%, 18.0%, and 14.7%, respectively, compared with the **Kenaf**/polyester composite of 10.7 ± 1.0 GPa. Although TS of **Kenaf**/magnetite40/polyester composites (24.8 ± 3.0 MPa) were reduced by 44.3%, the other types of composites were comparable with the **Kenaf**/polyester composite (44.5 ± 3.7 MPa). The TEB of **Kenaf**/magnetite20/polyester ($1.48 \pm 0.79\%$), **Kenaf**/magnetite30/polyester ($1.28 \pm 0.42\%$) composites were increased by 30.2% and 12.7%, compared with the **Kenaf**/polyester composite ($1.14 \pm 0.50\%$). The same as TS, the TEB of **Kenaf**/magnetite40/polyester composite ($0.69 \pm 0.11\%$) was decreased by 39.1%. In summary, the tensile properties of **Kenaf**/magnetite20/polyester and **Kenaf**/magnetite30/polyester composites are comparable or exceeded those of the **Kenaf**/polyester composite. However, with highest content of magnetite, the tensile properties of **Kenaf**/magnetite40/polyester composite decreased.

Fig. 4. Tensile modulus (a), tensile strength (b) and tensile elongation at break (c) from the tensile tests of the four composites including **Kenaf**/polyester (A), **Kenaf**/magnetite20/polyester (B), **Kenaf**/magnetite30/polyester (C), and **Kenaf**/magnetite40/polyester (D).

3.3. Dynamic mechanical properties of composites

Storage modulus is an index of resilience that measures the energy storage capability of material after elastic deformation. Fig. 5a shows the E' of the four composites. In general, the E' of the four composites decreased as temperature increased because of the increasing chain mobility of the polymer matrix [44]; the E' of the composites with additional magnetite were much higher than **Kenaf**/polyester composite; and the E' of the composites decreased with the increase of magnetite content. It was similar to the mechanical properties (TE, TS and MOR), indicating that magnetite particles were able to help improving both static and dynamic mechanical properties. It's easy to find the peaks on the E'' and $\tan \delta$ curves for **Kenaf**/polyester composite (Fig. 5b-c), i.e. 108.5 °C for E'' , and 113.4 °C for $\tan \delta$, however, no clear peaks for the composites with additional magnetite were observed. **No unambiguous glass transition temperatures for the magnetite introduced composites were detected from DMA tests (Fig. 5b-c), which might result from the improved interaction between the components of the composites [45,46].** It was indicated that the addition of magnetite reduced the chain mobility of the polyester matrix, so that the mechanical properties were enhanced at high temperatures.

Fig. 5. DMA results of the four composites, including storage modulus (a), loss modulus (b), and damping parameter (c).

3.4. Water-resistant properties of composites

The results from 24-h water submission of the four composites, including thickness swelling and water absorption, are presented in Table 2. Compared with the **Kenaf**/polyester composite (19.7%), the thickness swellings of **Kenaf**/magnetite20/polyester, **Kenaf**/magnetite30/polyester, and **Kenaf**/magnetite40/polyester composites were 5.0%, 2.5%, and 2.4%, which showed reductions of 74.4%, 87.1%, and 87.6%, respectively. The statistical analysis (ANOVA, $\alpha = 0.001$) showed that the reductions in thickness swelling of the magnetite modified **Kenaf**/polyester composites were significant at the level of $\alpha = 0.001$. The same trends were found for the water absorptions, in which the **Kenaf**/magnetite20/polyester (4.9%), **Kenaf**/magnetite30/polyester (2.7%), and **Kenaf**/magnetite40/polyester (2.6%) composites were significantly (ANOVA, $\alpha = 0.001$) decreased by 73.4%, 85.4, and 85.7%, respectively, compared with that of **Kenaf**/polyester composite (18.3%). In the previous report [47], the 24-hour water absorption of the glass-fiber sheet molding compound (SMC) was determined to be 1.1%. Compared to the **Kenaf**/magnetite40/polyester composite with glass-fiber SMC, although the 24-hour water absorption was slightly higher (2.6% vs. 1.1%), the water-resistant property of the **Kenaf**/magnetite40/polyester composite performed excellent, in considering the less hydrophobic resin contents, glass-fiber SMC (20.7%) vs. **Kenaf**/magnetite40/polyester (26.0%), and the mineral contents (35.2% vs. 46.0%) [47].

In summary, the water-resistant properties of the composites were dramatically improved by adding the magnetite. Owing to the hydrogen bonding between magnetite and cellulosic fibers, magnetite adhered to the fiber surfaces and blocked the large amount of hydroxyl groups. The magnetite dramatically reduced the amount of hydroxyl groups on the fiber surface, resulting in better water resistance. The phenomena that deposited particles on the fiber surfaces block the hydroxyl groups resulting an improvement of the water-resistance could also be found when calcium carbonate particles were used [47,48].

3.5. Electromagnetic interference shielding properties of composites

The results of EMI SE at the range of 8–12 GHz for the four types of composites are compared in Fig. 6. The average SEs of the **Kenaf**/polyester, **Kenaf**/magnetite20, **Kenaf**/magnetite30, and **Kenaf**/magnetite40 composites were $41.4 \pm 5.5\%$, $64.4 \pm 7.6\%$, $77.0 \pm 3.9\%$, and $79.2 \pm 3.9\%$, respectively. Compared to the SE of **Kenaf**/polyester composite (41.4%), SE of the composites after using **Kenaf**/magnetite20, **Kenaf**/magnetite30, and **Kenaf**/magnetite40 were increased to be 64.4%, 77.0%, and 79.2%, respectively. In Fig. 6, it was also found that, although the composite SE increased with the magnetite content, it was almost independent of frequency in the measured frequency range. The results showed that, generally, the larger the magnetite content, the higher the value of EMI SE was obtained. However, the increase of EMI SE showed a limitation in Fig.5. When the magnetite content was increased from 29.5% (the **Kenaf**/magnetite30/polyester composite) to 35.2% (the **Kenaf**/magnetite40/polyester composite), the both composites showed the approximately similar EMI SE values.

Fig. 6. Electromagnetic interference shielding effectiveness of the four composites.

3.6. Magnetic properties of composites

Fig. 7 shows the magnetic hysteresis curves of the four composites measured with the VSM meter, and the results of H_c , M_s , and M_r are presented in Table 3. The magnetic hysteresis curves showed that the **Kenaf/magnetite/polyester** composites exhibited a clear hysteretic behavior but not for the **Kenaf/polyester** composite. Regarding H_c and M_r , the **Kenaf/magnetite/polyester** composites showed negligible coercivity and remanence, confirming the superparamagnetic properties [40,49]. The M_s of the **Kenaf/magnetite20/polyester**, **Kenaf/magnetite30/polyester**, and **Kenaf/magnetite40/polyester** composites were 19.3, 25.5, and 29.2 emu g⁻¹, respectively, which showed a gradual enhancement with the increase in magnetite content. However, the values of specific M_s of magnetic composites (81.1, 86.4, and 83.0 emu g⁻¹, respectively) were smaller than that of the bulk magnetite (93 emu g⁻¹) [50]. The reason could be that the composite structure probably affects the magnetic properties of magnetic particles [41].

Fig. 7. Magnetic hysteresis curves of four composites.

Table 3. Coercivity, saturation magnetization, and retentivity of the four composites.

Composite	H_c^a (Oe)	M_r^b (emu g ⁻¹)	M_s^c (emu g ⁻¹)	Specific M_s^d (emu g ⁻¹)
Kenaf/polyester	-	0.0021	0.0191	-
Kenaf/magnetite20/polyester	115.8	3.0	19.3	81.1
Kenaf/magnetite30/polyester	119.5	4.1	25.5	86.4
Kenaf/magnetite40/polyester	112.2	4.8	29.2	83.0

Notes: ^a H_c = coercivity; ^b M_r = retentivity; ^c M_s = saturation magnetization; ^d Specific M_s was calculated in accordance with Eq. (5).

4. Conclusions

Kenaf fiber reinforced polyester composites were successfully fabricated through the VARTM process. The composites were endowed with electromagnetic shielding and paramagnetic properties by introducing magnetite. After introducing 23.9%, 29.5% and 35.2% magnetite into the composites, the electromagnetic shielding, paramagnetic, and water-resistant properties of the composites were significantly improved while the mechanical properties were not compromised **except the tensile property of the composite with the addition of 35.2% magnetite**. The following conclusions were drawn from this study: (1) the electromagnetic interference shielding effectiveness was increased from 41.4% to 64.4%, 77.0% and 79.2%; (2) the saturation magnetization was increased from 0.0191 emu g⁻¹ to 19.3, 25.5 and 29.2 emu g⁻¹; (3) the 24-h thickness swelling was reduced from 19.7% to 5.0%, 2.5% and 2.4%, and the 24-h water absorption was reduced from 18.3% to 4.9%, 2.7% and 2.6%.

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