Composites Science and Technology 108 (2015) 32–40

Contents lists available at ScienceDirect

Composites Science and Technology

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

# Effects of resin inside fiber lumen on the mechanical properties of sisal fiber reinforced composites

Li Yan [a,b,*], Ma Hao [a], Shen Yiou [a], Li Qian [a], Zheng Zhuoyuan [a]

[a] School of Aerospace Engineering and Applied Mechanics, Tongji University, Shanghai 200092, PR China
[b] Key Laboratory of Advanced Civil Engineering Materials, Ministry of Education, Tongji University, Shanghai 200092, PR China

ARTICLE INFO

*Article history:*
Received 14 May 2014
Received in revised form 11 November 2014
Accepted 5 January 2015
Available online 14 January 2015

*Keywords:*
Plant fiber
A. Polymer-matrix composites (PMCs)
B. Mechanical properties
D. Acoustic emission
D. Scanning electronic microscopy (SEM)

ABSTRACT

Sisal fiber reinforced composites with different amounts of resin inside the fiber lumens were prepared. The effects of resin penetration into fiber lumens on the mechanical and water-absorption properties of the composites were studied. Acoustic emission (AE) was used to characterize the fracture mechanisms of the composites by analyzing the different AE signals released during the failure process of the composites. Tensile, flexural and impact strength were all improved with the increasing of the amount of resin inside the fiber lumens due to the changes of the fracture modes. No significant effects on the tensile and flexural modulus were observed. The water absorption resistance of the composites could be improved when fiber lumens were filled with resin. The micro-failure morphologies of the composites possessing different amounts of resin inside the lumens were revealed with the aid of scanning electronic microscopy (SEM). It was found that the resin inside the lumens of the fibers strengthened the bonding between the micro fibrils within a single sisal fiber. Meanwhile, crack bridging effect of the penetrated resin could hinder the crack propagation to ensure fibers reaching their failure strain as much as possible.



## 1. Introduction

Life cycle assessment has shown that plant fibers reinforced composites (PFRC) possess superior environmental performance compared to the composites reinforced with glass fibers [1]. The promising mechanical properties of plant fibers have been investigated by many researchers [2–5]. Taking the low density of plant fibers into consideration, the mechanical performance seems more impressive. Low price and abundant availability of plant fibers further promote the world's interest in replacing synthetic fibers in some applications, especially in the transportation industry [6].

Unlike the synthetic fibers, which are uniform and homogeneous, plant fibers possess complex multi-layered cell wall and lumen structures [7]. Their cell walls are reinforced with spirally oriented cellulose in a hemi-cellulose and lignin matrix. Meanwhile, technical plant fiber itself is also a composite structure with elementary fibers bonded by pectin matrix [6]. Therefore, plant fibers and their reinforced composites always fail in a complex way because of their particular multi-scale structures, which have been proved by some previous works [8–11]. Bos and Donald [8] found that the primary and the secondary cell wall of flax fiber showed a different tensile deformation behavior. The primary cell wall failed in a brittle manner, while in secondary cell wall, a coarse crack grew, bridged by micro fibrils. Dai and Fan [9] also reported that the crack initiated in a weak point of primary wall and subsequently propagated along radial direction from S1 to S2 layers in the secondary wall of hemp fiber. Furthermore, Newman et al. [10] suggested that, during the tensile test of phormium leaf fiber reinforced composites, the cellulose micro fibrils would be torn out from the cell walls and cell–cell debonding was abundant on fracture surfaces. Singleton et al. [11] reported that the technical flax fibers would split into individual elementary fibers during the Charpy impact test of flax fiber reinforced HDPE composites.

However, a limited number of studies have been conducted on the effect of fiber lumen structure on the composite performances. Actually, lumens account for significant proportion in plant fibers [3–5], especially in sisal fibers, as high as 25.2% reported by Fidelis et al. [5]. In previous study, hollow lumens were found to be beneficial to sound absorption and thermal resistance properties. Liu et al. [12] found that lumens played an effective role on thermal resistance in hemp fiber reinforced composites. The multi-scale and hollow lumen structures of plant fibers contribute to superior sound absorption performance of their reinforced composites [13]. In addition, Li et al. [14] reported that the fiber lumens can partly

* Corresponding author at: School of Aerospace Engineering and Applied Mechanics, Tongji University, 1239 Siping Road, Shanghai 200092, China. Tel.: +86 021 65985919; fax: +86 021 65983950.

*E-mail address:* liyan@tongji.edu.cn (Y. Li).

http://dx.doi.org/10.1016/j.compscitech.2015.01.003
0266-3538/

function as water transportation organ during the plants growth which means the low-viscosity resin can also penetrate into plant fiber lumens during the composite fabrication process. This phenomenon has been observed by Newman et al. [10] and Hepworth et al. [15]. Penetration of resin into fiber lumens will partly change the micro-structures of plant fibers, which would also lead to different failure modes of the composites. The effect of resin penetration into fiber lumens was reported by Hepworth et al. [15]. They found that resin penetration into the lumens of flax fibers could largely improve the tensile modulus of the composite, which was approximately 30% enhancement, whereas rarely affected the strength of the composite. They suggested that the resin penetration inside fiber lumens can lock the cell wall structures and increase the co-operations between fibers within a bundle, which can lead to an improvement in the stiffness of composites [15].

Therefore, fully understanding the mechanisms of the effects of resin inside plant fiber lumens exhibits a direct influence on mechanical performance, selection and optimizing the fabrication process of plant fiber reinforced composites. In this work, composites with different amount of resin inside sisal fiber lumens were fabricated. The mechanical properties, such as tensile, flexural and impact properties, and water absorption properties of the composite laminates were studied. Field-emission SEM was used to characterize the fracture surface. The crack propagation mechanisms of the composites were revealed by acoustic emission.

## 2. Experimental

### 2.1. Materials

Sisal fibers were obtained from Guangxi Province, China. The diameter of sisal fiber was 225.41 ± 35.20 μm. The tensile strength and modulus of sisal fibers were 411.73 ± 99.76 MPa and 29.64 ± 11.58 GPa, respectively, which was tested according to ASTM D3379-75. The density of sisal fiber was 1.45 g/cm$^3$. The bisphenol-A-based epoxy resin was provided by Nanya, Taiwan. The anhydride-based curing agent and tertiary amine-based accelerating agent were obtained from Zhongsi Industry Company in Shanghai, China. The resin system was made by mixing epoxy with 26% anhydride hardener and 8% accelerator by weight, and density of the resin system was 1.2 g/cm$^3$. The viscosity of the resin could be regarded as a constant value which was 0.26 Pa·s during the resin injection process (less than 1 h) as instructed by the measurement results with Rotational rheometer (Hakke MARS III, Thermo Fisher Scientific Company, Germany).

### 2.2. Fabrication of composite laminates

Firstly, the cluster sisal fibers were washed and straightened in water, then dried in an oven at 105 °C for 2 h. The well-arrayed, hackled fibers were chopped to desired length for making unidirectional fabrics by sewing method as shown in Fig. 1a. The sisal fibers were first sewed on one paper (Fig. 1b), and then the paper was tore off to get the unidirectional sisal fabrics. The composite laminates were fabricated by resin transfer molding (RTM). Two different resin injection methods were used in order to control the amount of resin penetrating into the lumens of sisal fibers, as shown in Fig. 2. The resin injection directions were along (0°) and vertical (90°) to the fibers, respectively. The hollow microstructure of sisal elementary fibers (Fig. 2) could be presented as porous channels for resin penetration if the resin was injected along the fiber direction. Based on the preliminary study, 0.1 MPa and 0.3 MPa were regarded as the optimal minimum and maximum 0° injection pressure and used to make the composites. As for 90° injection, the inlet pressure was selected as 0.3 MPa. The sealing strips were used to prevent the edge flow during the mold filling process. Moreover, the lumen openings of sisal fibers were blocked by sealing strips during 90° injection, as shown in Fig. 2. The same weight of sisal fibers were laid into a steel mold with dimensions of 300 mm × 150 mm × 3 mm to ensure a fixed fiber volume fraction. The resulting three types of composites were named as VIFC0.3 (vertical injection fabricated composites with pressure of 0.3 MPa), AIFC0.3 and AIFC0.1 (axial injection fabricated composites with injection pressures of 0.3 and 0.1 MPa, respectively).

### 2.3. Characterization

Tensile properties of the composites were measured based on ASTM D3039, with a crosshead speed of 2 mm/min. Three point bending test was conducted according to ASTM D790. The nominal dimensions of the tensile and flexural specimens were 180 mm × 15 mm × 3 mm and 60 mm × 12.7 mm × 3 mm, respectively. Both tensile and flexural tests were carried out on a universal mechanical testing machine, Wance (Shenzhen China). Charpy impact tests were carried out using Instron CEAST9350. The dimension of the specimens was 68 mm × 10 mm × 3 mm with a 60 mm span according to ISO 179-1, and the capacity of the impact energy was 20 J. The water absorption properties of the composites were investigated in accordance with ASTM D570. The nominal dimension is 50 mm × 50 mm × 3 mm. At least five specimens were measured for each test. The microstructures of the fibers and the failure modes of the composites were observed using a SEM (PHILIPS XL30 FEG).

Acoustic emission monitoring was applied by using a SAEU2S system supplied by Soundwel Technology CO. LTD (Beijing, China). AE measurements were performed using single SR150M sensor with a resonant frequency range of 60–400 kHz. The Preamplifier (40 dB) having a bandwidth of 10 kHz to 2 MHz was used. The threshold was set as 40 dB in order to exclude the majority signals of background noises.

## 3. Results and discussions

### 3.1. Morphologies of sisal fibers and sisal fiber reinforced composites

Fig. 3a illustrated the microscopic photo of part of the cross-section of a sisal fiber obtained from VIFC0.3 composite, which was brittle fractured right after the specimen was immersed in liquid nitrogen for 15 min. A technical sisal fiber showed a horse-shoe shaped cross-section, and both clusters of fiber cells and lumen structures can be observed in each sisal fiber. The lumen ratio inside each fiber can be calculated by reversing the gray-level of each SEM images in Matlab software. The calculation processes were shown in Fig. 3. The regions with low gray-scale in Fig. 3b represented the lumen areas. The lumen ratio could be obtained by dividing the lumen areas by the corresponding area of a technical sisal fiber which were calculated by MiVnt software from Shanghai Optical Instrument Factory (China). The average statistical lumen ratio of selected 30 sisal fibers was 27.16 ± 9.87%. The distributions of lumen diameters (300 fiber cells in 30 different fibers involved) of sisal fibers were shown in Fig. 4, and the average value was 10.08 ± 4.61 μm. The relatively high deviations of lumen ratio and diameter were caused by the diversity of sisal fiber cells, such as mechanical, ribbon and xylem fibers [16]. Table 1 showed that sisal fibers possessed much bigger lumen size and fraction compared to those of other plant fibers, which meant the resin penetration process in sisal fibers would be much easier.