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Acoustical properties of Lyocell, hemp, and flax composites

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Abstract

This study characterizes the acoustical behavior of natural fiber composites. Regenerated cellulose fibers (Lyocell), hemp fibers, and flax fibers were embedded in an epoxy-matrix. These unidirectional composites were tested for their logarithmic damping decrement, the resonance frequency, the ultrasound velocity, the dynamic and static modulus of elasticity, and bending strength and density. Glass-epoxy composites served as a reference. All tested cellulosic fibers showed a significantly higher damping at lower densities. The ultrasound velocity was in the range of the reference for Lyocell– and hemp–fiber composites. Taking the low density into account, the dynamic and static modulus of elasticity of the samples were relatively high compared to the glass reference. The specific acoustical properties of these natural fiber composites point at high value applications, e.g., devices that require high damping of the body structures.

Keywords

natural fibers, Lyocell, acoustical properties, dynamic modulus of elasticity, logarithmic damping decrement, ultrasound velocity

Introduction

Fiber-reinforced plastics (FRP) were developed in the 1950s to improve the stiffness of monolithic plastics and to serve as lightweight, non-corrosive substitutes for metals with a high specific strength and modulus.[1–3] These 'advanced' plastic composites are used in the aerospace industry and to manufacture automotive parts, building materials, and recently in special sporting equipment and entertainment devices. In 95% of the cases glass fibers are used as reinforcing agents in FRPs.[3,4] Due to the difficulties in the recycling and re-use of these glass fiber composites[5] and motivated by European regulations on composite waste management such as 'End-of-life vehicles regulation (ELV)' and 'European Composite Recycling Concept', new composites called biocomposites appeared in the late 1980s in which glass fibers were replaced by renewable natural fibers.[4,6]

The advantages of natural fibers such as flax, hemp, ramie, and others are low density, low cost, ease of processing, enhanced energy recovery, 'CO_2 neutrality,' and biodegradability.[7–11]

However, natural fibers also have a number of disadvantages with respect to their uses in composites.[8,12–14] The most important disadvantage is the considerable variation in their mechanical properties.

The micromechanics of natural and regenerated cellulose fibers as well as their composites have not been fully studied by now, but some studies contribute to that field.[15–17] The mechanisms of adhesion between

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cellulose fibers and polymer matrices have also not been reported in detail yet.[18,19] With the aim of assessing their suitability for polymer reinforcement these fibers were subjected to single fiber tensile testing[14] to determine strength, stiffness, and elongation. In addition the fibre–matrix adhesion and the mechanical behavior of a cellulose fiber–epoxy composite system were investigated.[20]

This study characterizes the unidirectional epoxy composites with different kinds of fibers (Lyocell, hemp, flax, glass) in terms of vibrational behavior (damping, resonance frequency, sound velocity) as well as mechanical properties (modulus of elasticity, strength).

The aim of this study was to characterize the acoustical behavior of cellulose fiber composites in order to derive possible fields of application.

Materials

Fibers

Four different kinds of fibers were used as reinforcing agents in the composites. Lyocell filament fibers (Lenzing AG, Austria), 10.5 µm in diameter represented the regenerated cellulosic fibers. Hemp fibers 10–40 µm in diameter (Hanf-Faser-Fabrik, Uckermark, Germany), and flax rovings (Holstein Flachs GmbH, Mielsdorf, Germany) stood for the group of renewable natural cellulose fibers within this project. E-Glass (14 µm) served as a reference fiber.

Matrix

A two-component epoxy matrix (resin LF, hardener LF1 1101001) with a pot life of 40 min was used in combination with an active diluent (EPD BD), which was obtained from R&G Faserverbundwerkstoffe GmbH, Waldenbuch, Germany.

Composites

Unidirectional composites (UD) were produced using a special steel mold allowing for a straight and parallel alignment as well as an even distribution of fibers within the composite before pressing. Priming wax and film release agent PVA were applied on the steel molds. The fiber bundle rovings were placed in the mold and the ends were fixed to align the fibers straight. The epoxy resin and the hardener were mixed in a ratio of 100 : 40. To decrease the resin viscosity, 5% (volume) diluent was added and the whole mixture was preheated to 50°C. Fiber rovings were slowly impregnated with the resin. Parallel metal disk rollers were used for de-airing and to compact the roving. The composites were pressed at 80°C and 18 bar pressure for 2 h. Final composite dimensions were $300 \times 20 \times 2\,mm^3$ with 67% fiber content by weight. A total of 53 samples were investigated (Lyocell $n = 32$, hemp $n = 4$, flax $n = 6$, glass $n = 11$).

Methods

Density

The density of the composite materials was determined gravimetrically.

Mechanical testing

Three-point bending tests according to the DIN 53 186 standard[21] were performed on a universal testing machine (Zwick/Roell Z100). Stress was measured with a resolution of 0.167 N, whereas strain was measured using a macro sensor with a resolution of 1.5 µm. Strength (MOR) and modulus of elasticity (MOE) were determined for each sample. The MOE was additionally calculated from the sound velocity measurements applying Equation (1) and from the resonance frequency of the first mode using Equation (2):[22]

$$E = v^2 \cdot \rho \quad (N/mm^2), \tag{1}$$

where v is the sound velocity (m/s), E, the modulus of elasticity (N/mm^2), and ρ, the density (g/cm^3).

$$E_{dyn} = (4\pi^2 \cdot L^4 \cdot f_n^2 \cdot \rho)/(m_n^4 \cdot k^2), \tag{2}$$

where E_{dyn} is the dynamic Young's modulus (N/m^2), L, the freely oscillating length (m), f_n, the resonance frequency of mode n (Hz), ρ, the density (kg/m^3), m_n, the constant, determined by certain end conditions and the mode of vibration. For example, first mode, one free end one fixed end $m_n = 1.875$ (–), $k^2 = b^2/12$ where b (m) is the depth of the rod in the plane of bending (m^2).

Acoustics

Sound velocity

The sound velocity was measured at 54 kHz in the longitudinal direction. The transit time was determined by means of an ultrasonic tester (PUNDIT – C.N.S. Electronics Ltd., London, UK) with a resolution of 0.1 µs. The transmitter was attached with a constant pressure on all samples. No contact medium was used to transmit sound waves from the transmitter to the specimens. The sound velocity was calculated according to Equation (3):

$$v = l \cdot t^{-1}, \tag{3}$$

where v is the sound velocity (m/s), l, the specimen length, path length (m), and t, the transit time of ultrasound (s).

Logarithmic decrement (damping)

The logarithmic decrement (related closely to the loss tangent) was determined according to DIN EN ISO 6721-1 and DIN EN ISO 6721-3.[23,24] The specimens (UD) were clamped at one end (Figure 1). The remaining free end was deflected to a defined position. After the release of the flexed end a laser device (M7L/2 sensor, MEL Mikroelektronik GmbH) picked up the amplitude of the damped vibration over time.[25] The logged amplitude–time signal was used to calculate the logarithmic decrement by applying Equation (4):

$$\Lambda = \ln(X_q \cdot X_{q+1}^{-1}), \tag{4}$$

where Λ is the logarithmic decrement (–), X_q, the amplitude q, and X_{q+1}, the amplitude $q+1$ (directly following X_q).

The logarithmic decrement was averaged over 15 oscillations starting at a certain amplitude to avoid the noise in the initial phase of vibration. Note that the relationship between the logarithmic decrement and the loss tangent is $\Lambda = 2\pi \tan \delta/2$.[26]

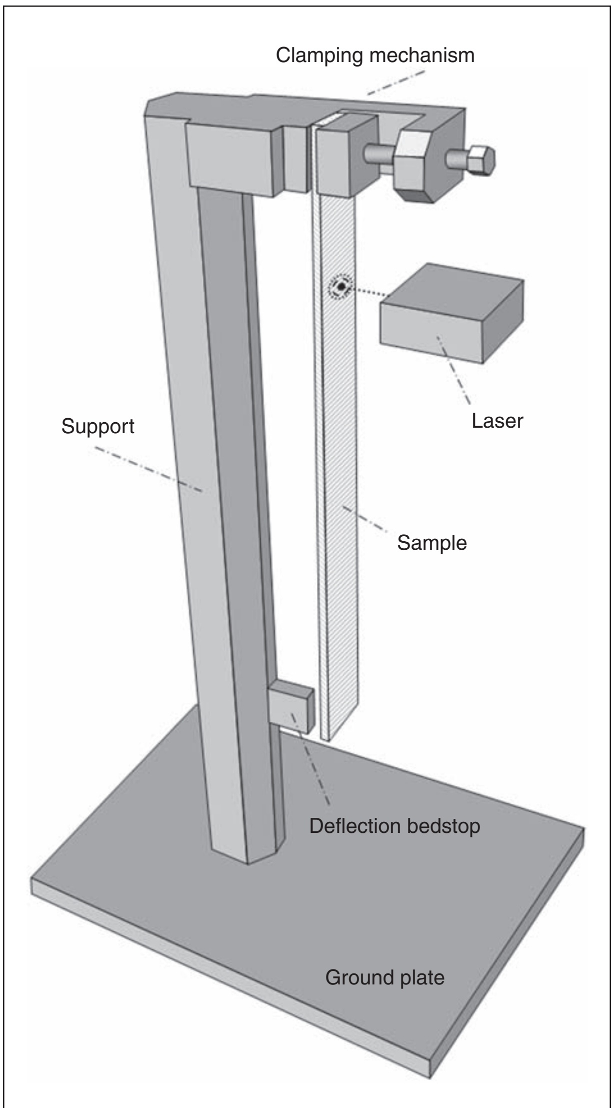

Figure 1. Experimental setup for the measurement of the logarithmic damping decrement and the resonance frequencies.

Resonance frequency

The resonance frequency (first bending mode) was derived from Fourier transformation of the amplitude–time signal. The resonance frequency was computed by a standard computer program (Diadem) using the signal from the test set-up described for derivation of logarithmic decrement.

Results and discussion

Mean values and standard deviation of the density and modulus of rupture are shown in Table 1 for all tested composite types. The acoustical properties and the modulus of elasticity are illustrated in Figures 2–5.

The density of the natural fiber composites (mean: hemp 1.24 g/cm^3, flax 1.10 g/cm^3; standard

Table 1. Mean values and standard deviations of density (g/cm^{3}m) and modulus of rupture (MPa) of the Lyocell–, hemp–, flax–, and glass–epoxy composites

Parameter	Arithmetic mean	Standard deviation
Density (g/cm^3)		
Lyocell	1.27	0.023
Hemp	1.24	0.009
Flax	1.10	0.028
Glass	1.69	0.096
Modulus of rupture bending (MPa)		
Lyocell	197.6	15.03
Hemp	221.8	21.75
Flax	144.5	17.20
Glass	835.2	149.48

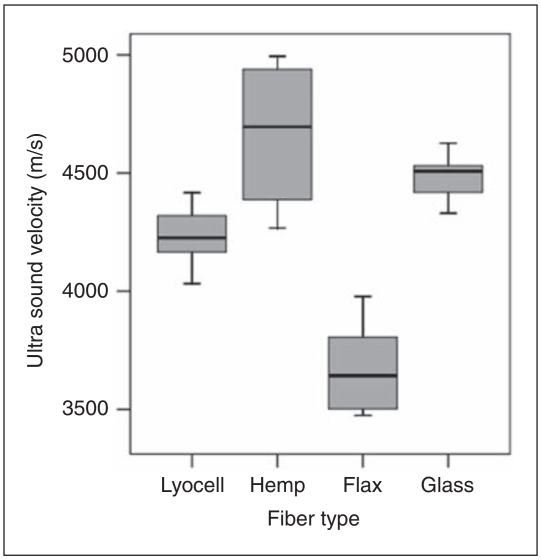

Figure 2. Ultrasound velocity (m/s) for Lyocell–, hemp–, flax– and glass–epoxy composites measured at 54 kHz.

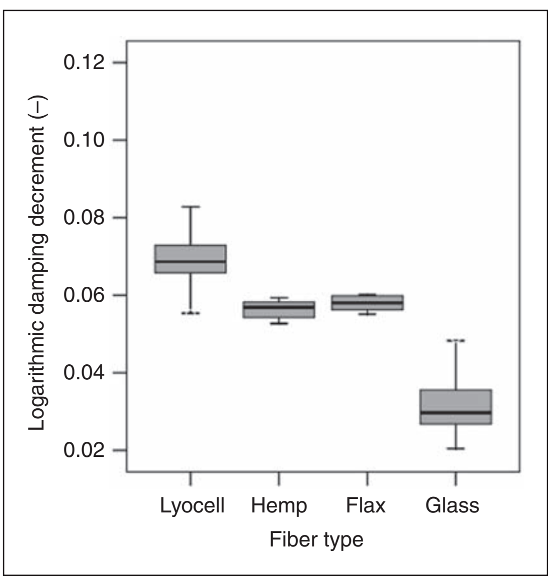

Figure 3. Logarithmic damping decrement (–) of the Lyocell–, hemp–, flax–, and glass–epoxy composites.

deviation: hemp 0.009 g/cm^3, flax 0.028 g/cm^3) as well as the density of the Lyocell composites (mean: 1.27 g/cm^3; standard deviation: 0.023 g/cm^3) was significantly lower than the density of the glass–epoxy composites (mean: 1.69 g/cm^3; standard deviation: 0.096 g/cm^3). This density offset can also partly explain the four times higher modulus of rupture for the glass–epoxy-composites. The deficiencies in mechanical performance can be partly ascribed to the fact, that the high mechanical properties often quoted for these materials are not representative for longer fiber bundles used in the manufacturing of composite materials.[27] The

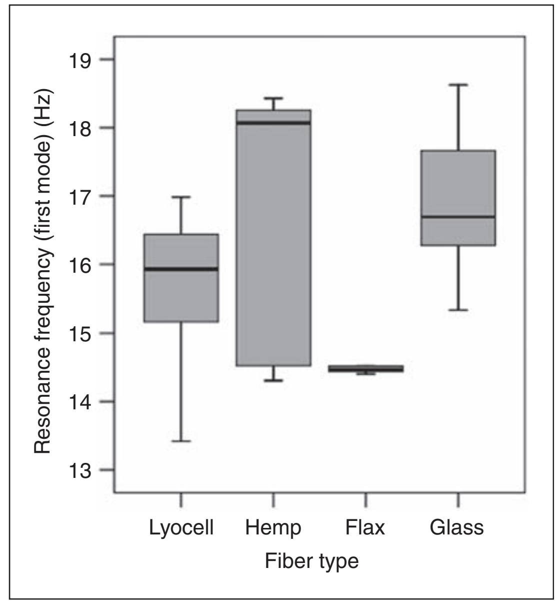

Figure 4. Resonance frequency (first mode) (Hz) of the Lyocell–, hemp–, flax–, and glass–epoxy composites.

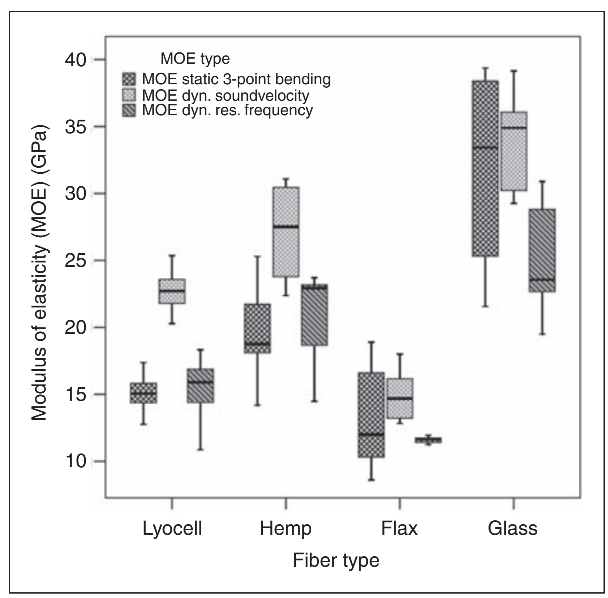

Figure 5. Modulus of elasticity (GPa) of the Lyocell–, hemp–, flax–, and glass–epoxy composites determined by the three-point bending test, sound velocity, and resonance frequency.

difference between Lyocell, hemp, and flax to the reference glass–epoxy composite is less distinct for the MOE. The dynamic MOE shows higher values than the ones determined by the three-point bending tests and resonance frequency. This pattern can be observed through all tested kinds of composites (Figure 5). Ultrasound velocity is around 4500 m/s for Lyocell, hemp and glass composites (mean: Lyocell 4218 m/s, hemp 4663 m/s, glass 4481 m/s; standard deviation: Lyocell 130 m/s, hemp 336 m/s, glass 101 m/s), whereas flax shows significantly lower values (mean: 3674 m/s; standard deviation 200 m/s). The resonance frequency of flax shows little variation (mean: 14.78 Hz; standard deviation: 0.98 Hz). The values for the tested hemp–epoxy composite specimens show a stronger variation (mean: 16.58 Hz; standard deviation: 1.94 Hz) (Figure 4).

A material property that clearly distinguishes regenerated and natural fibers from glass as a reinforcement fiber in composites is the logarithmic damping decrement (mean: Lyocell 0.0708, hemp 0.0558, flax 0.0595; standard deviation: Lyocell 0.0109, hemp 0.0032, flax 0.0048), which is significantly lower in glass–epoxy composites (mean: 0.0317; standard deviation: 0.0070) (Figure 3).

Conclusion

High damping capacities of regenerated cellulose fiber or natural fiber reinforced composites at a good stiffness to density ratio point to high value applications of these materials. The logarithmic damping decrement is exceptionally high for the Lyocell–epoxy composite system, which leads to specific properties in comparison to glass–epoxy composites. The natural fiber composites tested in this study not only show common trends for damping, bending strength, and density, but also show significant differences in parameters such as ultrasound velocity. Flax had relatively low ultrasound velocities, while hemp exceeded the level of the glass reference composites.

Besides all kinds of environmental aspects these properties can be favorable for applications such as bodies of devices requiring a high damping of vibrations or damping structures in leisure-time or professional gear. Regenerated fibers such as Lyocell inherit the additional advantage of low variation in material properties, which makes them more competitive to glass fiber in the manufacture of composite materials. In any case natural fiber composites can contribute to the reduction of glass FRP with poor recyclability.[28]

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