DEVELOPMENT OF BIOBASED SANDWICH STRUCTURES FOR MASS TRANSIT APPLICATIONS

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Development of Biobased Sandwich Structures for

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ABSTRACT

Efforts to increase biobased content in sandwich composites are being investigated to reduce dependence on synthetically produced or mined, energy-intensive materials for numerous composite applications. Vegetable oil-based polyurethane foams are gaining recognition as good substitutes for synthetic counterparts while utilizing bast fibers to replace fiberglass is gaining credence. In this study, soy oil-based polyurethane foam was evaluated as a core in sandwich constructions with facesheets of hybridized kenaf and E-glass fibers in a vinyl ester matrix to replace plywood sheeting on steel frame for mass transit bus flooring. As a first step, the static performance of the biobased foam was compared to 100% synthetic foam. Secondly, biobased sandwich structures were processed and their static performance was compared to plywood. Biobased sandwich composites show promise towards replacing plywood for bus flooring by displaying an increase of 130% for flexural strength and 135% for flexural modulus plus better indentation values.

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1. INTRODUCTION

1.1. Overview of Biobased Sandwich Composites

A limited number of literature articles addressing biobased sandwich composites indicate that biobased sandwich composites for structural applications are a novel idea worth pursuing. Replacing the synthetic foam core and synthetic fibers used in conventional sandwich structures with biobased foams and fibers have been investigated by various researchers and research groups over the past 15 years with the goal to investigate increased renewability without adversely affecting mechanical properties. Petrovic [1], Bandyophadhyay-Ghosh et al. [2], Pechar et al. [3] and Canmpanella et al [4] have investigated the use of vegetable oils as a viable potential replacement for petroleum-based polyurethane foams. Further studies by Guo et al. [5] Ning et al. [6] and Latere Dwan'Isa et al. [7] have investigated the viability of soybean oils as the renewable resource with the most attractive properties.

Sandwich structures provide advantages such as low density, high stiffness to weight ratio, and high edgewise-compressive strength that make them an ideal choice for aerospace, marine, and mass-transit applications. They are usually constructed using thin stiff facesheets that are separated by a low-density core, which serves the purpose of maintaining the distance between facesheets and to sustain shear deformation. Manipulating the core thickness and the materials in the facesheets allows for varying properties to be obtained as reported by Gupta et al. [8]. The core structure is usually a honeycomb or low-density foam. The core structure is usually the weakest component of the sandwich structure and fails due to shear; therefore understanding the shear properties of the sandwich composites is of paramount importance as reported by Shahdin et al. [9]. Composite facesheets are usually made out of engineered fibers

such as E-glass and carbon fibers in a thermoset matrix. Recently, researchers such as Dweib et al. [10] have started to investigate the viability of incorporating natural fibers into composite sandwich structures as hybridized mats with engineered fibers or all natural fiber mats to increase the renewability of these structures while maintaining critical performance metrics.

In the U.S. the biobased product market is becoming a major economic slice in the 21st century. There is potential for this to create a boost in income for farmers and rural America by $15-20 billion a year [11]. Annual growth rates until the year 2020 are projected to be 20% based on currently known technologies [11]. In Europe the drive towards environmentally friendly products is well established. The End-of-Life Vehicle (ELV) directive implemented by the E.U. has set that 95% of each vehicle made in Europe after January 2015 to be made out of reused or recycled materials [12]. The E.U.'s Landfill of Waste Directive has made it illegal to dispose of polymer composite materials in many E.U. nations due to the restriction of organic material that can be land filled [13].

1.2. Constituents Materials in Biobased Sandwich Composites

Biobased sandwich composites are generally considered those made out of renewable core sections or facesheets. The core structures can be made out of vegetable-oil based polyurethane foams, balsa wood, or other suitable core systems. Facesheets can be composites reinforced with fiber mats made from synthetic or natural fibers and the polymer matrix that is used can be a thermoplastic or thermoset matrix, although the most popular matrix used is generally in the thermoset form. The following section will explain in detail about the core, fibers and matrix components.

1.2.1. Polyurethane Foam

Rigid Polyurethane (PU) foams are used in many diverse applications such as transportation, construction, thermal insulation, coatings, sealants, adhesives and packaging. This is because of its low viscosity, decent thermal stability, fast reaction time, moderate physical properties and excellent strength-to-weight ratio. The widespread use of PU foams is because of its ease of processing, variety of achievable properties, and the capability to be formed in complex shapes. Today, the majority of rigid foams used in the market are derived from petroleum-based polyols and isocyanates [14]. The synthesis of PU foams is accomplished through the mixture of a hydroxyl-functionalized monomer with another monomer that contains the isocyanate group and leads to the formation of a urethane linkage [15]. The mixing of the polyol and the isocyanate induces the foaming reaction that creates the final PU foam formation which sometimes requires water as a blowing agent to assist the reaction. The reaction of these chemical structures releases CO_2 which assists in the cell formulations inside the final PU foam formulation.

Most PU foams are cross-linked, so the rigidity is controlled by the configuration of cross-linked structures and urea linkages [16]. The versatility of the chemical structure of polyurethane allows the usage of it in many of the aforementioned applications and also many other new applications [17]. Petroleum-based polyols were relatively inexpensive in the early history of PU foams and this led to widespread use. Annual North American product demand for polyols represented 3.4 billion pounds in the year 2006 [18]. The ever increasing prices of oil, the widespread fact that fossil fuels are being depleted at an increased rate and most importantly the major thrust in environmental concerns have sparked an awareness to create alternatives for PU foams such that the dependence on non-renewable resources can be reduced. This thrust to

find an alternative source has led many adept researchers down the path of biobased renewable resources [15, 16].

1.2.2. Fibers

Fibers are considered a reinforcing element because of their large length-to-diameter ratios (i.e. aspect ratio) and are usually made from aramid, carbon, glass, ceramic, natural materials (hemp, kenaf, flax, etc) or other suitable materials. A popular fiber is E-glass, which is composed of the oxides of silica, aluminum, boron, calcium and other compounds. It is strong, cheap, posseses good electrical resistance and is used extensively in the automotive, construction, sports and marine industries. Fibers are available in different diameters and lengths and generally possess unique properties depending on form such as chopped fibers, prepregs and textile fabrics. Woven composites are used extensively in structural applications due to better dimensional stability, good impact resistance, conformability and good out-of-plane properties. E-glass fibers were used in this research to fabricate the sandwich composite panels. The E-glass fibers used in the lay-up sequence were prescribed by the Composites Innovation Centre (CIC), Winnipeg, MB, Canada.

1.2.3. Matrix

Polymer matrices used in forming sandwich structures are often liquid molding resins. The resins used are critical to the properties of these polymer matrix composites even though the fibers are the main load carriers. The resin plays an important role because it provides adhesion of the fibers. The type of matrix used also dictates the fabrication technique used and the maximum temperature allowed during the fabrication process. Resins also play the important role of protecting the fibers from environmental effects.

Resins can be classified in to two distinct types: thermosets and thermoplastics. Thermoplastics can be shaped and molded in semi-fluid states and then becomes rigid when cooled. Thermoplastics can be converted to the initial form through reheating whereas thermosets once "cured" cannot be returned to its original form. Thermosets require a catalyst or heat applied, or the combination of both in order to achieve cure. Common thermoset resins used in composites are epoxies, vinyl esters, polyesters and polyurethanes. The matrix used in this study is a vinyl ester system for the sandwich composite panels.

1.3. Soy-Based Polyurethane Foams

One path towards the development of biobased renewable resins has led to the conversion of vegetable oils to PU foams. A few major driving forces in the usage of vegetable oils to produce these polyurethane foams are their wide availability, reduced fossil fuel dependence and added value to existing agricultural products, which in turn benefits the agricultural industry [18]. A variety of different vegetable oils have been used to create biobased polyurethane foams [19]. Castor-oil based polyurethane foams have been in production for years [20]. This is because it is the only vegetable oil that possesses natural functional hydroxyl groups. Other vegetable oils such as palm oil, linseed oil, rapeseed oil and soy oil are increasingly being used and some of these oils are also produced on a limited commercial scale [21].

Soybean oil is a renewable resource with multiple sites of reactivity such as double bonds, allylic hydrogens, esters and their corresponding alpha carbons [3]. Soy is available extensively in North America as a major crop and is cost competitive to other vegetable oils that have also been investigated for PU formulation.

Polyurethane foams produced from soybean oil reduce greenhouse gas emissions [22]. In 2004, Omni Tech International conducted an experiment to compare the life cycle emissions of

soybean oil-based polyols used to make PU foams in comparison to petroleum-based polyols. The study indicated that producing 1 kg of soybean oil-based polyol helped eliminate 2 kg of CO_2 from the atmosphere because the soybean plant reduces CO_2 during growth compared to producing 1 kg of petroleum polyol, which contributed 3.5 kg of CO_2 to the atmosphere [22].

Soybean based polyol has found its way into PU foams, binders, coatings, adhesives and sealants. North American demand for polyols is about 3.4 billion pounds/year and a conservative estimate for the annual demand of soybean oil-based polyols is about 650 million pounds/year. Specifically, priority markets for soy-based polyurethane are listed in the table below (in millions of pounds of product) [23].

Table 1. Market Size for Soy Polyol [23]

Segment	**Market Size ('02) (M. lb.)**	**Soy polyol ('07) (M. lb.)**
Construction	455	200
Transportation	720	100
Furniture	310	50
Carpet	250	40
Appliances (insulation)	120	25
Packaging	125	15
Other*	450	70
Total	**2430**	**500**

*Other: Bedding, footware, marine, foundry, tanks and pipes, misc.

The North American market represents only a third of the global market for PU foams, and the ultimate potential for soy utilization could be tripled from the 650-million-plus-pound level. Urethane Soy Systems Company, Inc. (Volga, SD), BioBased Technologies Inc. (Rogers

AR), Cargill (Wayzata, MN), Dow Chemical (Midland, MI), and Arkema (Bloomington, MN), have each developed a series of soybean based polyols that are being commercially utilized in PU formulations in the transportation, furnishing and construction industries [23].

As the current market is mainly using petrochemical-based polyols in their respective markets, soybean oil-based polyols has to be able to replace them with similar or better mechanical properties so that industrial users will switch over with ease. Then the renewable resource characteristic will be an added benefit. Petrovic et al. have done many studies on rigid PU foams based on soybean oils since 1999 [5]. They have investigated the compressive strength and thermal stability of these soybean oil-based PU foams compared to petrochemical based PU foams. The thermo insulating property comparison of both the soybean oil and petroleum oil-based PU foams showed that soybean oil were actually more thermally stable towards thermal degradation and thermal oxidation. They surmised that this was due to the lack of ether linkages in the soybean-based foams [5].

In a similar study done by the same group, they compared thermal properties of a series of vegetable oils such as soybean, corn, castor, sunflower, peanut, olive, canola and safflower oil with petroleum oil based foams [24]. Soy oil showed the highest glass transition value compared to the other respective vegetable oils. And these findings correspond with the findings in a previous study by the research group [5].

1.4. Natural Fibers

Natural fibers such as flax, hemp, kenaf and sisal have been identified as effective replacements for conventional fibers such as glass in the fabrication of certain composite materials. They are abundant, renewable and potentially inexpensive, which is advantageous as they help to reduce the energy required to mine, melt and draw mineral-based fiber. They also

offer benefits in terms of low density, high toughness, less abrasion on tooling, comparable specific strength properties and CO_2 neutrality. Bast fibers in particular exhibit superior flexural strength and modulus of elasticity even when compared to glass fibers [25].

A major drawback associated with natural fiber usage is the hydrophilic nature of the fiber which leads to adhesion problems with hydrophobic resin matrices. Another disadvantage is fiber degradation in high temperature processing. This results in natural fibers being used in processes that do not require high temperature processing such as compression molding and vacuum assisted resin transfer molding. In recent times, several researchers such as Bledzski et al. [26], Gassan [27], Zampaloni et al. [28] and Chen et al. [29] have investigated the potential of using natural fibers in various composite applications with some success.

Linen flax fibers have been steadily replacing fiberglass for specific automotive applications especially in Europe and North America. Europe has very strict laws when it comes to recycling and usage of renewable materials, especially in the automotive sector. Therefore these flax fiber reinforced parts are rapidly finding their way into the automotive sector, from interior dash and trim components as well as covers and underbody shields. These natural fibers parts require 83% less energy and cost 40% less than glass fiber parts [30].

1.5. Reaction Injection Molding

Reaction Injection Molding is a processing technique where mixing and then injecting the polymer solution into a fixed volume mold where it finally cures to form its final product. Polyurethane is the popular polymer used in this technique and fillers, reinforcements and coloring agents can be mixed in to achieve superior properties. It is a low-cost manufacturing process for large-scale parts. This technique is used often in the automotive industry, construction and structural parts [31].

1.6. Vacuum Assisted Resin Transfer Molding

Vacuum Assisted Resin Transfer Molding (VARTM) is a low-cost composite manufacturing process used to manufacture large complex shapes. It has many advantages compared to Resin Transfer Molding (RTM) such as low tool cost and room temperature processing. In this process, dry fabric mats are layered according to lay-up specifications in the mold and then is vacuum bagged with a distribution media, vacuum line and resin line. The pressure difference between the composite panel and atmospheric pressure is the driving force that allows resin through the fabric preforms efficiently [32].

2. OBJECTIVES OF THE RESEARCH

A growing trend in mass transit vehicles is to improve the sustainability of materials and manufacturing used in addition to light-weighting the vehicles for better fuel economy. Specifically, flooring systems have become of particular interest for finding a substitute. The current conventional flooring for transit buses consists of 12.7-mm thick plywood flooring supported by a welded steel frame. These plywood flooring systems degrade relatively quickly despite being chemically treated to prevent decay; they therefore require repeated replacement over the lifecycle of the vehicle [33]. Developing renewable sandwich composite flooring to replace plywood could present an economical advantage because the ease of decay is minimized; material and labor expenses are reduced, as well as vehicle downtime is avoided. However, rigorous design, processing, and testing must be conducted in order to meet the mechanical performance required as an alternative flooring structure in mass transit systems.

Biobased sandwich structures have the potential to offset petroleum dependence in structural materials for applications such as mass transit vehicles. The early objective for this work was the selection of suitable soy-oil based rigid PU foam as the foam core. This was achieved through closed cell compression molding followed by mechanical and physical testing to obtain a mechanical and physical profile. The next objective of this work was to process the required sandwich composite structures with the selected foam core utilizing VARTM. The CIC prescribed a hybridized kenaf/E-glass fiber lay-up sandwiching a rigid foam core with vinyl ester as the matrix to produce sandwich structures for mass transit applications as shown in Table 2. The floor lay-up sandwich panels are to be utilized in the construction of a bus as replacement

for plywood that utilizes biobased resources such as shown in Figures 1 and 2. The lay-up utilized for the floor panels in Figure 2 corresponds to Table 2.

The uses of soy-based PU foams as a substitute for synthetic PU foams is being investigated in this study to reduce the dependence on petroleum for materials. Natural fibers such as bast fibers are also being considered as a direct replacement for glass fibers to further reduce the dependence of synthetic materials. However it is necessary to include synthetic fibers such as glass fibers in the fabrication of these sandwich structures to ensure that the mechanical properties are maintained within the allowed parameters for their specific applications.

The mechanical and physical profile for the biobased sandwich structure will be developed through utilizing the testing methods requested by the CIC. The main objective of producing these mechanical and physical profiles was to prove that the biobased sandwich structures can compete effectively with currently used commercial plywood used in mass transit applications.

Table 2. Layer-wise Floor Lay-Up Scheme

ELTM 1808 (CSM next to kenaf) Vectorply
Kenaf mat
EM 0015 (Vectorply)
6.35 mm foam core
EM 0015 (Vectorply)
Kenaf mat
ELTM 1808 (CSM next to kenaf) Vectorply

Figure 1. Bus utilizing biobased sandwich composites.

Figure 2. Floor lay-up for bus.

The tasks required to meet the objectives stated earlier were achieved through the steps that are listed below. All these tasks were conducted in sequence to establish the necessary knowledge to progress towards the final goal.

1. Full mechanical and physical characterization of commercial petroleum- based PU foam (Nida Core PU-6R)
2. Processing of polyurethane foam from four chosen PU foam systems through compression molding (Agrol 7, Agrol Diamond, Urethane Soy Systems 2 lb, Bay One 102633)
3. Full mechanical and physical characterization of four chosen PU foam systems
4. Selection of most suitable soybean oil based PU foam for sandwich core
5. Processing of sandwich structures using VARTM
6. Full mechanical characterization of biobased sandwich structures
7. Comparison of behavior amongst sandwich composites evaluated

3. MATERIALS

3.1. Soy Based Polyurethane Foam

The PU foaming reaction includes a polymerization reaction where a diol reacts with a di-isocyanate to form a urethane group, with the expulsion of carbon dioxide that aids the creation of a cellular structure. The two major raw components of this polymerization are (a) polyol (diol) resin and (b) polymeric methylene(diphenyl diisocyanate) resin. In some cases, water may be used in addition as a blowing agent if the polyol in question does not have enough water pre-added into the solution.

3.1.1. Polyol Resin

The four polyol resins obtained for this investigation were (a) Bay One 102633 (petroleum-based control), (b) Agrol 7.0 (soy-based), (c) Agrol Diamond (soy-based) and (d) Urethane Soy Systems 2lb (soy-based). In addition to these polyols, Nida-Core PU-6R foam, a common core for sandwich structures used in mass transit applications, was tested to obtain baseline data. All the resins are polyether-based PUs. The viscosity and specific gravity data as obtained from the vendor are listed in Table 3.

Table 3. The Viscosity and Specific Gravities of the Four Resins Used in the Trials

Resin System	Viscosity (cP) (25 °C)	Specific Gravity
Bay One 102633	550 – 650	1.030
Agrol 7.0	21500	1.023
Agrol Diamond	3400	1.017
Urethane Soy Systems	775 – 975	1.100

3.1.2. Polymeric Methylene Diphenyl Diisocyanate

The polymeric methylene(diphenyl diisocyanate) (pMDI) used in this experiment was Bay One ISO 70344, for the Bay One 102633, Agrol 7.0 and Agrol Diamond, obtained from Bay-One Corporation, St. Louis, MO. The published viscosity at 25 ºC is 600 cP –650 cP with a specific gravity of 1.24. The pMDI used with the Urethane Soy Systems 2lb Agent 051-37 B-side was Agent 051-376 A-side, with a viscosity of 200 cP – 300 cP and specific gravity of 1.22.

3.1.3. Natural Fibers (Core Trial)

A 750 g/m^2 areal density hemp mat was used as reinforcement within the USS 2lb foam system. The initial dry mass of the fiber mat accounted for 20% – 25% of the final panel weight. This trial was conducted to investigate the feasibility of utilizing fiber reinforcement in the foam core to increase the biobased content and mechanical properties.

3.2. Biobased Sandwich Composite

The materials required for the formulation of the sandwich composites in the applications studied were closed cell soy-oil based PU foam, E-glass fiber mats or natural fiber mat (kenaf) as reinforcements and vinyl ester resin as the matrix.

3.2.1. Foam

The foam ultimately selected from the first part of the study was the USS 2lb system obtained from USS (Volga, SD) that was processed by Space Age Synthetics, Inc., Fargo, ND with a thickness of 6.35 mm. Glass fiber webbing was used as reinforcement for processing ease and stability into (2438.4 × 1219.2 × thickness) mm^3 foam slabs.

3.2.2. Glass Fibers

The glass fibers used in the manufacturing of the floor lay-up were ELTM 1808, EM 0015, ELTM 1208 (VECTORPLY Corp., Phenix City, AL) and 300-D3-300 Rovicore (Composites Innovation Center), which are specifically designed for resin infusion processes.

3.2.3. Natural Fibers (Facesheet Trial)

The natural fiber mat used as reinforcement for the sandwich composites was made from kenaf fiber with an areal density of 500 g/m^2 and obtained from the CIC. The kenaf fiber mats are dried for 24 hours at 80 °C to remove moisture trapped before the processing.

3.2.4. Resin

The resin used in the manufacturing of the panels was ArmorStar® IVSXH210 (CCP Composites, North Kansas City, MO) which is a pre-promoted, vinyl ester blended resin containing styrene monomer. It is commonly used for processing reinforced composite parts using closed molding processes and specific infusion processes such as vacuum bagging, SCRIMP® and resin injection.

3.3. Manufacturing Processes

The desired core specimens of soy-based polyurethane foam were molded utilizing Reaction Injection Molding (RIM). The biobased sandwich composite specimens were manufactured using Vacuum Assisted Resin Transfer Molding (VARTM), a low cost technique used to fabricate large, complex composite pieces.

3.3.1. Reaction Injection Molding

The PU foam core panels were fabricated using RIM. A (304.8 × 304.8 × 12.7) mm³ aluminum mold was used with a bagging film to provide the required enclosure and shape of the final product (Figure 3). The polyol and isocyanate resins were mixed using a Stir-Pak Laboratory Stirrer from Cole-Parmer Instrument Co., (Vernon Hills, IL) and poured into the open mold, which was covered by a plate. The mold was loaded in a Carver Laboratory Press with the platens heated to a temperature of 60 °C. This mold was closed in the compression press with a simultaneous application of a 5 metric ton (~50 kN) force.

Distilled/ionized (DI) water was used as a foaming agent for the all resin systems to aid the processing of certain polyols that require extra water to assist the foaming reaction. The mixing times and ratios of the resin, isocyanate, and water are listed in Table 4. Mixtures utilizing additional water required additional time for a complete foaming and cure to occur.

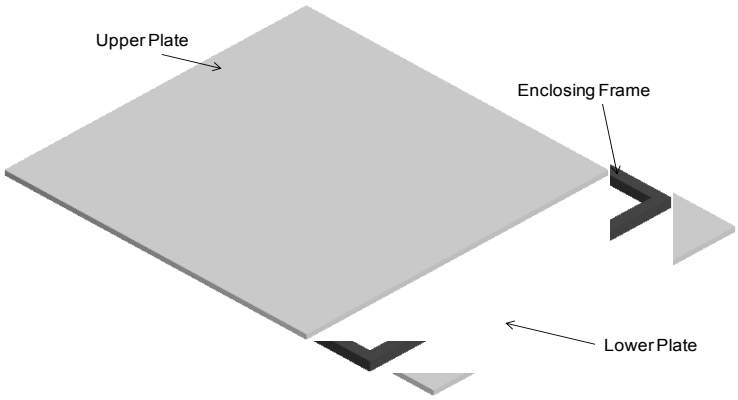


Figure 3. Schematic of the enclosure used for RIM processing.

Panels containing the hemp fiber mat were filled with an excess amount of resin to ensure complete wetting of the reinforcement. The initial mass of a 280 mm × 280 mm fiber mat for a single panel was in the 45 g – 55 g range. The cream time is the point where the initial reaction between the polyol and isocyanate occurs and this generally is observed when the mixture turns

into a creamy yellow color. After the cream time, the rise time occurs and this is where the CO_2 starts to be released and aids in the foaming process of the PU foam and this stops after an average of 2-3 minutes. The total cure time signifies the time for the reaction to reach a complete standstill with no more reaction occurring and the part is completely cured.

Table 4. A List of Processing Parameters

Resin System	Ratio Isocyanate: Polyol: Added Water	Cream Time (s)	Rise Time (s)	Total Cure Time (min)
Bay One 102633	140 : 100 : 0.0	46 – 50	125 – 130	15
Agrol 7.0	170 : 100 : 8.5	60 – 90	120 – 150	25
Agrol Diamond	170 : 100 : 17.0	45 – 60	120 – 130	20
Urethane Soy Systems[1]	113 : 100 : 0.5	40 – 50	190 – 215	15

3.3.2. Vacuum Assisted Resin Transfer Molding (VARTM)

VARTM was the fabrication method chosen for the sandwich panels. The panels were fabricated at a size of 508 mm × 610 mm each. Breather material and distribution media were not required for the fabrication of these sandwich composites due to the porosity of the kenaf mats which facilitated resin transfer uniformly through the panel. Vacuum pressure was held constant at 90 kPa and the sandwich panels were subjected to debulking for an average of 2 hours per panel to help remove air pockets prior to infusion.

[1] Water is present as medium (carrier) in the polyol component, however, additional water was used in formulation

4. EVALUATION METHODS FOR POLYURETHANE FOAMS

4.1. Introduction

The soy-based polyurethane foam specimens were tested for physical and mechanical properties that were deemed important for the performance as a core in a sandwich composite. The target PU foam characteristics were prescribed by the CIC and the selected formulations to meet those needs were Agrol 7, Agrol Diamond and Urethane Soy Systems 2lb for the soy-based PU foams; whereas Bay One 102633, a petroleum-based PU foam and Nida Core PU 6R, also a petroleum-based PU foam were also included for comparison purposes.

4.2. Foam Physical Properties Characterization

The physical properties that were tested include density, moisture absorption, buoyancy, thermal aging and thermal conductivity to determine which PU foam system displayed comparable values to the Nida Core PU 6R system.

4.2.1. Density

The density of the processed foams was measured according to the ASTM D1622 standard [34]. Five specimens measuring 50.8 mm x 50.8 mm were used to obtain the average density value using a simple mass/volume ratio.

4.2.2. Moisture Absorption

Moisture absorption experiment was conducted using Test Method–I specified in ASTM C272 [35]. Five specimens with dimensions of 76.2 mm × 76.2 mm were held down by a mesh and weights while submerged in a tank of DI water for 24 h. After the 24 h of submersion the samples are wiped down by a towel to remove any adsorbed moisture so only the moisture

absorbed is calculated. The initial and final masses were recorded, and the percentage of water absorption was calculated as a percentage gain in final mass of the specimen.

4.2.3. Buoyancy

Buoyancy was measured as a difference in the mass of the specimen in the dry (in air) condition, and in the submerged (in water) condition. After the 24 h of submersion the three samples are wiped down by a towel to remove any adsorbed moisture so only the moisture absorbed is calculated. The initial mass (0 h) and final mass of the specimen after immersion in DI water for 24h were recorded. The change in mass was divided by the volume of the specimen and was referred to as buoyancy.

4.2.4. Thermal Aging

Thermal aging experiments were carried out according to ASTM D2126 guidelines [36]. The temperatures and duration of aging were selected from the suggested values in the standard, also as an upper bound for common heat index under the hood of an automobile. Three foam samples with dimensions of 152.4 mm x 152.4 mm were tested at 150 °C for duration of 336 h and the mass loss and volume loss (dimensional change) were calculated.

4.2.5. Thermal Conductivity

Thermal conductivity measurements were conducted according to ASTM C518 [37]. In this test, a foam specimen (50.8 mm × 50.8 mm) is subjected to heat transfer between two steel plates equipped with heat flux transducers and thermocouples. As one of the plates in contact with a heating source (hot-plate) is heated and maintained at a constant temperature, the heat flux and temperature are monitored at the two contact faces of the specimen until a steady-state is

reached. This steady-state temperature gradient obtained across the specimen thickness is used for calculation of the thermal conductivity values of the three specimens tested.

4.3. Foam Mechanical Properties Characterization

The mechanical properties tested were tensile, flexural, compression and compressive shear properties to compare to Nida Core PU-6R values.

4.3.1. Tensile Testing

Tensile testing was performed according to ASTM D638 on a 5-specimen sample set using an MTS 647 load frame [38]. The dimensions of the specimens used were 50.8 mm x 203.2 mm and the speed of the crosshead was approximately 5.0 mm/min. The specimens were tested until failure. The specific tensile strength and specific tensile modulus were calculated.

4.3.2. Flexural Testing

Flexural testing was performed through a three-point bend testing, as specified in Procedure-A of ASTM D790, using an Instron 5567 load frame [39]. The speed of the crosshead was calculated according to the guidelines in the standard, and was 5.4 mm/min on average. Five specimens with dimensions of 38.1 mm x 292.1 mm were used in the testing with an output of flexural stress and flexural modulus.

4.3.3. Compression Testing

Compression testing was performed to ASTM C365 on a 5-specimen sample set with dimensions of 50.8 mm x 50.8 mm using an MTS 647 load frame [40]. The speed of the crosshead was approximately 0.5 mm/min. The compressive modulus and compressive stress at 5 % strain were calculated for each sample set.

4.3.4. Compressive Shear Testing

The compressive shear properties of the foams were tested according to the ASTM C273 standard with a 3-specimen sample set measuring 50.8 mm x 203.2 mm respectively [41]. A set of two mild steel blocks machined according to the guidelines of the standard, were used as guides for the foam to be loaded in an angle to the loading axis as shown in the Figure below. A 3M Scotch-Weld DP 110 epoxy-based adhesive with a 20 min curing time was used to bond the specimen to the steel blocks. The surface was roughened using 1000 grit sandpaper. The compressive shear test was conducted on an MTS 647 load frame with 250 kN-capacity load cell, with a crosshead displacement rate of 0.5 mm/min until failure, as suggested in the testing standard.

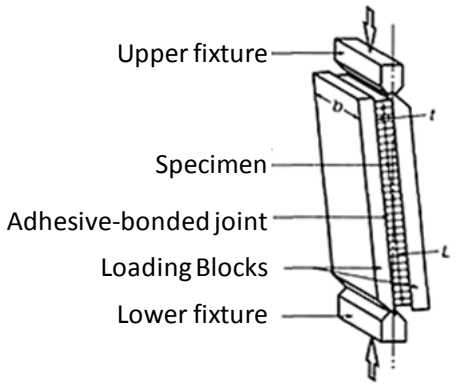


Figure 4. Schematic of ASTM C273 compressive shear experiment [41].

4.4. Microscopy

A Zeiss-Axiovert optical microscope was used to investigate the cellular structure of the foams. To visualize the foam structure, multiple drops of the resin mixture were poured on a glass slide and the structure was observed from the flat bottom side of the glass slide.

5. EVALUATION OF FOAM PERFORMANCE

The results obtained for the PU foams produced are reported and discussed in the following sections. At the conclusion of this chapter a justification for the foam chosen for the sandwich structure development will be provided.

5.1. Density

The densities measured for the four foams are shown in comparison to the density of PU-6R in Figure 5. At 106 kg/m³, both Urethane Soy System and Bay One 102633 foam systems showed an increase of 16% as compared to the density of PU-6R at 91 kg/m³. The density of the Urethane Soy System reinforced with a hemp mat was highest, as expected, at a value of 173 kg/m³. The nominal density of hemp fiber is 1.4 g/cm³, which causes this increase. The percentage of natural fibers in the USS Fiber Reinforced foam was 20% of the total weight. In addition, the high standard deviation in the reinforced foam is likely due to variations in the degree of consolidation and resin fill within the fiber mat of the panel.

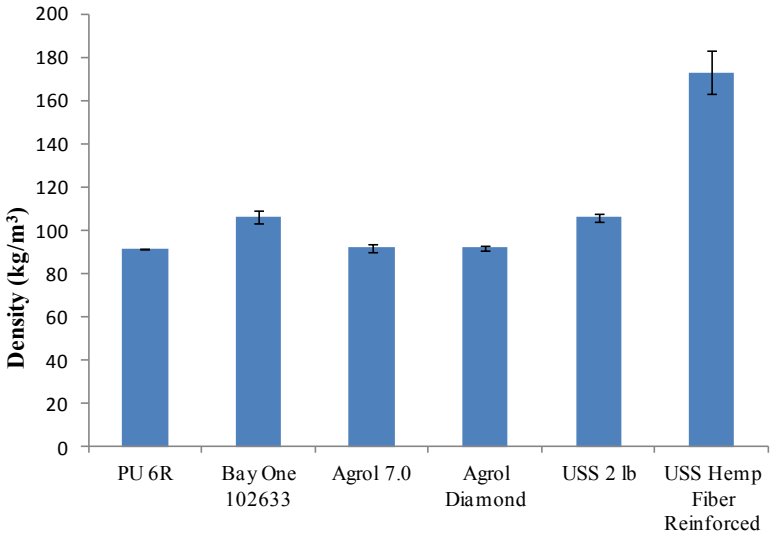


Figure 5. Density of polyurethane foams.

5.2. Moisture Absorption and Buoyancy

The moisture absorption weight gain percentages and buoyancy of the trialed foam systems are shown in Figure 6. All foams exhibited an average moisture absorption weight gain percentage in the range of 7-10 %. The low moisture absorption values of Bay One 102633 and USS 2lb were expected due to the lower biobased content in the PU foam. Agrol Diamond displayed the highest moisture absorption value at 10% and this can be attributed to the larger (as will be shown in section 5.6) cell wall structures of the foam compared to the other PU foam systems. The USS Hemp Fiber reinforced sample had similar moisture absorption value compared to all the neat foam samples and this was considered a surprise as it was expected that the moisture absorption values should have been much higher due to presence of the natural fibers which are hydrophilic.

All of the buoyancy values calculated was in the range of 6-10 kg/m^3 apart from the USS Hemp Fiber reinforced sample which had a buoyancy value of 17 kg/m^3 which is counterintuitive based on the fact that there are natural fibers inside it which in theory should decrease the buoyancy due to natural fibers being hydrophilic. An explanation for this could be that the natural fibers are already saturated with the PU foam thus does not attract more moisture or that the hydroxyl groups on the cellulose in the natural fibers reacts with the isocyanate present in the PU foam liquid mixture which eliminates some of the hydrophilic character of the natural fibers used. The intimate bond that occurs between them leads to less moisture absorption and this explains the low moisture absorption and buoyancy values obtained for the USS Hemp Fiber reinforced sample.

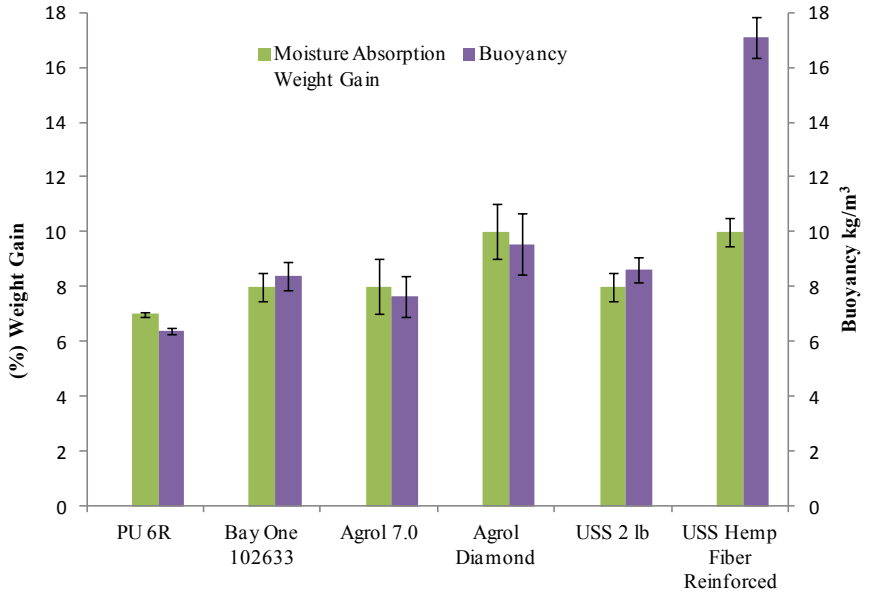


Figure 6. Moisture absorption weight increase and buoyancy.

5.3. Thermal Aging

The color change and other surface effects of thermal aging are qualitatively shown in Figure 7. The Bay One 102633(Fig. 7b) and Urethane Soy Systems 2lb (Fig. 7e) foam systems showed discoloration and high warpage in comparison to all the other foams. The extensive degradation of Bay One 102633 and Urethane Soy Systems was manifested in the form of high degree of warpage, and loss of dimensional stability. The Agrol 7.0 and Agrol Diamond systems (Fig. 7c and 7d) and the Nida-Core foam (Fig. 7a), on the other hand, did not show any visual signs of surface cracking under the same conditions but did exhibit color change. The PU foam systems with higher biobased content (e.g. Agrol 7.0 and Agrol Diamond) display higher thermal stability compared to Bay One 102633 (petroleum-based) and this is attributed to the hydrocarbon and ether linkages of the soy-based foams being more thermally stable compared to the petroleum-based foams [42]. The Urethane Soy System Hemp Fiber Reinforced showed

surface deformation but no structural deformation due to the natural fibers present that prevents such deformation from occurring.

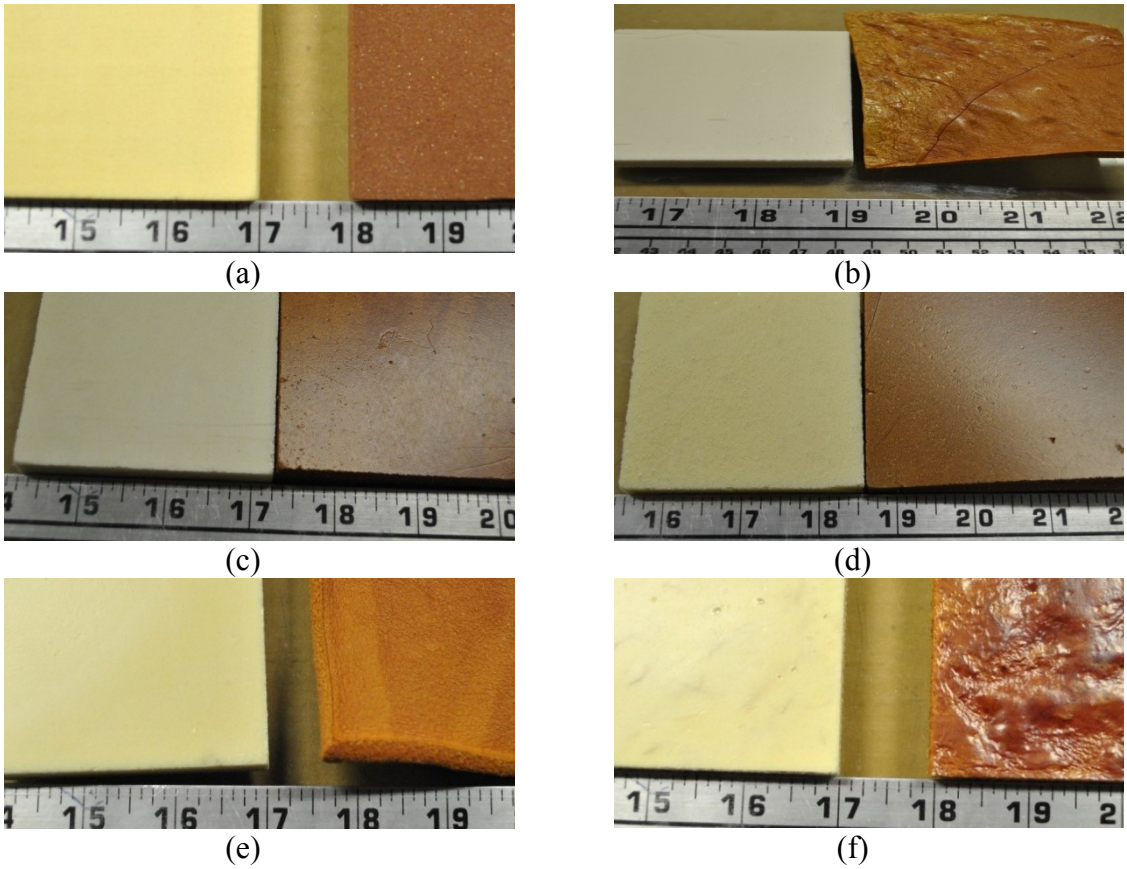


Figure 7. Stereographs of the unexposed and aged specimens showing the color change (qualitative) from pre-aging and post-aging for (a) Nida Core PU-6R, (b) Bay One 102633, (c) Agrol 7, (d) Agrol Diamond, (e) Urethane Soy Systems 2lb and (f) Urethane Soy Systems Hemp Fiber Reinforced. [The scale is in inches.]

The thermal aging weight and volume loss percentage are shown in Figure 8**.** All foam systems show a consistent weight loss in the range of 2% to 6%. The volume loss in Bay One 102633 and Urethane Soy Systems was significantly higher than the Agrol systems. The Bay One 102633 and Urethane Soy Systems 2lb displayed 40% and 55% volume loss respectively compared to Agrol 7.0 and Agrol Diamond that showed 5% loss and 10% loss respectively. At high temperatures such as 150°C, PU foams begin to undergo thermal degradation where the urethane bond decomposes first and this is followed by the degradation of the polyol backbone at

higher temperatures than the glass transition of PU foams at about 180° C. And due to the higher ether linkages in the petroleum based foams that are less stable in comparison to the ester linkages in soy foams, it is understood that the thermal stability of soy foams are much more stable compared to its counterpart. These findings are similar to results obtained by Javni et al. where they compared the thermal stabilities of vegetable oil based foams and petroleum based foams [24]. The addition of hemp fibers to the USS foam (Fig. 7f) aids in the maintenance of thermal dimensional stability as observed in the aging volume loss, which decreased from about 55% without fibers to 7% with presence of fibers.

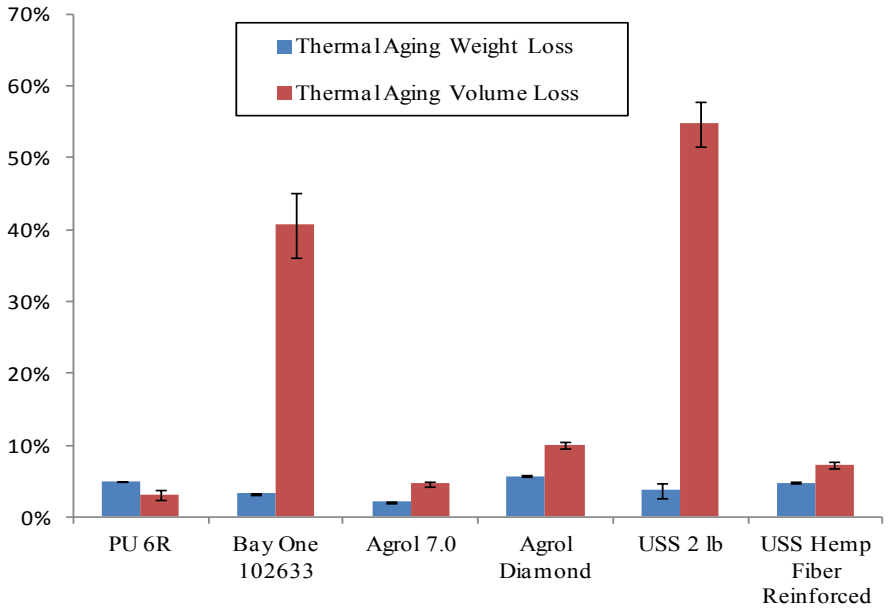


Figure 8. Thermal aging weight and volume loss.

5.4. Thermal Properties

The thermal conductivities of the foams are shown in Figure 9. These k-factor values for all systems are comparable to the PU-6R system and are expected to show similar thermal resistance in common service temperatures for mass transit applications. The k-factor values indicate the rate at which heat flows through a material and it is noted that the age of the material

affects the k-factor value. The R-values for USS 2lb system, Agrol Diamond and Bay One 102633 indicate that they have similar ability to PU-6R in reducing the heat flow rate through conduction, convection and radiation under specified test conditions. The higher the R-value, the better it reduces the rate of heat flow.

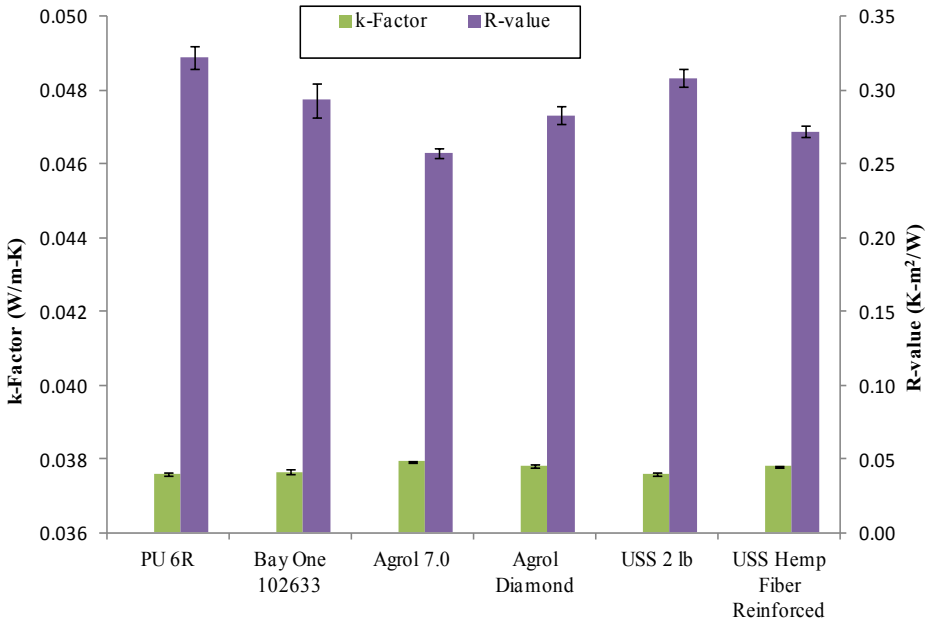


Figure 9. Thermal conductivity and thermal resistance values for the foams.

5.5. Mechanical Properties Results

The respective modulus values from tensile, flexure, compression and shear tests are shown in Figure 10 and the corresponding strength values are shown in Figure 11. The modulus and strength data is presented in such a format for ease of comparison of each foam system. All samples are compared with PU-6R (petroleum-based) control system to easily compare the difference in values for all the soy-based PU systems (Agrol 7, Agrol Diamond, and USS 2 lb), the other petroleum-based system (Bay One 102633) and also the USS Hemp Fiber Reinforced system.

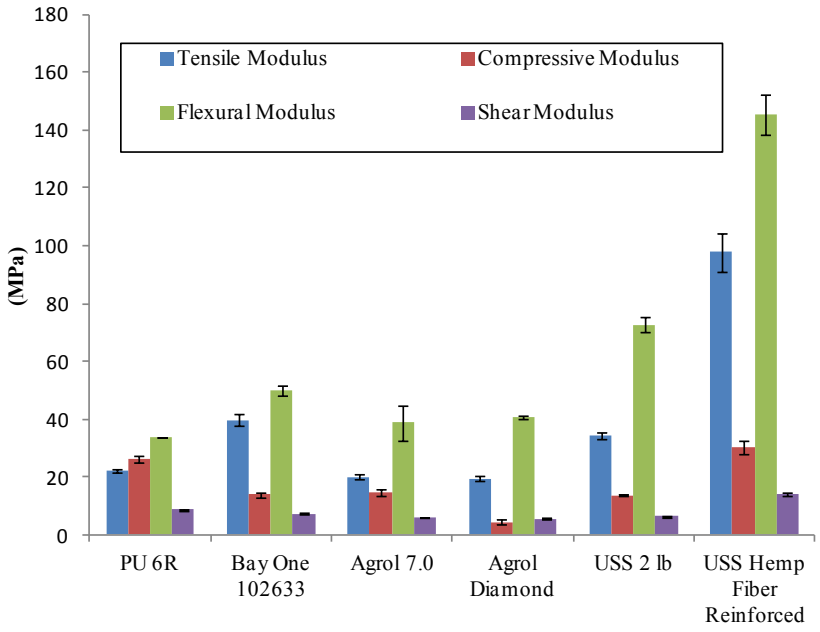


Figure 10. Tensile, compressive, flexural and shear modulus.

Bay One 102633 at 40 MPa and Urethane Soy Systems 2lb at 34 MPa display nearly double the tensile modulus value of the control system PU-6R which was recorded at 22 MPa. Both Agrol 7.0 and Agrol Diamond are nearly equivalent to the PU-6R system. The compressive modulus of Bay One 102633, Urethane Soy Systems 2lb and Agrol 7.0 are all noted to be 54% lower than PU-6R, whereas Agrol Diamond is at nearly 83% lower. PU-6R displays a higher value than all the other systems at 26 MPa. The lack of a proper RIM system led to the mixing and pouring of the PU foam being done manually and this potentially had a direct effect on the compressive modulus values.

Urethane Soy Systems 2lb at 73 MPa is double the flexural modulus of the control PU-6R at 34 MPa, whereas Bay One 102633, Agrol Diamond and Agrol 7.0 are all higher than PU-6R by about 47%, 15% and 20%, respectively. All systems display lower shear modulus values compared to PU-6R with both Agrol systems displaying the lowest values and this also can be suspected to be attributed to the manual hand mixing and pouring of the foam systems. The

hemp fiber reinforced Urethane Soy Systems foam exhibited consistently higher values for all tested properties compared to all the neat foam systems tested and this is expected as the fiber mat acts as a reinforcement causing load transfer between the foam matrix and natural fibers that increases the mechanical properties.

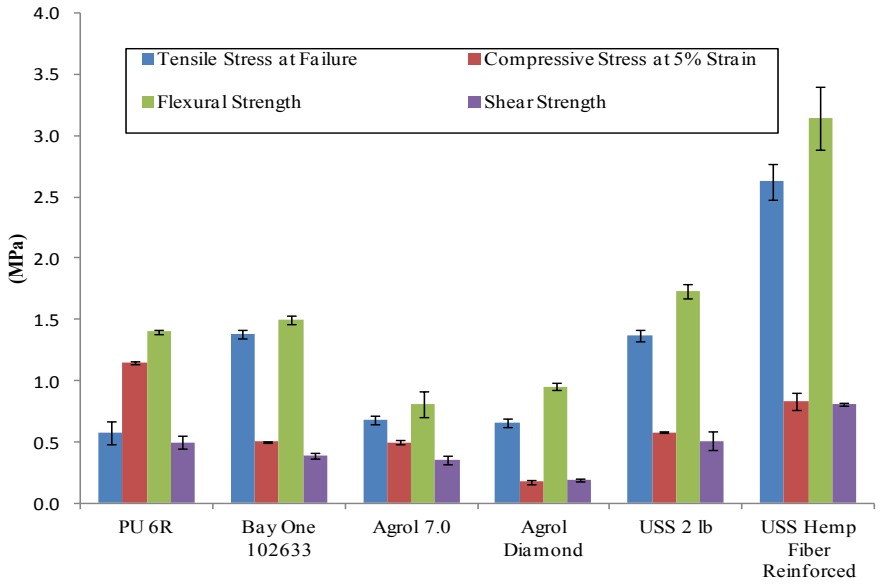


Figure 11. Tensile strength, compressive stress, flexural strength and shear strength.

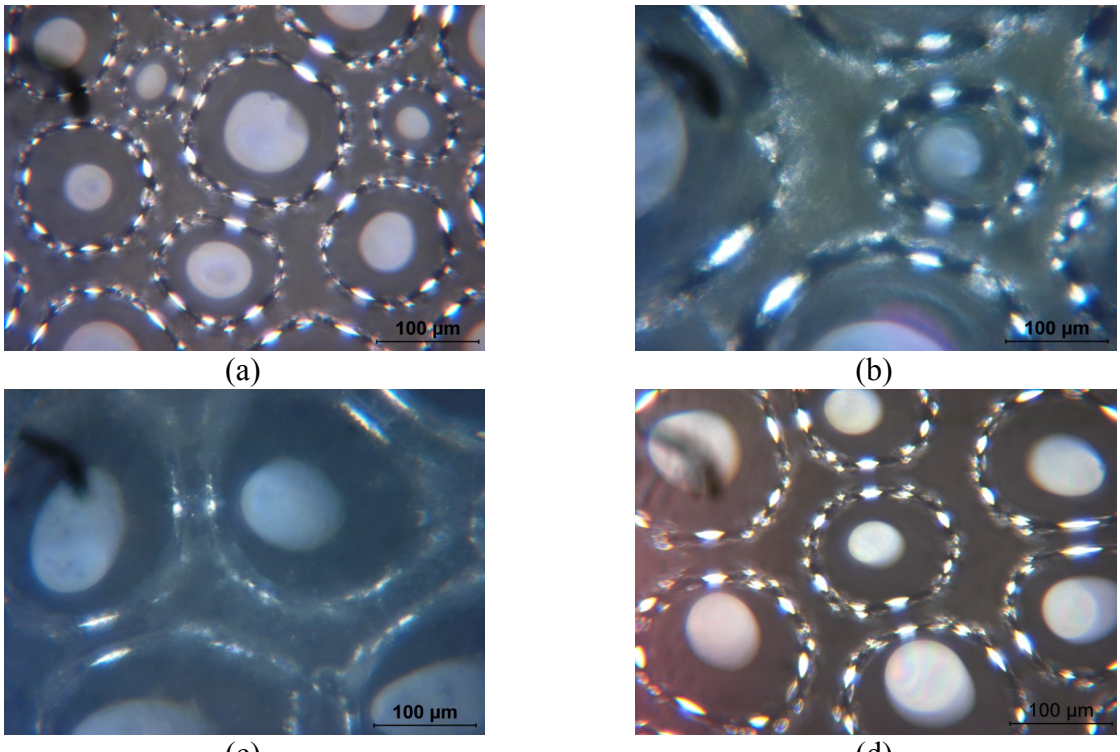
Bay One 102633 and Urethane Soy Systems 2lb displayed the highest tensile strength at failure with an increase of about 130% compared to PU-6R. The Agrol 7.0 and Agrol Diamond systems recorded a 15% increase over the PU-6R system which was observed to be 0.6 MPa. The compressive stress at 5% strain shows that the PU-6R has the highest value at 1.2 MPa followed by Urethane Soy Systems Hemp Fiber Reinforced at 0.8 MPa, Urethane Soy Systems 2lb at 0.6 MPa, Bay One 102633 and Agrol 7.0 at 0.5 MPa and Agrol Diamond at 0.2 MPa. Urethane Soy Systems Hemp Fiber Reinforced displayed the highest value for flexural strength at 3.1 MPa. It was observed that Urethane Soy Systems and Bay One 102633 have higher flexural strength compared to PU-6R, whereas Agrol 7.0 and Agrol Diamond were lower than PU-6R. Urethane Soy Systems Hemp Fiber Reinforced and Urethane Soy Systems 2lb both

showed higher shear strength compared to PU-6R and in comparison Bay One 102633, Agrol 7.0 and Agrol Diamond displayed lower shear strength.

5.6. Microscopy

5.6.1. Cell Structure Characterization

Within the four experimental foams, the closed cell content was observed to be highest in the Bay One 102633 and Urethane Soy Systems foam. The physical appearance of these foams was also more uniform as compared to the two Agrol Systems. Within the two Agrol Systems, Agrol 7.0 showed higher consistency in the final part appearance and cell distribution at the cross-section. The foam structure is shown in Figure 12.



(a) (b) (c) (d)

Figure 12. The cell structure of the foams as observed under an optical microscope showing the presence of closed cells with varying cell sizes for (a) Bay-One 102633, (b) Agrol 7.0, (c) Agrol Diamond, and (d) Urethane Soy Systems.

5.7. Biobased Content of the Foams

The biobased content of the soybean based PU foams is presented in Table 5. The first column of the table shows the biobased content with water considered as 100% biobased, whereas in the second column, water is not considered. The biobased content was calculated based on the ratio of components in the initial mixture. The aggregate biobased content of the Agrol 7.0 foam is highest among the foams because of the high (~96%) biobased content of the polyol resin. The Bay One 102633 resin is constituted by about 30% (w/w) of soybean-oil derivative, and the calculated effective biobased content of the foam is 16%. The overall biobased content of the USS/hemp fiber composite is about 40 %, considering the dry fiber mat with areal density of 750 g/m² at a weight fraction of 25 % (w/w).

Table 5.Calculated Biobased Content of Processed Foams

	Ratio pMDI: Polyol: Added H_20	**Biobased Content (H_2O = 1) (%) (w/w)**	**Biobased Content (H_2O = 0) (%) (w/w)**
PU-6R	--	--	--
Bay One 102633	140 : 100 : 0.0	--	--
Agrol 7.0	170 : 100 : 8.5	61.7	58.6
Agrol Diamond	170 : 100 : 17.0	56.9	50.9
Urethane Soy Systems	113 : 100 : 0.5	20.0	20.0
USS Reinforced Hemp	113 : 100 : 0.5	40.0	40.0

5.8. Selection of Suitable Foam as Core System

Within a constricted volume/thickness requirement, the density of the foam is governed by the mass of reactant mixtures. Since the four reactant mixtures possess different reaction kinetics, the cellular growth and structure was expected to be different. The cellular structure of Bay-One 102633 and Urethane Soy Systems showed a higher closed cell content (qualitative) as shown in Figure 11 (a) and (d), and thus the mechanical properties were projected to be the highest among the four experimental foams. Agrol Diamond was the next best system in terms of closed cell content and overall appearance and cell distribution.

Moisture absorption as shown in Figure 6 was comparable for all systems and thus inferred to as a function of density over closed cell content. The equivalent moisture absorption of the reinforced foam can be attributed to the balance of two phenomena: 1) lower foam fraction, and 2) excessive wicking/capillarity shown by the fibers.

Mechanical properties indicate that Urethane Soy Systems and Bay One 102633 consistently matched or exceeded the properties procured from PU-6R the control system. The higher closed cell content and uniformity of cell structure in Urethane Soy Systems and Bay One 102633 lead towards higher tensile, compressive and flexural properties in comparison to both Agrol Systems which show lower cell uniformity and closed cell content display lower values in these respective categories. Agrol 7.0 and Agrol Diamond with the higher biobased content are lower when compared with the synthetic PU-6R most properties tested. Urethane Soy Systems with a lower biobased content consistently displayed positive values compared to both PU-6R and also the petroleum-based Bay One 102633.

Based on the physical and mechanical properties obtained Urethane Soy Systems 2lb system was chosen as the foam that was to be used as the core foam for the sandwich composite due to its superior performance despite its lower biobased content.

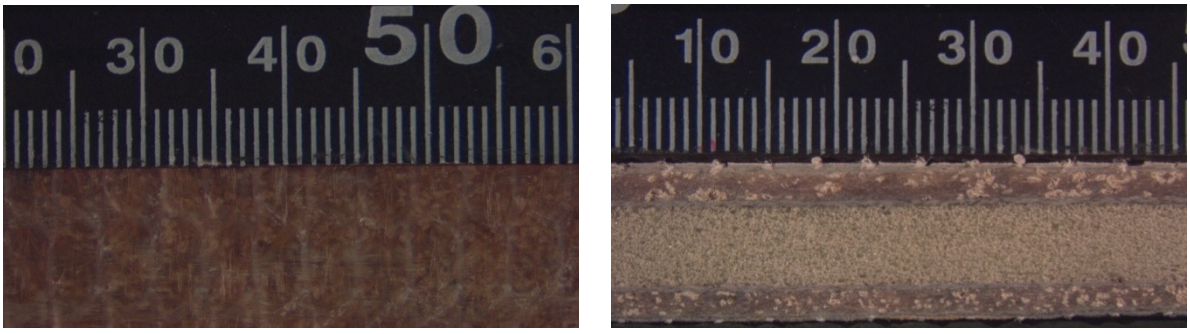
6. EVALUATION METHODS OF SANDWICH STRUCTURES

6.1. Introduction

After selection of the core system, Urethane Soy Systems 2lb was used to fabricate the sandwich composite specimen. Table 6 illustrates the thicknesses of the composite specimen itself and the facesheet thickness with the final density of the panel also included. Figures 13a and 13b illustrate the floor lay-up sandwich panel after processing from a top view (Figure 13a) as well as side view (Figure 13b). The floor lay-up panel has a density that is 36% higher than that of plywood.

Table 6. Composite Thickness, Facesheet Thickness and Final Density

	Composite Thickness (mm)	**Facesheet Thickness (mm)**	**Final Density (kg/m^3)**
Floor Lay-Up	12.8	3.31	711
Plywood	12.7	-	522



(a) (b)

Figure 13. Stereo photographs of (a) top surface and (b) section of a floor layup panel.

6.2 Sandwich Composite Mechanical Characterization

6.2.1. Flexural Testing

Flexural testing was performed through a three-point bend testing, as specified in ASTM D790, using an Instron 5567 load frame [39]. The speed of the crosshead was calculated according to the guidelines in the standard, and was 5.4 mm/min on average. Five specimens with an L/d ratio of 20 were used in the testing with an output of shear deflection which is used to obtain core shear modulus. The sample widths used were 38 mm for the floor lay-up.

6.2.2. Compression Testing

Compression testing was performed to ASTM C365 on a 5-specimen sample set using an MTS 647 load frame [40]. The speed of the crosshead was approximately 0.5 mm/min. The compressive modulus and compressive stress at 5% strain were calculated for each sample set. The sample sizes used were 50.8 mm x 50.8 mm for all specimens.

6.2.3. Compressive Shear Testing

The compressive shear properties of the foams were tested according to the ASTM C273 standard with a 3-specimen sample set [41]. A set of two mild steel blocks machined according to the guidelines of the standard, were used as guides for the foam to be loaded in a 10° angle to the loading axis. A 3M Scotch-Weld DP 110 epoxy-based adhesive with a 20 min curing time was used to bond the specimen to the steel blocks. The surface was roughened using 1000 grit sandpaper. The compressive shear test was conducted on an MTS 647 load frame with 250 kN-capacity load cell, with a crosshead displacement rate of 0.5 mm/min until failure, as suggested

in the testing standard. Sample sizes were measured to be 50.8 mm x 203.2 mm for all specimens tested.

6.2.4. Quasi-static Indentation Test

Concentrated quasi-static indentation test was performed according to the guidelines in ASTM D6264 with a 3-specimen sample set [43]. A vinyl sheet was placed on top of the specimen and with a crosshead rate of 0.25 mm/min force was applied up to 670 N and then the test was stopped and visual inspection of the samples were conducted to observe any damage that had occurred. The set-up utilized to perform the indentation test is shown to better illustrate the testing method in Figure 14.

Figure 14. Set-up of indentation test.

7. EVALUATION OF SANDWICH STRUCTURES PERFORMANCE

7.1. Sandwich Composite Mechanical Testing Results

7.1.1. Flexural Strength and Modulus

The flexural strength and modulus of the sandwich composite obtained from ASTM 790 are shown in Table 7.

Table 7. Flexural Strength and Modulus

	Flexural Strength (MPa)	**Flexural Modulus (MPa)**
Floor Lay-Up	74.0 ± 2.7	7551 ± 340
Plywood	32.0 ± 10.0 [44]	3200 ± 250 [44]

All specimens display local wrinkling failure type which occurs at the load bar in contact with the top facing of the sandwich composite. This wrinkling occurs due to the localized short-wave buckling of the compressive face which is held up by the core [45]. This failure is observed due to the usage of long beams whereas if shorter beams are used then the failure that occurs would most likely be core failure due to the significant shear loading component. Figure 15 illustrates the failure mechanism of the beam.

The flexural strength value of the floor lay-up is observed to be 130% higher than the obtained value for plywood and this is expected due to the sandwich configuration with a foam core which increases the strength of the panel.

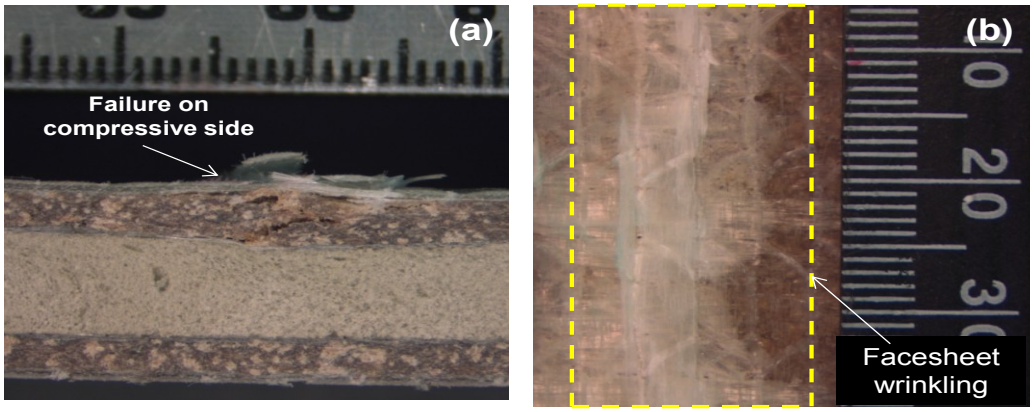


Figure 15. Long beam flexure floor lay-up specimen failure mode of facesheet wrinkling: a) side view and b) top surface view.

7.1.2. Shear Properties

The shear strength and modulus value is shown in Table 8. The shear properties were calculated from the equations specified in ASTM C273. The failure modes observed for the sandwich composite samples were shear core failure for all specimens.

Table 8. Shear Strength and Modulus

	Shear Strength (MPa)	**Shear Modulus (MPa)**
Floor Lay-Up	0.76 ± 0.03	9.04 ± 0.80
Plywood	2.90 ± 2.00[46]	172.00 ± 21.50[46]
Foam Core	0.51 ± 0.15	6.30 ± 0.95

It is observed that the sandwich composite has higher shear strength of about 50% compared to the neat foam core. It also has a higher shear modulus of about 43% compared to the foam core. This can be attributed to the glass fiber webbing and the resin that permeates the whole sandwich composite that may have seeped into the foam core. The higher plywood

properties are expected as the failure that occurs in the sandwich composite is in the foam core which has low shear values.

7.1.3. Compressive Strength and Modulus

The compressive strength and modulus values obtained from ASTM C365 are shown in Table 9. The compressive strength and compressive values both showed an increase in values compared to the neat foam system that was tested and shown in Section 5.5. This can be attributed to the glass fiber webbing that was present inside the foam system and to the presence of the facesheets, which enhance the compressive values. Compressive buckling of the foam structure was the failure method for all specimens and this explains the lower compressive strength value obtained compared to plywood.

Table 9. Compressive Strength and Modulus

	Compressive Strength at 5 % Strain (MPa)	**Compressive Modulus (MPa)**
Floor Lay-Up	0.58 ± 0.20	16.2 ± 0.9
Plywood	20.60 ± 16.70[46]	4.6 ± 18.9[46]
Foam Core	0.51 ± 0.18	11.5 ± 3.3

7.1.4. Quasi-static Indentation Test

The load/displacement plot obtained using ASTM D6264 by modifying parameters of a compression test on the floor lay-up is shown in Figure 16. The load increased as a two-stage function of extension, with the first stage corresponding to the vinyl layer, and the second stage corresponding to the composite facesheet.

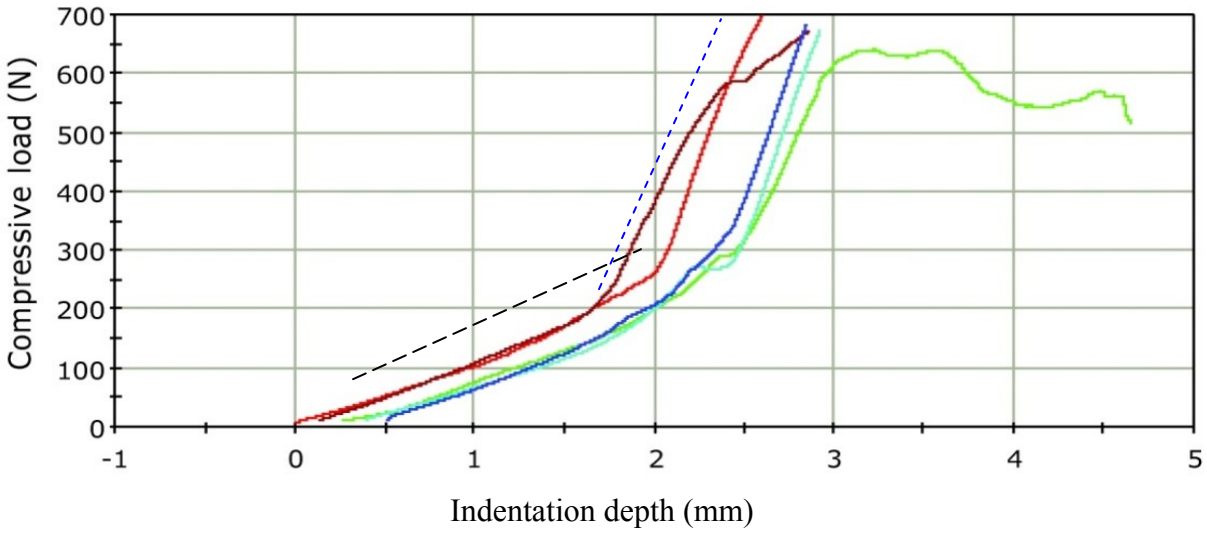


Figure 16. Compressive load/extension plot for the ASTM D6264 indentation test on a sample of five floor lay-up specimens.

The indentation/surface failure on the samples is shown in Figure 17a – 17f. A surface contact area of indentation was approximated using the iSolutionDT® software as a circle with a radius of approximately 1.570 mm, 1.651 mm, and 1.527 mm for three floor layup specimens. The extent of indentation ranged from no visible puncture to a fully visible indent that propagated through the composite facesheet.

The load/displacement plot obtained using ASTM D6264 by modifying parameters of a compression test on plywood samples as comparison is shown in Figure 18. The load increased as a two-stage function of extension, with the first stage corresponding to the vinyl layer, and the second stage corresponding to the plywood. Sample 2 did not achieve the required 670 N load and this could be attributed to the indentation force directly penetrating a weak point of the plywood sample whereas the other samples achieved the necessary required force of 670N.

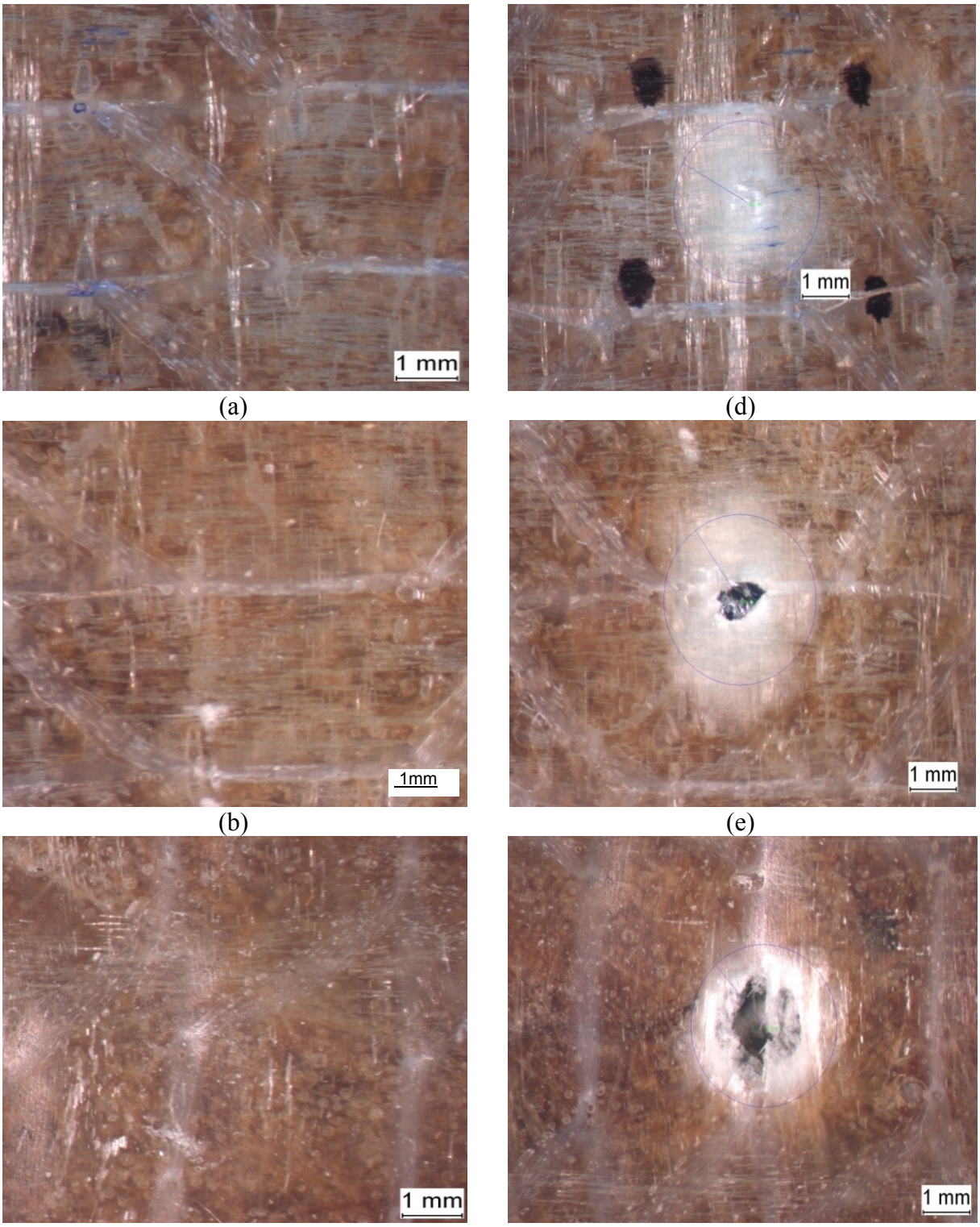


Figure 17. (a – c) Pristine, and (d – f) indented surfaces of the floor lay-up facesheet imaged using a stereoscope.

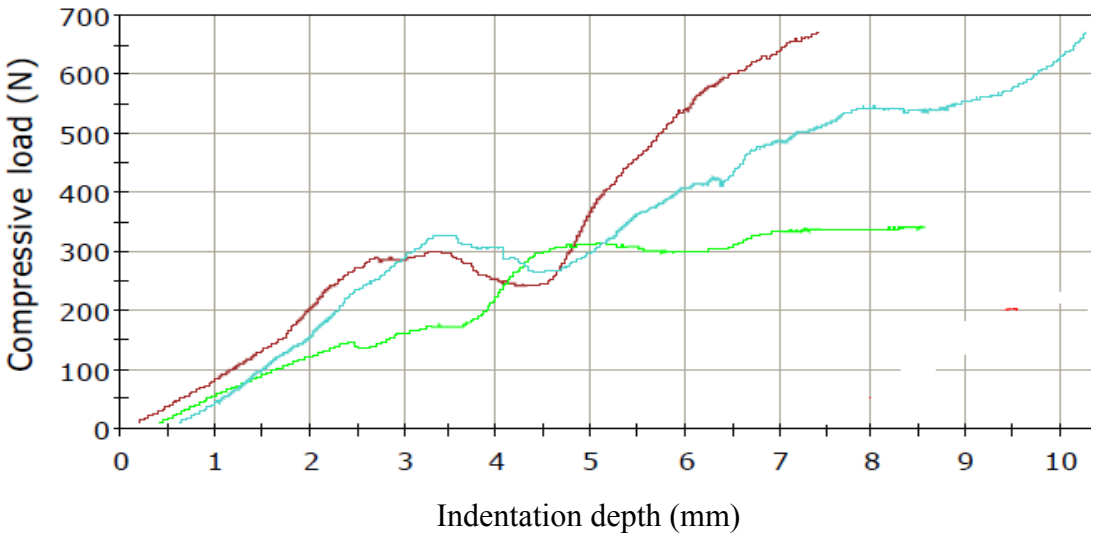
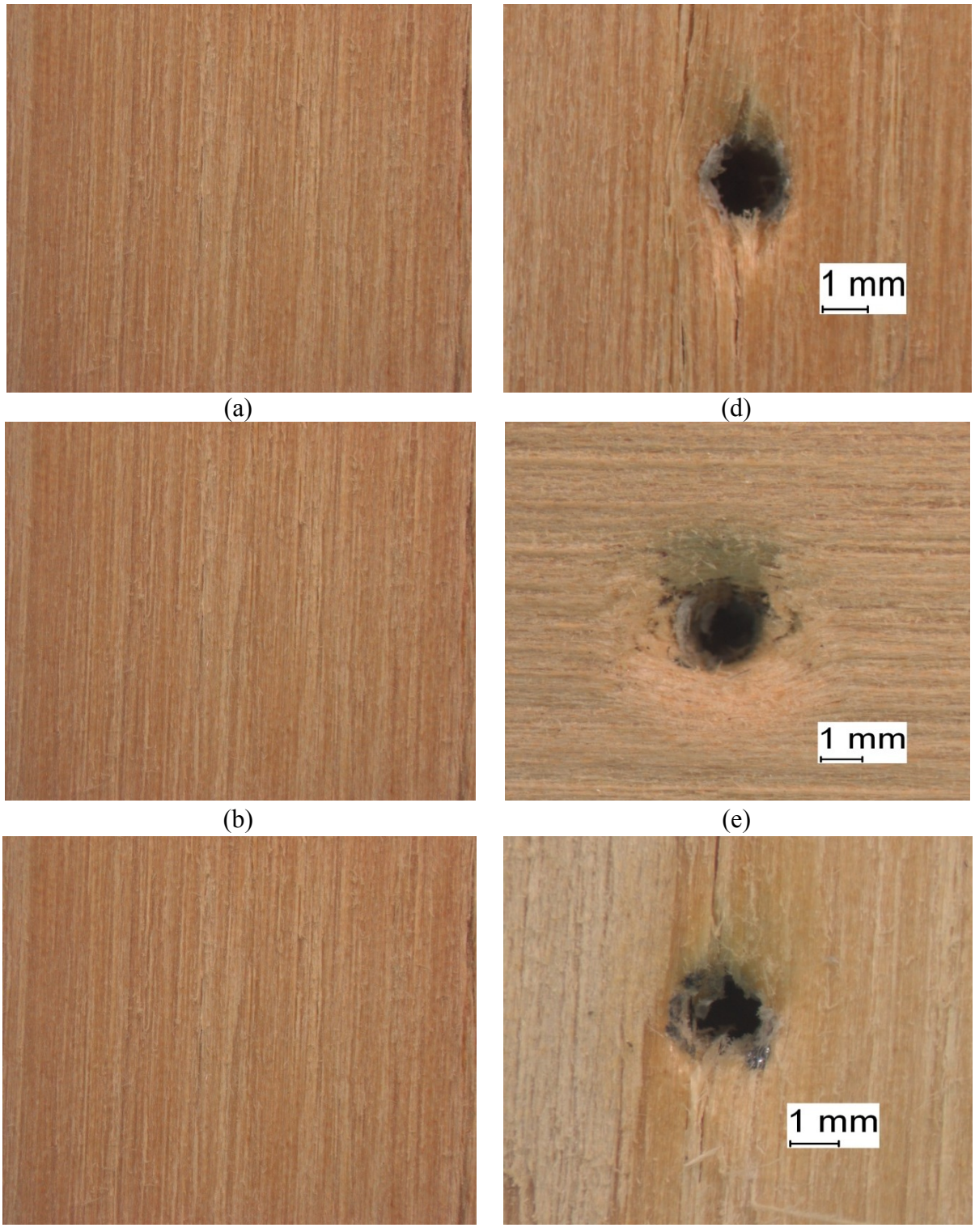


Figure 18. Compressive load/extension plot for the ASTM D6264 indentation test on a sample of three plywood specimens.

The indentation/surface failure on the samples is shown in Figure 19a – 19f. A surface contact area of indentation was approximated using the iSolutionDT® software as a circle with a radius of approximately 1.508 mm, 1.817 mm, and 1.649 mm for three plywood specimens. All samples showed puncture damage with varying depths.

The quasi-indentation test was conducted to assess the penetration of a stiletto on the floor panel of a mass-transit application. The force of 670 N is supposed to simulate the weight of an average passenger that might be wearing a stiletto heel that will cause an intense pressure point at the exposed surface. The comparison of the floor lay-up panel and the plywood is essential to prove that the sandwich composite could hold up to the pressure exerted better than the plywood and this was proven. It is shown by the testing that the penetration on the plywood is much more distinct and pronounced compared to the floor lay-up sandwich panel where the penetration was not as severe. This test therefore increases the viability of using these sandwich composites as an alternative to the plywood used currently as a bus floor replacement.



(a) (d)

(b) (e)

(c) (f)

Figure 19. (a – c) Pristine, and (d – f) indented surfaces of the plywood imaged using a stereoscope.

7.2. Biobased Content

The biobased content of each sandwich composite structure was calculated by weight percent. The renewable content contained in the composite specimen was driven by the kenaf fiber mat that is 100% renewable and 20% of the soy-oil polyurethane foam core. The non-renewable content present in the sandwich composite panels were the glass fiber mats, vinyl ester resin system, the isocyanate used in the PU foam and the remaining percentage of non-renewable resources used in the polyol. An approximation was used for the light glass webbing inside the PU foam in the core. It was assumed to be about 20% by weight of the final foam content. The approximate renewable content of the respective samples were calculated using these parameters and assumptions and are shown in Table 10.

Table 10. Weight of Components in Floor Lay-Up Structure

Sandwich Structure	**Renewable Content (% w/w)**
Floor Lay-Up	15

8. CONCLUSION AND FURTHER RESEARCH

Soy oil-based polyurethane foam used as a core in a sandwich composite construction with facesheets of hybridized kenaf and E-glass fiber in a vinyl ester matrix to replace traditionally used plywood sheeting on steel frame for a mass transit bus flooring system shows favorable potential. The floor lay-up sandwich structure with renewable content incorporated in its construction exhibited improved performance in comparison to plywood. The flexural strength exhibits a 130% increase and the flexural modulus value displays an increase of 135% compared to plywood values with a good level of biobased content by weight in the component as compared to the plywood it is replacing in this application. The consistent indentation data obtained for the sandwich composites indicate better performance compared to plywood which is erratic. The low shear and compressive values were expected and are not as critical compared to the flexural and indentation values in the utilization of these sandwich composites as direct replacement for plywood.

Further research to evaluate similar renewable based sandwich structures with higher biobased content to replace other selected components in mass transit systems needs to continue to realize the final goal of fabricating 100% biobased sandwich composites that will help reduce the dependence on petroleum based products. The use of only water as a blowing agent for the PU foam formulation effectively reduced the need for the use of other synthetic blowing agents, surfactants, and catalysts which would decrease the biobased content of the PU foam is a significant step towards a more sustainable processing method. If higher mechanical properties are desired in the PU foam core, then the use of these blowing agents, surfactants and catalysts can be used.

The use of natural fiber webbing in place of the glass fiber webbing in the foam core would also increase the biobased content without decreasing the mechanical properties. In addition, due to the reaction of the hydroxyl groups in the PU foam formulation that react with the natural fibers to reduce the hydrophilicity of the fibers, the mechanical properties would potentially increase. Increasing the biobased content in the soy-based PU foam has the hazard of reducing mechanical properties but it helps increase the thermal properties. Another option to be considered is hybridizing the PU foams with the mixture of higher biobased content soy-based PU foam with one that has a lower biobased content to achieve a good balance in properties. In addition, the incorporation of biobased fillers could also help increase the biobased content without adversely affecting the properties.

There are a few promising steps that can be explored in the fabrication of the sandwich composites such as increasing the biobased content of the PU foams as discussed above, increasing the number of natural fiber lay-ups and also using a biobased matrix as an alternative for the vinyl ester resin system used. An advantage observed from the usage of the natural fiber mats instead of its synthetic counterpart from a processing standpoint is that breather materials and distribution media which are critical in the processing of synthetic fibers in VARTM do not need to be used. This is due to the porosity of the natural fiber mats that effectively replicates the purpose of both aforementioned articles. This reduces the cost of processing and the surface finish of the composite as it now does not have the distribution media's imprint on the part produced.

A disadvantage that is observed from natural fibers compared to synthetic fibers is that it absorbs more resin thus increases the weight of the sandwich structure. Increasing the number of

natural fiber mat lay-ups increases the biobased content but further research needs to be conducted to ensure that mechanical properties are not adversely affected. The current lay-up sequences with the highest biobased content only utilizes two natural fiber mats and four glass fiber mats and this can be altered by increasing the natural fiber mats. The sandwich composite weight is higher than the weight of plywood but a point that needs to be accounted for is that due to the higher flexural properties obtained for sandwich structures, this allows for a reduction in the steel reinforcement used with plywood in bus floor panels to be reduced and the weight differences would be less drastic.

In addition, considerations to the life cycle analysis of these sandwich structures as replacements in mass transit applications needs to be conducted to ensure that the biobased direction taken is a sustainable solution. The sustainability of the materials used in the processing procedures also need to be further examined to further justify the usage of natural resources in this application and other similar applications in the future.

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