C. R. Chimie xxx (2018) 1–10

Contents lists available at ScienceDirect

Comptes Rendus Chimie

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Account/Revue

Extraction and refinement of agricultural plant fibers for composites manufacturing

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ARTICLE INFO

Article history:
Received 25 May 2018
Accepted 5 July 2018
Available online xxxx

Keywords:
Plant fibers
Composite
Mechanical properties
Fiber–matrix interface
Compatibilization
Chemical modification
Surface treatments

ABSTRACT

Because of their excellent tensile properties, low density, and natural abundance, cellulose-based plant fibers are a sustainable and biodegradable alternative for synthetic fibers in fiber-reinforced composite materials. However, the extraction of plant fibers can be costly and difficult to control because the fibers are enmeshed in a complex network of biopolymers (principally lignin, pectin, and hemicellulose), which serve both to strengthen the fibers and to bind them to their parent organism. It is necessary to extract or degrade these biopolymers to produce fine plant fibers without adversely altering the fibers themselves in the process. In particular, it is important that both the molecular weight and the degree of crystallinity of the cellulose in the fibers be kept as high as possible. This article reviews chemical treatments, which have been used to extract and refine fibers both from purpose-grown fiber crops, such as hemp and flax, and agricultural waste such as coconut husks and pineapple leaves. The treatments are discussed in terms of changes in the mechanical properties and surface chemistry of the fibers.

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1. Introduction

Plant fibers are a biodegradable and sustainable substitute for synthetic fibers. They have relatively low density, are abundant in nature, and their tensile properties are comparable to those of glass and carbon fiber. Reviews have already been published on the use of plant fibers as reinforcement in concrete [1,2] and in polymer matrices [3–5]. There have also been considerable studies on the cultivation and cellular structure of plant fibers [6–11].

Virgin plant fibers have several shortcomings which adversely affect their performance in many value-added applications (e.g., in composite materials). Because they are hydrophilic, the fibers do not adhere well to common polymer resins. Their capacity for moisture retention can also lead to void spaces being formed at the fiber–matrix interface. The fibers also swell when wet, which can result in internal stresses developing in materials which contain the fibers. Natural fibers can also be difficult to refine because of the pectin- and lignin-rich gum which binds clusters of fibers together. If this gum is not removed, it can be difficult to disperse individual fibers during compounding.

A wide array of treatments has already been applied to plant fibers to make them suitable for use in a variety of roles, most notably in the production of paper [12–14], textiles [15,16], and high-voltage insulation [17]. Treatment of plant fibers to improve their performance in composites is a subject which has received relatively poor attention. Moreover, the body of academic literature on plant fibers contains relatively little discussion of how the performance of composite materials is affected by a given fiber treatment. This review presents the effects of chemical and enzymatic refining processes on the cellular structure and composition of plant fibers in the context of their use in composite materials.

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https://doi.org/10.1016/j.crci.2018.07.001
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Please cite this article in press as: G. Bousfield, et al., Extraction and refinement of agricultural plant fibers for composites manufacturing, Comptes Rendus Chimie (2018), https://doi.org/10.1016/j.crci.2018.07.001

2. Plant fiber–reinforced composites

2.1. Plant fibers as substitute for glass fiber

Fiber-reinforced composites (referred to here as FRCs) contain rigid fibers, which are responsible for the tensile strength of the material, contained in a polymer matrix which can easily be molded to a desired shape and transfers stresses to the embedded fibers. The fibers must be very stiff, so they are typically made from a material with high elastic modulus and tensile strength. Table 1 compares the tensile strength, modulus, and density of some commonly used fiber reinforcements with other common building materials for reference. The polymer matrix which coats the fibers tends to be significantly weaker but protects the fibers from wear and degradation and distributes load evenly across the array of fibers.

2.2. Fiber–matrix interaction

The performance of FRCs also depends on strong fiber–matrix adhesion [22]. If adhesion is poor, then the fibers will be more likely to aggregate during compounding rather than dispersing in the matrix. Void spaces are also more likely to form at the fiber–matrix interface. Both of these phenomena result in reduced surface contact, and therefore less efficient stress transfer, between fiber and matrix. This is a considerable problem for plant fibers because their hydrophilic surface chemistry is incompatible with many commodity polymers [22].

Several review articles describe thus 'pretreatments' for plant fibers to improve their interaction with polymer matrices [23–25]. The effects of compounding on the morphology of composites have also been reviewed [26]. There are also reviews of composites with specific plant species, including bamboo [27], kenaf [28], and flax [29].

2.3. Moisture retention

Because they are hydrophobic, plant fibers absorb a significant amount of moisture. For instance, hemp fibers have been shown to retain more than 40% of their dry volume in water [30]. If fibers are not suitably dried prior to compounding, the moisture can form a barrier between fiber and matrix, thereby preventing effective adhesion between the two phases. Water droplets can also cause void spaces to form within the polymer which weaken the resulting material [31]. Composites produced with improperly dried fibers also have lower tensile strength and elastic modulus [32]. Fiber-reinforced composites are also sensitive to moisture after compounding; a flax–polyester composite which was stored in a humid environment had a lower elastic modulus and tensile strength, even after being dried [31].

Table 1
Tensile strength, modulus, and density of selected fibers [18–21].

Fiber	Elastic modulus (GPa)	Tensile strength (MPa)	Density (g/ml)
E glass	73	2400	2.55
Kevlar 29	70.5	2920	1.44
1080 Steel	207	2550	7.9
Nylon 66	3.5	85	1.14
Hemp	70	550–900	1.48
Flax	60–80	800–1500	1.4
Sisal	38	600–700	1.33

2.4. Improving the performance of plant fibers

To summarize, plant fibers could be used in FRCs as a sustainable and biodegradable substitute for glass fibers. They can be harvested at low cost and have suitable mechanical properties for this application. However, their poor adhesion with conventional bulk polymers is a substantial barrier to their use in the manufacture of composite materials. The surface chemistry of the fibers can also cause them to absorb large quantities of water, which can be detrimental to FRC behavior.

To more effectively prepare plant fibers for use in FRCs, a process is needed which produces plant fibers of high aspect ratio with hydrophobic surface chemistry, without degrading the desirable tensile properties of the material. To understand how the fibers behave in response to proposed treatments, it is necessary to examine the structure and composition of the fibers.

3. Physicochemical and morphological characteristics of plant fibers

3.1. The structural approach

Apart from cotton, all intensively cultivated plant fibers are structural fibers from either the leaves of monocot plants, such as sisal or abaca, or from the bast of dicot plant stems. Hemp and flax, the principal textile fibers in Northern Europe, are bast fibers. In both cases, these structural fibers have a role in the plant which is analogous to that of the skeleton in vertebrates. The fibers are an aggregate of many long, thin, rigid cells called sclerenchyma cells, also called 'ultimate fibers' or 'elementary fibers'. Once they reach their final dimensions, mature sclerenchyma cells develop a thick, cellulose-rich secondary wall that greatly augments the mechanical properties of the fibers. Soon after the secondary wall is complete, the cell dies. Inside the secondary cell wall, the space formerly occupied by the cytoplasm becomes a hollow center cavity called the lumen. This hollow cavity reduces the overall density of the fibers and increases their capacity for water retention. The secondary wall is itself divided into three layers, denoted S_1, S_2, and S_3, with 'S' standing for secondary and the subscript referring to the order in which the layers develop [33], so that S_1 refers to the outermost layer and S_3 the innermost. S_2 makes up the majority of the thickness of the cell wall, contains more cellulose than the other two sublayers, and is structurally the most important segment of the cell wall.

Each layer of the cell wall contains an array of thin strands of semicrystalline cellulose called fibrils. The fibrils are coated with an amorphous layer of hemicellulose and pectin. This layer serves both to prevent the fibrils from aggregating and to connect cellulose to the complex web of

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