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# Hybridized carbon and flax fiber composites for tailored performance

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ABSTRACT

Flax fiber composites have been found to exhibit suitable mechanical properties for general applications. Natural fibers exhibit lower mechanical properties than their synthetic counterparts as well as have a high degree of fiber to fiber mechanical variability based on growing conditions and plant varieties which lowers their mechanical performance predictability. However, Thermoset resins reinforced with flax fibers exhibit nonlinear behavior when subjected to loading which results in energy loss. This is beneficial in applications where vibration damping is anticipated. One potential method for increasing performance and strength of flax fiber is to hybridize it with synthetic fibers with the goal of improving composite mechanical properties as well as reducing composite to composite mechanical variability. In this study carbon fiber and flax fiber were used to manufacture different hybridized composites with varying flax fiber volume fractions. Resulting composites were characterized using tensile, flexural, impact and vibration tests. Also, results of experiments were compared against predictions of rule of mixture's model and Halpin-Tsai model. Findings of this study provides valuable information for designers for hybridizing flax and carbon fibers and results suggest that hybridizing synthetic fibers with natural fibers is an effective method of improving the mechanical properties and controlling vibration damping.



## 1. Introduction

### 1.1. Overview of hybridized composites

Composite materials are continually becoming a more attractive choice of material in various industrial applications as a result of their high strength-to-weight and high stiffness-to-weight ratios. However, natural fibers, when compared to their synthetic or mineral-based counterparts, generally have lower mechanical properties. These low mechanical properties are a major inhibitor when trying to develop high-performance products. One method for increasing their level of mechanical performance is to hybridize natural fibers with synthetic fibers or mineral-based fibers. The benefit of using hybrid composites is that the advantages of one type of fiber can overcome the disadvantages of the other type of fiber. As a result, a balance in cost, performance, and sustainability could be achieved through proper composite material design.

When discussing hybrid composites, the hybrid effect is often mentioned. The hybrid effect is used to describe the changes in properties of a composite containing two or more types of fibers, which can either be a positive or negative deviation of a certain mechanical property [1]. The hybrid effect is an important design consideration when determining the desired characteristics of the final composite product.

Hybridizing is commonly referred to as the combining of natural fibers with glass fibers [2–4]. Nonetheless, hybridizing can also be performed by combining different synthetic fibers together or by combining different natural fibers together. Several researchers have looked into the combining of different types of natural fibers to form hybridized natural fiber composites [5,6]. Both studies found a positive hybrid effect in mechanical properties by the addition of a stronger or longer fiber to the composite, gains in tensile modulus such as a 48% improvement with a 50 wt.% inclusion of sisal fibers to banana fibers [5] also a 10% improvement with a 20% inclusion of kenaf fibers to wood flour [6].

The focus of this research is the hybridizing of carbon fiber with flax fibers. Thermoset resins reinforced with flax fibers exhibit nonlinear behavior when subjected to loading [7,8]. This nonlinear response results in energy loss [8,9]. This is beneficial in design of sports equipment where vibration damping is anticipated [8]. The hybridization of flax and carbon fiber offers good potential for developing high stiffness composites for various structural and sports applications while simultaneously incorporating bio-based materials. Investigating optimum ratio of flax/carbon fibers to achieve a desired performance can help other researchers and industrial designers to target certain properties and achieve desired performance. To cite some examples, Museeuw Bikes can be mentioned. Flemish Bicycle Company, Museeuw incorporates flax fiber (Flaxpreg® 2.0) with carbon fibers in their professional bike frames. They use the vibration absorption advantage of flax fibers for the comfort of their users.

Origine, is another company (Canadian) that uses flax fiber in their tennis racquets both to enhance the performance and comfort. Their

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products are known as eco-friendly as well as elbow-friendly. Ratio of flax fiber in mentioned racquets is 15% by volume. This ratio guarantees both great performance and comfort [10].

### 1.2. Natural fibers

Whereas natural fibers offer many advantages, they also are accompanied by several drawbacks which must be considered when being incorporated into composite designs. Several drawbacks to using natural fibers are their high moisture absorption, inferior fire resistance, and low mechanical properties. Natural fibers are also susceptible to high mechanical property variation as a result of varied growing climates and harvesting conditions [11,12]. They also exhibit poor adhesion to various matrices [13,14].

When using natural fibers it is important to understand that unlike synthetic or mineral-based fibers, natural fibers exhibit nonlinear elastic tensile behavior. The nonlinear elastic behavior is the result of the natural fiber's structure. The multiple layers (primary and secondary walls) that make up the natural fiber's structure cause the viscoelastic behavior [16]. The structure of a single bast fiber and cross section of flax fiber can be seen in Fig. 1. In a single fiber, there are several different layers that make up the fiber's structure which are the primary wall, secondary wall, and the center lumen from outside to inside [17]. The different layers can be considered different plies within the composite. The primary wall which contains hemicelluloses and cellulose fibers is the first layer deposited during plant growth and the cell growth encircling the secondary wall [18]. The secondary cell wall consists mainly of helically wound cellulose microfibrils. These microfibrils are made up of 30–100 cellulose molecules. The secondary wall's middle layer is the thickest layer and contributes approximately to 70% of the entire fiber's Young's modulus [19]. The angle between the fiber's axis and the microfibril depends on the species of fiber. The microfibrillar angle along with the middle layer of secondary wall is largely responsible for the mechanical properties of the fiber, where a small angle generally results in higher fiber strength and modulus [20,21].

### 1.3. Carbon fibers

Carbon fibers are a commercially available fiber with a variety of tensile modulus values which range from 207 GPa to 1035 GPa [22]. As a general rule, the lower modulus fibers possess lower densities, lower cost, higher tensile and compressive strengths, and higher strain-to-failure than their higher modulus counterparts [22,23]. Carbon fibers are used in a wide range of high performance applications, although their primary usage is in aerospace [24].

Some of the advantages that carbon fibers have over other fibers are: high tensile strength-to-weight ratios, high tensile modulus-to-weight ratios, low coefficient of thermal expansion, high thermal conductivity, and high fatigue strength [22]. While some of the disadvantages to carbon fibers are: low strain-to-failure, low impact resistance, high electrical conductivity, and high cost [22].

The strength of carbon fiber comes from its structure which is comprised of planes of carbon atoms. Bonding between atoms within each plane is covalent and therefore strong [22]. These carbon fiber planes are then stacked together and planes are connected through van der Waals bonds, which are much weaker than covalent bonds [25]. As a result of these weaker bonds, carbon fibers exhibit anisotropic mechanical properties. This structure also provides a near linear elastic tensile behavior [22].

### 1.4. Modeling theory

#### 1.4.1. Rule of mixture's model

The rule of mixture's model uses the mechanics of material approach which is based on simplifying assumptions of either uniform strain or uniform stress in the constituents [26]. This method has been found to adequately predict the longitudinal properties such as Young's modulus ($E_1$) as well as the major Poisson's ratio ($\nu_{12}$) (which assumes uniform strain) [27]. One of the drawbacks to this method is that it underestimates the transverse and shear properties (which assumes uniform stress) such as the transverse modulus ($E_2$) and shear modulus ($G_{12}$) [26]. Generalized rule of mixture equation for the prediction of modulus in the longitudinal direction has the following form:

$$E_c = \sum_{i=1}^{n} E_i V_i \tag{1}$$

where, $E$ is the modulus of elasticity and $V$ is the volume fraction. Subscripts $c$ and $i$ are the composite and individual constituents respectively.

When the loading of the composite is in the direction of the fiber such as is in tension, the rule of mixture's model predictions are in good agreement with those obtained experimentally. However, when a compressive load is applied the experimental values deviate from the predicted values [28].

#### 1.4.2. Halpin-Tsai model

Semi-empirical relation, also known as the Halpin-Tsai, have a consistent form for all properties and represent an attempt at carefully interpolating between the series (uniform stress) and parallel (uniform

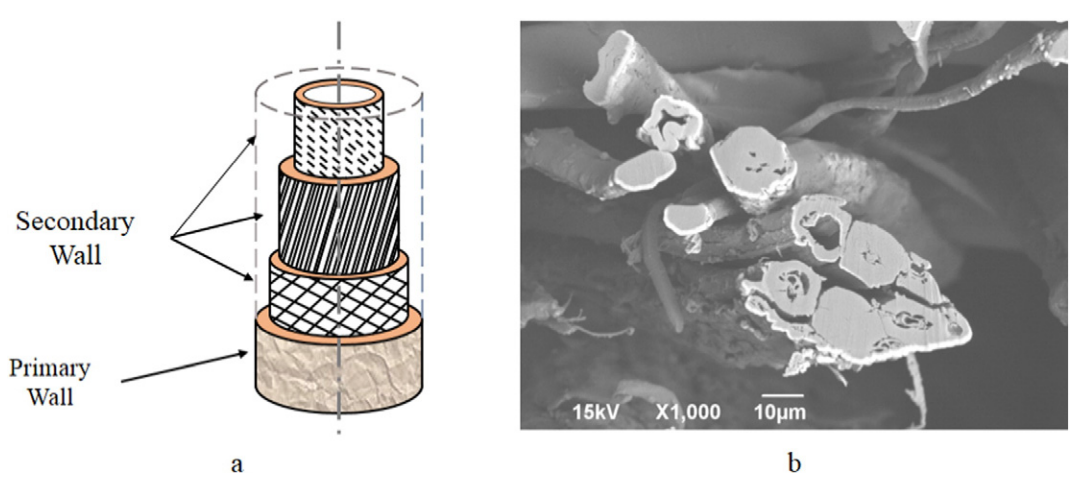


**Fig. 1.** a) The structure of an elementary bast fiber, b) cross section of flax fiber [15].