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Bio-based composite roof structure: Manufacturing and processing issues

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Abstract

Bio-based composite materials were tested for suitability in roof structure. Structural beams were designed, manufactured and tested, yielding good results. Based on the beam results, large-scale composite structural panels were made. Soy oil-based resin and cellulose fibers, in the form of paper sheets made from recycled cardboard boxes, were successfully used to manufacture the composite structures. This recycled paper was previously tested in composite sheets and structural unit beams and gave the required stiffness and strength required for roof construction. The roof was designed and a 1/3 scale structure was manufactured. Following this 1/3 scale design, two composite panels of 2.59 m × 1.52 m × 0.089 m were manufactured to serve as the two sides of a pitched roof connected at the ridge. The depth of the panels and thickness of the composite skin were dictated by the design as a function if the two other dimensions to give the optimum strength and cost result. To test the manufacturing process for a full-depth roof structure, a 1.27 m × 0.53 m × 0.279 m panel was successfully manufactured. In the latter structure, a modified VARTM process was used to replace the solid mold surface with a bagging film. This enabled a visual inspection of the resin flow and provided a window for using additional vacuum and injection lines on the normally hidden bottom side. This bagging method was very successful without the need for mold modification or electronic sensors. Issues related to natural fibers composite processing such as moisture inhibition and drying are also discussed in this work.

Keywords: Biomaterials; Soybean; Recycled fiber; Green structural composites

1. Introduction and background

Bio-based composite materials have been successfully manufactured and tested as reported in the literature [1,2]. Several bio-fibers were tested in composite sheets made of soybean oil-based resin. The stiffness increased to over 5 times that of the neat resin [1] when recycled paper from corrugated cardboard boxes was used. Foam-core structural beams were then manufactured and tested giving comparable values to that of the most common structural woods [2]. The structural behavior and performance analysis of the composite beams were also investigated [3,4] and studied for their suitability in building roofs, yielding good results. Seven different beams representing the different manufacturing options were tested and analyzed for stiffness, strength and failure modes [3]. The latter study showed that the beams manufactured by wrapping the paper around the foam cores, followed by top and bottom paper sheets, gave the best performance in terms of strength and stiffness. These beams failed either in tension (the bottom sheet) or buckling (the top sheet), while the beams that had a web separated from the top and bottom sheets failed in shear when the foam and web broke away from the

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sheets. A scale model unit width beam from a roof was also manufactured and tested [4]. The beam was tested using three- and four-point bending with different span lengths, a quasi-distributed load test, and tested to failure. The beam was modeled using Timoshenko beam theory and the results agreed with the experimental predictions for stress and deflection. The model beam satisfied the design deflection criteria and had an ultimate strength 11 times the design load.

Structural members used in the construction of civil structures, such as roofs, tend to be very large. Since structural applications (e.g., buildings, bridges, houses, etc) require large-scale manufacturing, the work presented herein focuses on large-scale manufacturing of bio-based composite roof structures for housing applications The monolithic roof is a sandwich construction and is designed to carry all of the normal and in-plane loads a roof system must carry. Another advantage of this roof structure is that it is designed and manufactured in a way that makes it survive the static and mechanical loads generated by hurricanes. In recent years, the United States has been hit by several major hurricanes, Hugo (1989), Andrew (1992), and Iniki (1992) causing over $27.5 billion dollars cumulatively in damage to insured property [10,11]. In 2004, the damage from the four hurricanes which impacted Florida (Charley, Frances, Ivan and Jeanne) is expected to reach at least $30 billion dollars and according to the NOAA hurricane forecasters, there exits an ominous potential for continued hurricane damage in the next several decades.

The shape, size, and dimensions of large structures are very important because they affect the resin flow and wetability in composite manufacturing. Besides the shape and size of the composite, the permeability, resin viscosity, and gel time are also important parameters. In addition to the design and manufacturing, this paper will discuss the issues and variables that a Process Engineer faces when making such large structures. The reinforcing fiber used in this work is cellulose mats in the form of recycled paper. The paper is a hygroscopic material which presents a challenge to the curing reaction of the resin when water is absorbed by the fiber mats. This requires that the fiber be treated in a way that eliminates all of the moisture that could inhibit polymerization by reacting with the resin, the initiator or activator additives. Many researchers looked into the problems posed here and tried to address them. Permeability of pulp and paper was studied by Nilsson and Stenstorm [5], where Darcy's Law and simplified Navier–Stoke equations were used. Assuming a specific shape and fiber aspect ratio, they concluded that further work is needed to model transport processes through sheets of pulp and paper. Natural fiber treatment to reduce the water sorption was discussed by Sreekala and Thomas [6], in which sodium hydroxide, latex coating, γ radiation, silane, TDIC (Toluene diisocyanate), acrylation and benzoyl peroxide treatments were investigated as possible methods to eliminate water-sorption by oil palm fibers. Drying of cellulose based materials, such as fibers, wood, and paper, is widely investigated and published in the literature. It has been modeled by many authors as a capillary flow and as a mass transfer process [7–9].

The main objective of this work is to successfully manufacture large-scale composite components, suitable for residential roof construction, from natural resources such as plant oil-based resins and natural fibers, at low material and operational cost.

2. Materials

The materials used in making the structural composite panels were soybean oil-based resin, cellulose fibers, and closed cell structural foam.

2.1. Soybean oil-based resins

Soybean oil is composed mainly of triglyceride molecules. Each triglyceride contains three fatty acid chains joined by a glycerol center, as shown in Fig. 1. The fatty acid chains have 0–3 double bonds and vary in length from 16 to 22 carbon atoms. In order to produce a rigid cross-linked thermoset, the triglycerides must be functionalized [12–16]. Several types of functionalization can be obtained at various active sites within the triglyceride structure: the double bond, the ester group, the allylic carbons, and the carbons alpha to the ester group. Various chemical pathways for functionalization of these triglycerides have been studied [17]. For this study, the triglycerides were first epoxidized and then reacted with acrylic acid to obtain Acrylated Epoxidized Soybean Oil (AESO). The resin was then blended with a co-monomer, e.g., styrene, and allowed to free radically co-polymerize via redox decomposition using a metal promoter.

The resin was prepared at a pilot plant using chemically modified soybean oil in the form of AESO, commercially known as Ebecryl 860 (supplied by UCB Chemicals). The AESO resin was first mixed with styrene in an optimized 2:1 weight ratio, respectively [1]. Styrene reduces the viscosity of the resin to about 118 cp with a fluid density of 1.01 g/cm^3. Also, styrene increased the strength, stiffness and glass transition temperature due to an increase in cross-linking density of the cured resin as reported by O'Donnell et al. [1] and Khot et al. [16]. The resin mixture was then mixed with 3 wt.% initiator, Cumyl Peroxide, commercially available as Trigonox 239A (supplied by Akzo Nobel), and 0.8 wt.% catalyst, Cobalt Naphthenate (supplied by Mahogany Co.). The resin was then infused into the preform using VARTM as described later, and