

Development of Flax Fiber/Soy-Based Polyurethane Composites for Mass Transit Flooring Application

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ABSTRACT

In this study, soy-based polyurethane foam was reinforced with randomly oriented flax fiber to create green composite paneling. This paneling can be used as replacement for plywood in mass transit flooring. To establish optimal material properties, the flax/foam composite's density was modified through manipulation of both fiber volume fraction and foam void content in order to determine processing modification upon mechanical performance. Both static flexural testing and dynamic low velocity impact were performed. Mechanical characterization was performed by both flexural testing and screw fastener pullout studies. Resultant properties demonstrate the feasibility of lower maintenance renewable composite materials as replacement for current transit flooring.

INTRODUCTION

A growing importance has been placed on the research of natural fibers and resins derived from natural resources due to the global energy crises, global warming, and ecological risks that are associated with the use of petroleum based products. In particular, a large amount of industry focus has been placed on their viability as recyclable and renewable reinforcement agents. This has been especially true within Europe, where the European Union has established directives promoting the necessity of recyclability. One of these is the E.U.'s End-of-Life Vehicle (ELV) Directive, which has set a requirement for 95% of each vehicle manufactured after January 2015 to be reused or recovered [1]. Another is the E.U.'s Landfill of Waste Directive, which severely restricts the amount of organic material that can be land-filled, which has caused the disposal of polymer composite materials to be illegal in many E.U. nations [2].

This legislation on the recycling of end of life vehicles has especially helped spur interest in the utilization of flax as fiber reinforcement. Compared to most bast fibers, flax fibers exhibit some of the highest specific tensile strength and modulus properties, lowest densities, and best non-abrasive and insulating qualities. Linen flax fiber has already found its way into replacing fiberglass for certain automotive applications in Europe and North America, from interior dash and trim components to underbody shields and covers. Among other benefits, natural fiber automotive components require 83 % less energy and are 40 % less expensive than glass fiber components [3].

Another promising area of development has been in the use of biobased resin systems, in particular, rigid biobased foams such as polyurethane (PU). In 2004, a study by Omni Tech International was conducted to compare the life cycle emissions of soybean oil-based polyols used to make PUs versus petroleum-based polyols [4]. This study used the Building Environmental and Economic Sustainability (BEES) software program developed by the National Institute of Standards and Technology and underwritten by the EPA Office of Environmentally Preferable Procurement [4]. Among many other environmental parameters, the study showed that producing just 1 kg of soybean oil-based polyol removed 2 kg of CO₂ from the atmosphere because the soybean plant sequesters CO₂ during the growth, whereas producing 1 kg of petroleum polyol added 3.5 kg of CO₂ to the atmosphere [4].

Several grades of soybean oil-based PU are already being used in industry and have had good commercial response due to favorable mechanical properties in conjunction with low cost when compared to other rigid foams [5,6,7,8,9,10,11,12,13,14]. In addition, many research groups have shown that through implementing fiber reinforcement into rigid thermosetting foams, significant property increases

can be accomplished [15,16,17,18]. This opens up the avenue for working with soy-based PU foam as a material in fiber reinforced composites.

Due to the intrigue and potential surrounding the natural fibers and resin systems, this study looks to analyze the potential of flax foam/soy-based PU composites as possible replacements for current components used in the transportation industry. In particular, the flooring systems of mass transit vehicles present an optimal choice for substitution. The current conventional flooring for transit busses consists of a steel frame supporting 12.7 mm thick plywood floor board. Despite the fact that this plywood is being chemically treated to prevent decay, they still require repeated replacement over the lifecycle of a transit vehicle [19]. Replacement of this flooring with a natural reinforced rigid foam could thus serve an economic benefit, as the nature of decay would be severely minimized, reducing both material and labor expenses, as well as vehicle downtime. In addition, with a flax fiber/soy-based PU composite being anywhere from 55 % to 70 % renewable materials by weight, there would not be a significant detrimental environmental impact caused by switching to a composite material from plywood.

However, the effects of process variation upon the mechanical performance of the soy-based PU when reinforced with flax mat are important to understand due to the inherent deficiencies that exist with soy-based PU. Compared to traditional polyol produced PU, soy-polyol derived foams have lowered crosslinking densities, as well as dangling polymer chains, which increase the network's free volume and act as plasticizers [20]. This behavior leads to lowered stiffness, a poor property for a rigid system.

Thus, an understanding of how fiber content and foam density affect mechanical performance may be critical towards developing useful structures for mass transit systems and is examined in the scope of this study. Another necessity when considering replacing the current plywood paneling is the means of fastening the system together. While plywood can easily be secured with screws, the cellular structure that rigid foam composites have makes mechanical fastening by such means more difficult. Therefore, characterizing the potential for use of wood screws for mechanical fastening PU foam when flax fiber is integrated into the system is examined in this work.

EXPERIMENTAL

MATERIALS

The flax fiber reinforcement utilized in this study was a randomly oriented linseed derived flax mat containing 55 % to 60 % fiber by weight. The average fiber length is between 10 mm and 60 mm and average fiber diameter is between 2

μm and 5 μm, yielding an aspect ratio of over 2000. The other 40 % - 45 % of the mat consists of a light polymer binder and of shive, which are thin fragments of the woody core of the flax stem. The mat is supplied by Flax Tech, LLC, located in Rock Lake, ND. The mat is currently marketed and sold for use as horticulture products such as mulch mats for gardens and trees, and hanging basket liners. As a lower cost higher shive content mat, it provides a unique economic incentive if suitable material properties can be yielded through its usage.

The soy-based polyol was supplied by Urethane Soy Systems, Volga, SD. The isocyanate was by BayOne Urethane Systems LLC, St. Louis, MO. Both systems are proprietarily licensed and cannot be further disclosed at this time.

PROCESSING

Composite panel processing was accomplished using a reaction injection molding (RIM) setup with a mass ratio mixture of 1 part polyol to 1.4 parts isocyanate to create the PU. This mix was entered into a stainless steel 30 cm × 30 cm mold cavity with a single layer of the Flax Tech random flax mat. Three mold heights were utilized, 4.50 mm, 9.00 mm, and 12.55 mm, allowing for variation of fiber volume fraction. The mold was placed inside a Carver® platen press for curing at 60 °C under 700 kPa pressure. The total processing time was 25 min. Varying the amount of PU during RIM processing of the flax fiber / soy-based PU foam composite panels resulted in densities ranging from 0.31 g/cm³ to 0.72 g/cm³. This range of densities provided a series of properties comparisons. After the flax fiber/soy-based PU foam composite panels were processed, they were sectioned as tensile, flexural, and impact specimens for testing.

MECHANICAL CHARACTERIZATION

Three-point flexural testing was done according to ASTM Standard D 790 using an Instron 5567 load frame (Norwood, MA) with a 2 kN-capacity load cell.

The effectiveness of mechanical fastening by means of screws was tested with a screw pullout test of each specimen set. For this test, a #6 gauge wood screw was inserted into a 25 mm by 25 mm square specimens to a depth of 4.5 mm, the thickness of the thinnest parts produced. The screw and specimen were then inserted into a slotted pullout fixture, as shown in [Figure 1](#). The fixture was mounted in an Instron 5567 load frame with a 2 kN load cell. The machine was then run in tension at a rate of 0.5 mm/min until screw pullout was achieved. The resultant peak force was then recorded for comparison against other specimens.

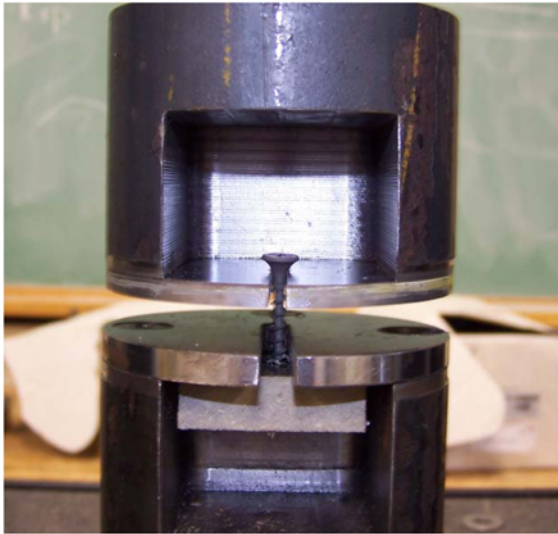


Figure 1. Screw pullout fixture with mounted specimen

RESULTS AND DISCUSSION

FLEXURAL PROPERTIES

With weight savings being a sought after potential advantage of using a foam system, it is important to take into consideration the effects that density has upon mechanical performance. As shown in [Figure 2](#), it is found that there is a relatively linear increase in flexural strength with composite density. In addition, although lower, the strength performance is comparable to that of plywood, demonstrating that the substitution of the flax fiber/soy-based PU for plywood holds viability.

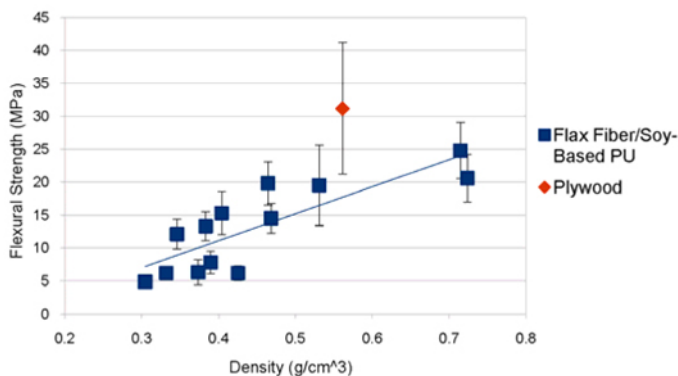


Figure 2. Flexural strength performance of flax fiber/soy-based PU and plywood versus specimen density.

There are two factors that play a role upon the density increase within the composites: a) Fiber volume fraction and b) Foam void content. With flax fiber holding a density of approximately 1.4 g/cm³, increases in fiber content will lead to higher density in final parts. At the same time, the foam density, and thus subsequent final composite density, will

decrease with an increased void content. Since the density is found to be directly related to the composite strength, both of these density-controlling parameters must be examined in order to determine the most effective parameters to control in part production.

Examining fiber volume fraction first, it is shown in [Figure 3](#) that increased fiber volume fraction leads to improved flexural strength performance. With the fibers acting as reinforcement within the panels, this is expected. Even with high shive content, the contribution of continuous structural fiber within the flax mat provides a clear advantage for the composite panels.

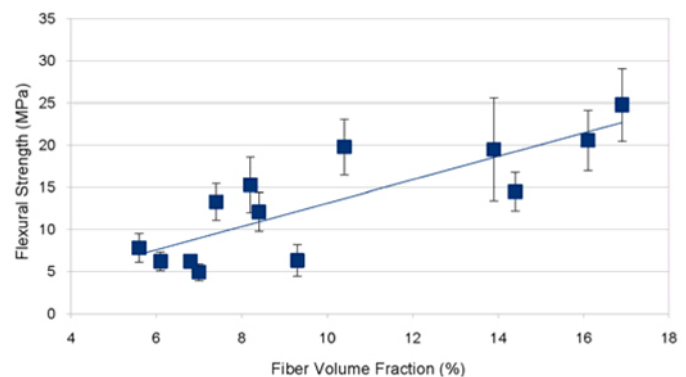


Figure 3. Flexural strength performance of flax fiber/soy-based PU versus fiber volume fraction.

The effect of void content upon mechanical performance was also determined, specifically as it plays a crucial role upon flexural strength. [Figure 4](#) shows the effect of foam density upon the flexural strength. These results mirror results about void content's role on mechanical performance of synthetic polyol derived PU foams reinforced with both natural fibers and glass fibers [16,21].

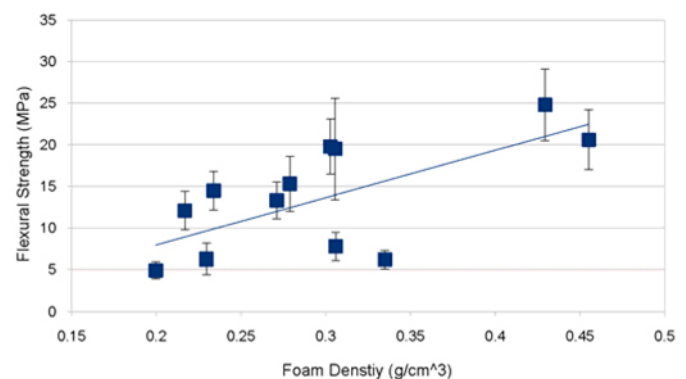


Figure 4. Flexural strength performance of flax fiber/soy-based PU versus foam density.

As void content is decreased, cell wall thickness increases, which has been shown to improve the compressive