Manufacturing of Lightweight Sandwich Structure Engineered Wood Reinforced With Fiber Glass: Selection of Core Materials Using Hybridized Natural/Engineered Fibers

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Lightweight sandwich engineered wood reinforced with fiber glass using a natural fiber wood foam core was investigated. A prepreg epoxy formulation was used as both wood adhesive and matrix for the prepreg fiber glass. Combining 3 phr of oxybis(benzenesulfonylhydrazide) (OBSH) with 10 phr of ethyl acetate~~,~~ as foaming agent enhanced the properties of the eucalyptus fiber (EF) wood foam. Incorporation of rice-husk fiber (RF) or bagasse (BG) into the EF reduced the mechanical properties due to the low aspect ratio and high non-compacted bulk density of RF and BG. The high hydrophilicity of BG increased the water uptake and decreased the dimensional stability of the wood core. The mechanical performance of the natural fiber cores was improved by using randomized unidirectional engineered glass (GF), carbon (CF), and Kevlar (KF) fibers. However, the hybridized cores with long fibers and high elastic modulus, with respect to the sample thickness, had a negative impact on the woods due to internal residual stress, leading to a spring-back effect. A fiber glass reinforcement lightweight sandwich structure with engineered wood derived from the EF/BG and its 30% hybrid lightweight cores yielded superior mechanical and durability properties.

Keywords: Lightweight pane; Sandwich LVL; Hybrid core; Mechanical and durability properties

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INTRODUCTION

Sandwich structures are used in a wide range of engineering applications, including airframes, transportation vehicles, boat hulls, radar systems, and space structures due to their many advantages such as being lightweight and having a high stiffness-to-weight ratio, corrosion resistance, good fatigue resistance, high durability, and good thermal and acoustical insulation compared with conventional structures (Vaikhanski and Nutt 2003; Fang *et al*. 2015; Mohamed *et al*. 2015). Most high-performance structural foams are made by expanding and blowing liquid polymers to form rigid, low density foams. Some of the thermoplastic foams made in this way are polymethacrylimide (PMI) and partly cross-linked polyvinyl chloride (PVC) (Vaikhanski and Nutt 2003). Moreover, foams typically do not contain fiber reinforcement, and thus the enormous potential of high performance fibers that is so successfully exploited in conventional polymer composites has not been widely applied to structural foams. High modulus fiber provides stiffness and load-bearing qualities, whereas low modulus fiber makes the composite more damage-tolerant and keeps the material cost low (Kedar *et al.* 2011). Foam materials made from thermoplastics reinforced with fiber include PP/wood flour composites and surface-modified rice husk-filled polyvinylchloride (Chand *et al*. 2012; Soares and Nachtigall 2013). Also, a wood/natural rubber composite and ethylene-propylene diene rubber (EPDM) foam made by compression molding technique has been created (Yamsaengsung and Sombatsompop 2009). Moreover, thermosetting foam based on epoxy has been reported (Mazzon *et al*. 2015).

Engineered wood is typically manufactured with a density of 0.8 to 1.2 g/cm^3, which is similar to natural woods. Lower density indicates inferior stiffness and *vice versa*. Construction materials that are lightweight and have a natural appearance are required for real estate applications, especially in the construction of high-rise apartment buildings. The foam core sandwich structures not only save weight but they also provide sound proofing and heat insulation. Engineered woods, particularly lightweight sandwich engineered wood reinforced with fiber glass, having high performance foam core, would be interestingly candidates for such need. Recently, there have been a number of research publications dealing with engineered woods made from foam structures (Dweib *et al*. 2004; Denes *et al.* 2008; Fajrin *et al.* 2013; Pishan *et al*. 2014).

For producing closed or open foam cell structures, there are three commercial methods: (*i*) chemical reaction, (*ii*) thermal degradation, and (*iii*) physical expansion foaming agent. In this report, oxybis(benzenesulfonylhydrazide) (OBSH) and ethyl acetate (EA) classified as thermal degradation and physical expansion or vaporization types, respectively, were combined and used as the foaming agent. The foam cell characteristics, size and distribution control the performance of the foam core in sandwich structures (Poapongsakorn and Carlsson 2013; Babaei *et al*. 2014; Del Saz-Orozco *et al*. 2014; Chen *et al*. 2015). Interfacial adhesion between the skin and core of the discontinuous phase constituents is a crucial parameter to determine the engineering performance of the material. Several approaches have been explored to enhance the bonding adhesion between skins and core (Sun *et al*. 2012; Sun *et al*. 2013; Wang *et al*. 2015).

In this report, the lightweight sandwich engineered woods reinforced with fiber glass were manufactured using wood foam cores derived from natural fibers with and without hybridization, reinforcement, and high performance engineering fiber. The epoxy adhesive with thermal degradation and degraded gas expansion type foaming agents were employed in a single step hot molding process.

EXPERIMENTAL

Materials

The materials used in this work were epoxy adhesive, fibers, and blowing agents. The prepreg epoxy formulation was manufactured in-house. The epoxy was blended with 5 phr of polycarbonate and 1 phr of silane. The hardener was based on amines and dicyanodiamide. It was used as wood adhesive and also the matrix for the fiber glass reinforced composite. Both natural and synthetic fibers were used. Eucalyptus (EF), bagasse (BG), and rice husk (RF) fibers were locally obtained. BG and RF were mechanically size-reduced in the internal mixer at 170 °C. The synthetic reinforcements; glass (GF), carbon (CF), and Kevlar (KF) fibers, were industrial waste and available in short pulp form with lengths of 5 to 8 mm. Fiber glass with an aerial density of 100 g/m^2 was employed as the laminated reinforcement structure on the teak veneer skins. All synthetic fibers were used without further treatment. The blowing agents ethyl acetate (EA) and oxybis(benzenesulfonylhydrazide) (OBSH) (A. F. Supercell Co., Ltd., Rayong, Thailand) were combined and employed, such that 10 phr of ethyl acetate(EA) was pre-mixed with the prepreg epoxy adhesive. EA was the blowing agent and also the resin diluent. All chemicals were used as received.

Woods Sample Preparation

Wood foam cores

Table 1 shows the formulation of lightweight wood foam employed in this study. The wood foam core had a density of 0.70 g/cm^3. The mold dimensions were 20×20 cm^2 with a depth of 0.50 cm, and the total weight of fiber(s)/epoxy resin mixture was 140 g. Fibers were vacuum-dried at 105 °C for 4 h, and precise amounts at the given blending ratio were vigorously pulped in a 25 liters high speed mixer equipped with the metal blades (LabTech Engineering Co., Ltd, Samutprakarn, Thailand) for 2 min. Three stop/pause actions were applied. The pre-calculated amount of epoxy resin, 40 phr corresponding to the total fiber(s), and foaming agents were prepared in a plastic cup. Robust high speed mechanical stirring was applied for the best mixing of the resin. Approximately half of the mixed resin was immediately poured onto the pulpy mixed fiber(s), and a mechanical force coating was achieved by high speed rotation. The rest of the epoxy adhesive was finally added and completely coated onto the fibers in the same fashion. The adhesive/foaming agent coated fiber(s) were evenly transferred into the mold cavity lined with PTFE sheets. Cold compression was applied. The mold was then placed on the compression machine (GT-7014-A30, GoTech Testing Machines Inc, Taiwan) at 180 °C and 120 kg$_f$/cm^2, with a press/decompress/press cycle at 240, 5, and 180 sec, respectively. The cured wood foam core was demolded and annealed at room temperature overnight. The test specimens were sawn, edge-polished, and post-cured at 120°C for 12 h before testing.

Table 1. Typical Base Formulation for Manufacturing the Wood Foam

Fiber (g)	Epoxy Resin Formulation			
	Epoxy Resin (g)	Silane (g)	EA (g)	Hardener (g)
100	31.5	0.4	4	8.5

Lightweight sandwich structure reinforced with glass based on wood foam cores

Teak veneers with a thickness of 0.8 mm and dimensions of approximately 20 × 20 cm^2 were used as skins for the manufacturing lightweight sandwich structure engineered wood. They were pre-laminated with fiber glass prepreg. The laminated veneer teak was placed in the mold cavity. The fiber(s) coated, with the epoxy adhesive were smoothly spread, as a core, on the laminated veneer skin. For producing the multilayer lightweight sandwich structure engineered wood, the equally divided cores were separated and reinforced with the prepreg fiber glass layers. Finally, another skin of the veneer teak laminated with prepreg glass was topped as the final layer. The molding was pre-formed by cold compression and then final consolidation at 180 °C in the same manner as producing the wood foam core. The lightweight sandwich structure engineered wood reinforced with fiber glass was demolded, saw-cut, edge-polished, and post-cured prior to the performance measurement.

Standards Testing

The mean mechanical properties including three-point bending fixture flexural and Izod impact strengths, both notched and unnotched, were measured in accordance with

ASTM D790-10 (2010) and ASTM D256-10e1 (2010), respectively. The heat distortion temperature (HDT) at 1820 kPa and the maximum service temperature of the woods were also evaluated followed by ASTM D648-07 (2007). The durability of the wood was measured in accordance with ASTM D570-98(2010)e1 (2010), evaluated by % water absorption (WA_i), % thickness swelling (TS_i), and dimension stability after removing the moisture or % thickness swelling after drying ($TS_{dried,i}$) during 1- and 7-day test periods. Fiber morphology and the fiber/adhesive interfacial adhesion were visually investigated by scanning electron microscopy (SEM) with a JSM-6010LV, JEOL Ltd., Tokyo, Japan.

RESULTS AND DISCUSSION

Effect of OBSH Foaming Agent on Eucalyptus Wood Foam Cores

As shown in Table 1, the ethyl acetate (EA) dilution solvent for the high viscosity prepreg epoxy adhesive was evaporated to form the opened foam cell during the high curing temperature. A non-uniform open cell, which is inferior in its properties, is normally observed. However, in a closed mold cavity, the expansion pressure during the foaming stage consolidates the fiber/adhesive constituent to form the hard network skeleton structure of the wood foam. The denser skeleton has better mechanical properties than the wood. The thermal degradation type foaming agent, OBSH, produces good foam cell structures in thermoplastic foam manufacturing. In this work, OBSH was used at 3 to 9 phr, corresponding with the epoxy adhesive, in conjunction with the EA to fabricate the wood foam core. The tested properties of the wood foam core obtained with various OBSH contents are summarized in Table 2.

Table 2. Effect of the Blowing Agent on Eucalyptus Foam Core Properties

OBSH[a] (phr)	Sample Thickness (mm)	Impact Strength (kJ/m^2)		Flexural Properties			HDT[b] (°C)
		Notched	Unnotched	Strength (MPa)	Modulus (GPa)	Max. Def. (mm)	
0	4.93 ± 0.06	3.22 ± 0.30	3.70 ± 0.47	10.00 ± 0.99	1.02 ± 0.12	3.50 ± 0.73	37.4 ± 0.72
3	4.96 ± 0.08	2.96 ± 0.22	3.81 ± 0.25	14.73 ± 0.83	1.56 ± 0.09	3.35 ± 0.74	41.5 ± 0.42
5	4.92 ± 0.05	2.87 ± 0.14	3.60 ± 0.20	8.99 ± 0.60	1.01 ± 0.05	2.85 ± 0.45	35.9 ± 1.03
7	4.96 ± 0.06	2.88 ± 0.29	3.43 ± 0.27	15.18 ± 0.97	1.42 ± 0.10	3.65 ± 0.49	37.5 ± 0.64
9	5.00 ± 0.04	3.04 ± 0.32	3.82 ± 0.29	11.74 ± 0.92	1.30 ± 0.04	2.90 ± 0.22	33.7 ± 0.42

[a] Oxybis (benzenesulfonylhydrazide) and [b] Heat Distortion Temperature

The notched impact strength was decreased with increasing OBSH contents. Unlike the notched samples, the unnotched impact strength was marginally increased with the addition of the OBSH foaming agent, which is typical for opened-cell structures. Notching the opened cell of the test specimen initiates a number of crack tips, which then propagate. Therefore, the notched impact strength is inferior. The three-point bending flexural properties – strength, modulus, and deformation at break – were also measured. The flexural strength of the wood foam manufactured with the combined EA/OBSH foaming agent was higher than the sample using only EA. However, the inferior trend was observed when increasing the OBSH content. These trends were also noted for the modulus and maximum deformation at break; the wood foams were brittle at high OBSH content. At 1820 kPa, the HDT values of the eucalyptus based wood foam samples were not significantly enhanced by introducing the thermal degradation foaming agent, OBSH, into the compression molding process. SEM images revealed obvious split crack traces in the sample using only EA (Fig. 1), and more dense areas were found on the sample with 9 phr of OBSH than on the 3 phr one. Generally, the toughness of the wood sample was caused by the non-uniform split crack traces. It was postulated that fast evaporation caused explosive behavior when only low boiling point ethyl acetate solvent was the foaming agent. Adding the high temperature degradation foaming agent OBSH into the adhesive generated the consolidation pressure during the gas expansion. Therefore, micro-network solid skeletons were formed, and the mechanical properties of the lightweight wood were improved.

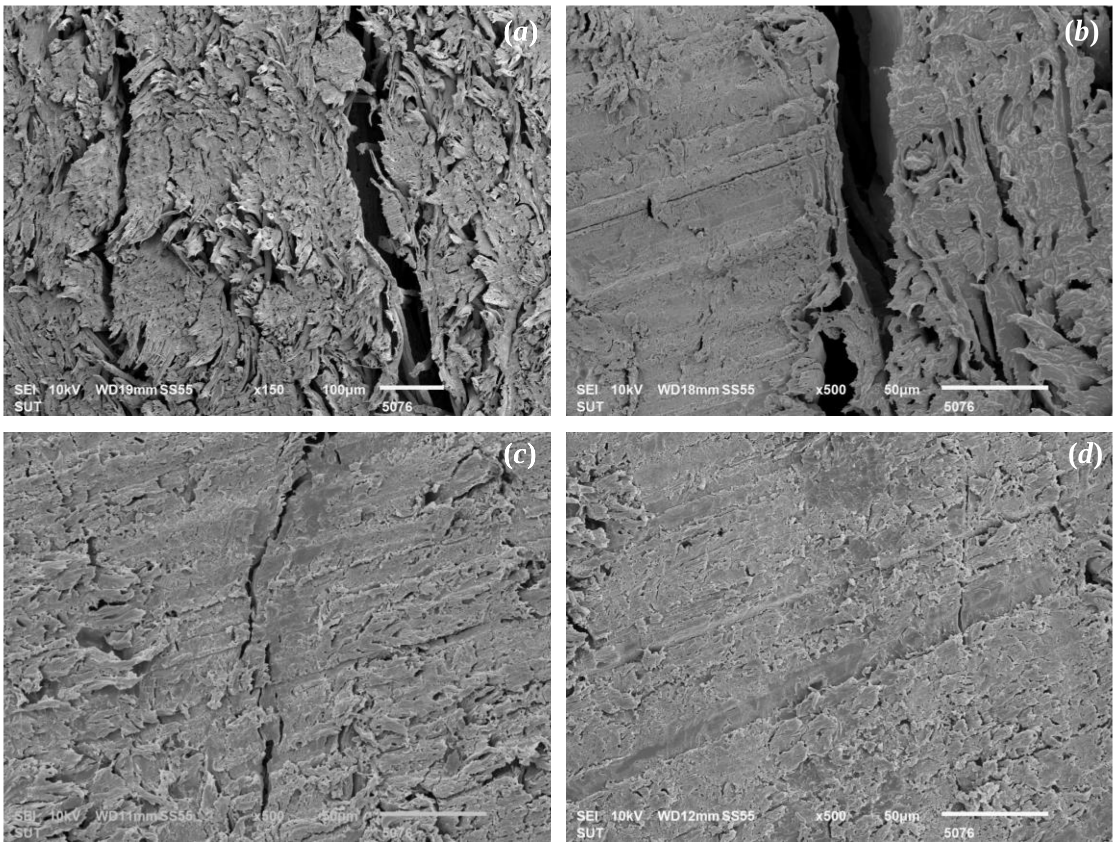

Fig. 1. SEM micrographs of eucalyptus wood foam (a) without OBSH at 150X, (b) without OBSH, at 500X, (c) with 3 phr OBSH, and (d) with 9 phr OBSH at 500X

Table 3 shows the mean dimension stability under extreme humidity. After 1 or 7 days, the % WA of the EA-containing wood was higher than that of the combined EA/OBSH foam. By elevating the OBSH ratio, the % water uptake in the samples also increased.

Similar trends were observed for the % TS_i and % $TS_{dried, i}$ values of the vacuum-dried samples. These results agreed with the performance test outcomes, such that a higher number of split crack/void traces resulted in higher values of water uptake and sample expansion. Thus, the combination of OBSH with the low boiling point diluent/solvent based foaming agent, ethyl acetate (EA), produced better properties in the manufactured wood foam product. The best properties were observed with 3 phr OBSH by weight.

Table 3. Durability Properties of the Eucalyptus Wood Foam Core with Difference OBSH Contents

OBSH (phr)	% Water Absorption (WA_i)		% Thickness Swelling (TS_i)		% Thickness Swelling After Drying ($TS_{dried,i}$)	
	1 Day	7 Days	1 Day	7 Days	1 Day	7 Days
0	90.9 ± 19.3	100.9 ± 9.2	24.2 ± 1.4	25.2 ± 2.4	9.0 ± 2.4	9.8 ± 2.5
3	71.7 ± 9.7	73.3 ± 2.2	20.4 ± 1.0	20.2 ± 1.7	4.9 ± 0.8	5.7 ± 1.1
5	71.8 ± 0.3	105.9 ± 8.4	22.6 ± 1.1	22.9 ± 2.2	6.6 ± 0.9	10.1 ± 1.4
7	79.9 ± 6.6	85.5 ± 11.3	23.6 ± 1.7	21.7 ± 2.4	8.9 ± 1.2	8.1 ± 2.2
9	93.9 ± 4.4	84.9 ± 2.7	24.7 ± 2.3	23.7 ± 0.2	9.1 ± 2.1	8.2 ± 0.2

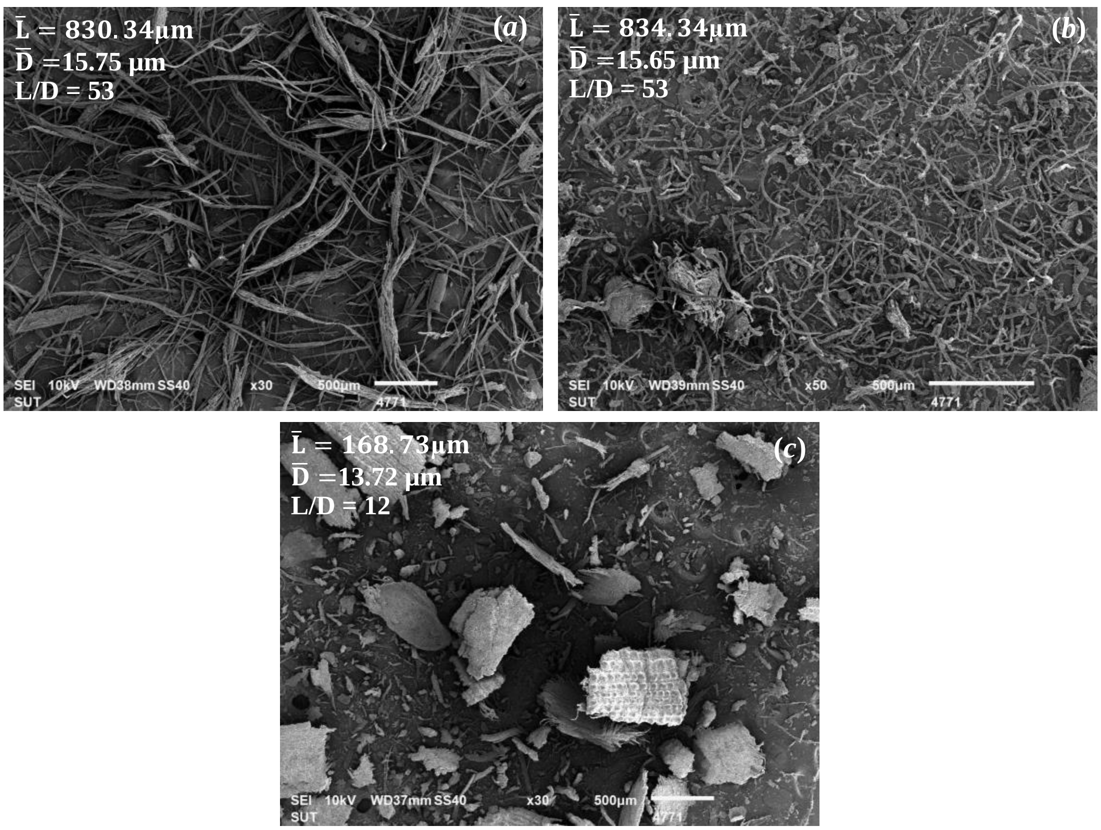

Fig. 2. SEM micrographs of (a) EF, (b) BG, and (c) RF

Wood Foam Cores Made from Combined Fibers

Bagasse and rice husk are agricultural wastes, and they are the most abundant agricultural by-product in Thailand. The performance of the man-made composite materials, including engineered wood, depend largely on the fiber aspect ratio or L/D ratio of the fiber used. Combining the economical forest wood fiber, eucalyptus, with by-product fibers from agro-industries was investigated for improving the wood foam properties. Figure 2 illustrates the physical forms of ground fibers observed by SEM. The average length (L), diameter (D), and L/D ratio, μm/μm, of the fibers were also digitally measured, and the average values were included on the micrographs. They were used to form the lightweight wood foam samples.

The fibers were combined at various fractions with the prepreg epoxy adhesive, 10 phr EA, and 3 phr OBSH foaming agent, corresponding to the adhesive, to manufacture wood foam cores.

The performance properties of the obtained woods are summarized in Table 4. The wood derived from only EF showed the most promising impact strengths, both notched and unnotched. The strengths were diminished when the BG fraction was introduced. Further increases in the low *L*/*D* fiber, RF, or fraction onto the fibers mixture reduced the impact toughness. Similar trends on the negative effect of the low fiber aspect ratio were found for flexural properties and HDT. Thus, the *L*/*D* ratio of the fibers, as one of the main constraints for regulatory the properties of the fiber reinforced materials, is the key factor responsible for the diminish properties of the lightweight wood foam. In addition to the *L*/*D* ratio, the nonconsolidated bulk density of the fiber plays a critical role in the physical properties of the wood foam. At a given foam density, reinforced fiber with a bulk density higher than the density of the foam product is loosely packed, forming a weak network skeleton for the open cell foam structure. Consequently, the lightweight foam product with poor mechanical properties would be obtained. Rice husk fiber, employed here in this work, had the highest bulk density. With an identical *L*/*D* ratio, the shorter and smaller bagasse fibers also had higher in bulk density than the pulpy, high aspect ratio, of the eucalyptus fiber. For that reason, combining RF or BG into the EF must reduce the mechanical properties of the wood.

Table 4. Properties of Eucalyptus Foam Core with Different Combinations of Natural Fibers

EF/BG/RF	Sample Thickness (mm)	Impact Strength (kJ/m^2)		Flexural Properties			HDT (°C)
		Notched	Unnotched	Strength (MPa)	Modulus (GPa)	Max. Def.(mm)[a]	
100/0/0	4.96 ± 0.08	2.96 ± 0.22	3.81 ± 0.25	14.73 ± 0.83	1.56 ± 0.09	3.25 ± 0.25	41.5 ± 0.42
50/50/0	5.22 ± 0.04	2.02 ± 0.22	2.05 ± 0.21	6.56 ± 1.05	0.70 ± 0.13	2.58 ± 0.63	33.7 ± 2.42
50/0/50	4.97 ± 0.04	1.72 ± 0.18	1.70 ± 0.17	7.80 ± 0.83	0.82 ± 0.11	3.42 ± 0.30	35.6 ± 2.27
33/33/33	4.97 ± 0.09	1.35 ± 0.23	1.70 ± 0.19	4.84 ± 0.53	0.62 ± 0.09	2.46 ± 0.25	31.4 ± 1.56

[a] Maximum deformation at break

In the dimensional stability tests, the woods made from a high fraction of EF and RF showed low % WA for both for 1 and 7 days immersion (Table 5), which could be explained by the hydrophobicity of the fibers. Eucalyptus fiber has a high oil content. Rice husk acts as a moisture barrier for the starch granule. Thus, it is the hydrophobic skin, which prevents water infusion to the fibers. Hence, the wood foam sample having a high content of EF and/or RF had low % water intake.

The samples with long fiber length, EF, showed the spring phenomenon, *i.e.*, high thickness expansion under water infusion and subsequent removal. With a high content of short length natural fibers, 33% BG and 33% RF, the thickness of the sample after immersion in water for 7 days and then vacuum drying was reduced. Therefore, the % $TS_{dried, 7}$ was below zero.

Table 5. Durability Properties of Wood Foam Core with Difference Combinations of Natural Fibers

EF/BG/RF	% Water Absorption (WA_i)		% Thickness Swelling (TS_i)		% Thickness Swelling After Drying ($TS_{dried, i}$)	
	1 Day	7 Days	1 Day	7 Days	1 Day	7 Days
100/0/0	63.9 ± 16.3	67.9 ± 8.2	16.8 ± 2.7	18.4 ± 0.8	2.6 ± 1.8	1.1 ± 0.8
50/50/0	97.6 ± 11.2	106.0 ± 17.7	16.9 ± 2.4	16.9 ± 1.6	3.1 ± 1.2	1.6 ± 2.0
50/0/50	77.8 ± 8.1	68.0 ± 3.1	12.3 ± 0.6	13.4 ± 1.6	1.7 ± 0.6	0.3 ± 1.1
33/33/33	66.0 ± 3.1	64.6 ± 3.7	14.1 ± 0.8	13.9 ± 0.7	1.5 ± 0.7	-0.5 ± 0.2

Enhancement of Wood Foam Cores using Synthetic Engineered Fibers

The uniformed diameter, *L*/*D* ratio, and mechanical properties of synthetic engineering fibers are easily controlled. The unidirectional synthetic fiber pulp employed in this work was the waste from a surfboard manufacturer. The fiber was roughly cut to 5 to 8 mm in length and mechanically beaten into monofilament pulp before use. Figure 3 shows SEM of the pulp form and the average values of *L*, *D*, and *L*/*D* of the engineered fibers combined with natural fibers in the lightweight wood foam cores. The CF monofilament had the smallest diameter (*D*) and longest length (*L*) at 6.50 μm and 6000 μm, respectively. The *L*/*D* ratio of CF, GF, and KF fibers were 923, 398, and 273, respectively.

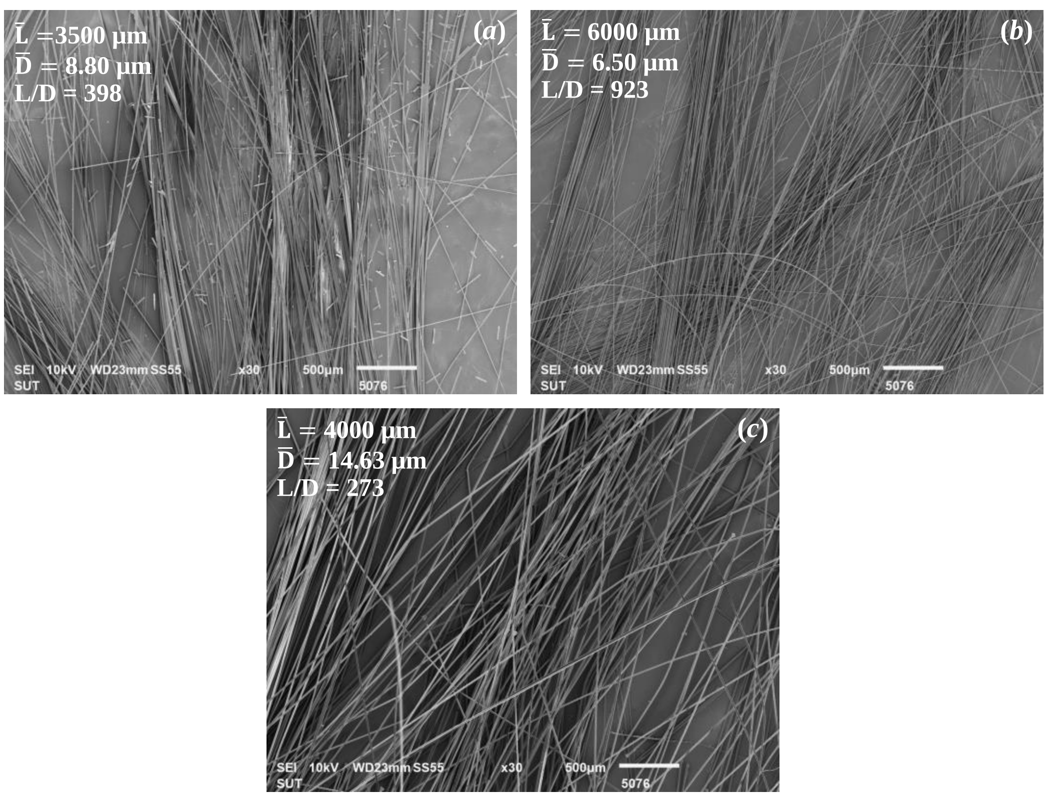

Fig. 3. SEM micrographs of (a) GF, (b) CF, and (c) KF fibers at 30×

Table 6 shows the properties of hybrid wood core foams. The number notations represent the weight fraction of each fiber. For the eucalyptus hybridized with 30% synthetic fibers, both notched and unnotched impact strengths were higher than the non-hybrid core. The order of increasing impact strength was CF, GF, and KF hybrid. Unexpectedly, the flexural strength and modulus of the core made from hybrid fibers were not very much improved. The CF- and KF-reinforced wood foam showed lower flexural properties than the non-hybrid sample. The randomized "long fiber" unidirectional reinforced type samples of CF would be responsibility for the drawback results. This statement will be explained later on. However, the maximum deformation at break of the hybrid systems was noticeably higher than the system using only eucalyptus fiber. Normally, engineered synthetic fibers have more flexibility than natural fibers. Combining the synthetic fibers with the bio-based fibers increases the elasticity of wood cores. The HDT of the wood foam core samples were more or less identical, which suggested that synthetic fibers had no effect on this property.

For the wood cores manufactured from binary natural fiber, EF/BG at 50:50, and hybridized with engineered fibers, the test results showed that the impact strengths were enhanced by the synthetic fibers. Moreover, the flexural properties were superior with the addition of engineered fibers, especially in the KF hybrid system. In addition to the mechanically enhancement, the HDT of the core was enriched by the hybridization.

Table 6. Properties of Natural/Synthetic Fiber Foam Core Hybrids

Wood Foam Cores	Sample Thickness (mm)	Impact Strength (kJ/m^2)		Flexural Properties			HDT (°C)
		Notched	Unnotched	Strength (MPa)	Modulus (GPa)	Max. Def. (mm)[a]	
100EF	4.96 ± 0.08	3.96 ± 0.22	3.81 ± 0.25	14.73 ± 0.83	1.56 ± 0.09	3.25 ± 0.25	41.5 ± 0.4
70EF/30GF	5.03 ± 0.05	7.58 ± 0.38	10.24 ± 0.96	16.67 ± 2.82	1.47 ± 0.14	4.00 ± 0.98	39.9 ± 0.3
70EF/30CF	6.11 ± 0.05	3.47 ± 0.38	5.15 ± 0.46	9.84 ± 0.96	1.00 ± 0.15	4.25 ± 0.54	43.3 ± 0.2
70EF/30KF	5.23 ± 0.07	12.39 ± 1.22	13.76 ± 2.12	12.40 ± 0.84	1.10 ± 0.09	4.04 ± 0.33	41.4 ± 0.5
50EF/50BG	5.22 ± 0.04	2.02 ± 0.22	2.05 ± 0.21	6.56 ± 1.05	0.70 ± 0.13	2.58 ± 0.63	33.7 ± 2.4
35EF/35BG/30GF	5.37 ± 0.04	2.66 ± 0.18	4.51 ± 0.43	8.08 ± 0.43	0.82 ± 0.04	3.13 ± 0.32	39.4 ± 3.7
35EF/35BG/30CF	5.66 ± 0.05	2.78 ± 0.19	4.19 ± 1.49	8.88 ± 0.74	1.07 ± 0.11	3.19 ± 0.24	42.9 ± 2.7
35EF/35BG/30KF	5.34 ± 0.05	9.74 ± 0.64	11.79 ± 0.77	10.70 ± 1.44	0.92 ± 0.06	4.19 ± 0.38	41.1 ± 2.4
50EF/50RF	4.97 ± 0.04	1.72 ± 0.18	1.70 ± 0.17	7.80 ± 0.83	0.82 ± 0.11	3.42 ± 0.30	35.6 ± 2.3
35EF/35RF/30GF	4.97 ± 0.08	3.74 ± 0.23	5.50 ± 0.79	9.33 ± 1.10	0.85 ± 0.03	3.50 ± 0.54	40.9 ± 0.8
35EF/35RF/30CF	5.83 ± 0.06	2.37 ± 0.25	2.75 ± 0.41	4.60 ± 0.60	0.53 ± 0.04	2.19 ± 1.01	37.7 ± 1.5
35EF/35RF/30KF	5.12 ± 0.11	7.92 ± 1.12	7.59 ± 0.71	12.14 ± 1.43	1.01 ± 0.08	4.50 ± 0.54	36.9 ± 1.6

[a] Maximum deformation at break

Eucalyptus and the lower *L*/*D* ratio of RF fibers were also investigated. As expected, loading the high *L*/*D* ratio and strong fibers into the natural fibers increased the mechanical performances of the wood foam cores. The order of enhancement was KF, GF, and CF. However, the HDT of the EF/RF hybrid systems did not significantly change with the synthetic fiber loading, except for the GF sample.

As noted previously, the performance of the wood foam core derived from absolute natural fibers depended on the *L*/*D* ratio and bulk density, converted into volume fraction, of the fibers. The properties of the wood foam cores were inferior when the highest *L*/*D* ratio eucalyptus fiber was combined with lower *L*/*D* ratio but higher bulk density fibers, BG and RF, respectively. Further enhancement of those fiber(s) with high *L*/*D* ratio and superior strengths of engineered fibers, GF, CF and KF, was established. The order of the mechanical enhancement was CF, GF, and KF. An excess *L*/*D* ratio and long fiber length (L = 6000 μm) of CF formed a randomized unidirectional "long fiber" reinforced sample. At the given wood foam core thickness of approximately 5 mm, the excess length of the CF was compressed and bended into the thickness of the wood sample. Hence, as CF has a high modulus of elasticity, the residual stress on the bended CF fiber caused it to behave like a "force-loaded spring" in the wood foam core test specimen. The vast internal residual stress was added to the adhesive solidification. When such the wood core reinforced with the compacted spring-like fiber is subjected to the external loading force during the mechanical testing, it would be easily broken. Consequently, low mechanical test results were observed. The spring-like phenomenon of the CF was visualized in the durability test. According to the rule of mixture, the effect of volume fraction of the engineered fibers on the mechanical properties of the wood cores was negligible. Generally, within these assigned engineered fibers waste, CF and KF have a relatively lower bulk density but higher modulus than the GF. Therefore, at a given equal weight fraction loading, the KF and CF hybrid samples must have the higher volume fraction. Consequently, the mechanical properties of KF and CF hybrid wood were enhanced more than the GF hybrid. However, the opposite trend was observed. In the wood core foam, the *L*/*D* ratio of the fiber used with respect to the sample thickness and also the unconsolidated bulk density are the main critical considerations. In contrast, too much lower *L*/*D* ratio and high bulk density fibers results in inferior properties in the wood foam core. However, a much higher aspect ratio of fibers with respect to the wood thickness, especially the engineered fibers, weakens the mechanical properties of the material because of the internal residual stress or "spring effect".

Table 7. Durability Properties of Natural/Synthetic Fiber Foam Core Hybrids

Wood Foam Core	% Water Absorption (WA_i)		% Thickness Swelling (TS_i)		% Thickness Swelling After Drying ($TS_{dried, i}$)	
	1 Day	7 Days	1 Day	7 Days	1 Day	7 Days
100EF	63. ±9 16.3	67.9 ± 8.2	16.8 ± 2.7	18.4 ± 0.8	2.6 ± 1.8	1.2 ± 0.8
70EF/30GF	102.6 ± 2.6	121.0 ± 7.9	13.9 ± 4.0	15.5 ± 0.4	1.8 ± 2.8	-1.3 ± 0.6
70EF/30CF	116.0 ± 18.2	125.8 ± 10.8	16.1 ± 1.0	15.1 ± 2.3	3.8 ± 1.0	0.9 ± 0.2
70EF/30KF	68.9 ± 14.4	121.2 ± 12.2	14.5 ± 1.8	14.2 ± 5.4	2.5 ± 1.5	-0.8 ± 0.4
50EF/50BG	97.6 ± 11.2	106.0 ± 17.7	16.9 ± 2.4	16.9 ± 1.6	3.1 ± 1.2	1.6 ± 2.0
35EF/35BG/30GF	75.2 ± 10.1	77.2 ± 12.8	11.4 ± 0.1	10.7 ± 1.1	0.7 ± 0.3	-1.1 ± 0.8
35EF/35BG/30CF	88.5 ± 9.9	97.7 ± 13.6	9.2 ± 0.7	7.9 ± 0.8	1.5 ± 0.5	0.6 ± 0.7
35EF/35BG/30KF	86.0 ± 6.9	74.9 ± 9.9	11.7 ± 6.8	9.7 ± 1.0	0.4 ± 0.2	-0.9 ± 0.6
50EF/50RF	77.8 ± 8.1	68.0 ± 3.1	12.3 ± 0.6	13.4 ± 1.6	1.7 ± 0.6	0.3 ± 1.1
35EF/35RF/30GF	76.1 ± 10.5	57.0 ± 24.6	8.8 ± 1.1	9.7 ± 4.2	0.1 ± 0.3	-1.0 ± 0.1
35EF/35RF/30CF	106.9 ± 6.6	81.6 ± 8.6	7.8 ± 0.8	7.2 ± 0.5	1.0 ± 0.2	0.11 ± 0.6
35EF/35RF/30KF	77.3 ± 5.0	67.1 ± 8.7	7.9 ± 0.5	7.4 ± 0.3	0.7 ± 1.1	-0.9 ± 0.2

The % WA_i, % TS_i, and % $TS_{dried, i}$ values of the hybrid wood cores are summarized in Table 7. The wood foam core samples fabricated from eucalyptus/synthetic hybrid fibers had higher % absorption, WA_1 and WA_7, than the piece made from only eucalyptus fiber. However, for the % TS_i, the 100% natural fiber core has the higher % expansion than the hybrid cores regardless of the immersion times. Within the hybrid cores, the CF hybrid showed higher % WA_i and % TS_i than the GF and KF hybrids. This result could be due to a spring-back effect based on releasing the internal residual stress of the "long" CF used for making the sample, as manifested earlier. After vacuum drying the samples after 1 day of immersion sample, the % $TS_{dried,\ 1}$ of the CF hybrid core was higher than the other samples. A similar trend was observed for the samples soaked for 7 days. Negative values for the % $TS_{dried,7}$ were recorded for the GF and KF hybrid systems. Prolonged soaking of the wood foam made from short length fibers and then sudden evaporation under vacuum drying collapsed the open cell foam structure. Consequently, the thickness of the vacuum-dried specimen was lower than the original one, showing the negative % swelling. Similar trends in the % WA and dimension stability were noticed for the wood foam manufactured from EF/BG and EF/RF and their hybrid system with GF, CF, and KF, which was explained by the high expansion of test specimen due to the spring-back effect of CF. The negative % $TS_{dried,\ 7}$ values of the wood derived from short length fibers supported this conclusion.

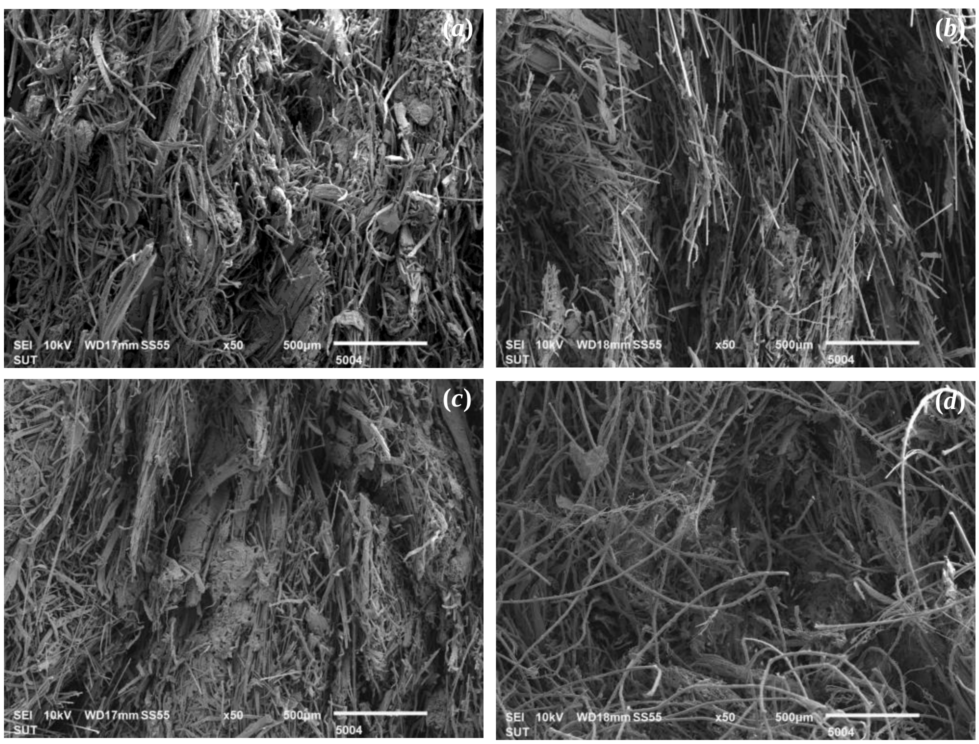

Fig. 4. SEM images of wood core made from (a) 50EF/50BG, (b) 35EF/35BG/30GF, (c) 35EF/35BG/30CF, and (d) 35EF/35BG/30KF at X50×

Figure 4 illustrates selected SEM observations taken on the fractured surface of the wood foam derived from EF/BG mixed with 30% GF, CF, and KF. Small, natural bundle fiber agglomeration was observed. The length of GF was broken and formed the shorter length, compared with the original length seen in Fig. 3(a), after mechanical mixing with the epoxy adhesive in the high speed mixer and compression on the mold to form the wood core specimen. In contrast, unbroken, long, and curved fibers were seen in the CF and KF hybrid wood cores. These results confirm that compression generated internal residual stress on the bent fibers during molding, creating a "compacted spring" in the thickness plane of the reinforced wood sample. The stressed sample then exhibited mechanical failure due to the release of internal stress. This SEM data explains the unexpected result when CF is used to reinforce the wood foam core.

Lightweight Sandwich Structure Engineered Woods Reinforced With Glass

To avoid the monopodial raw material dependency on only the high *L*/*D* ratio eucalyptus fiber, a further investigation was conducted for product upgrading the hybridized EF/BG cores by manufacturing the sandwich structure engineered wood having the teak veneer reinforced with fiber glass to form the lightweight wall panel. Teak veneer is used for its mechanical strength and termite resistance, but it is also important as a decorative surface. Moreover, the layers of fiber glass prepreg were laminated in between teak veneer and wood core for the additional strength enhancement. Single (1XLVL) and double layer (2XLVL) sandwich structures were made by single step compression molding (Fig. 5) and their properties were examined. The cores were uniformly separated by the prepreg fiber glass. Table 8 compares the EF/BG sandwich structures with their wood foam cores. For the sandwich structure derived from the non-hybrid EF/BG cores, both the notched and unnotched impact strengths were greatly enhanced. Furthermore, the impact strength of the 2XLVL was almost double that of the 1XLVL sample. The identical trend on the improvement of the 2XLVL over 1XLVL were also found in the flexural testing results. Under the three-point bending flexural testing, inclusively core debonding were observed.

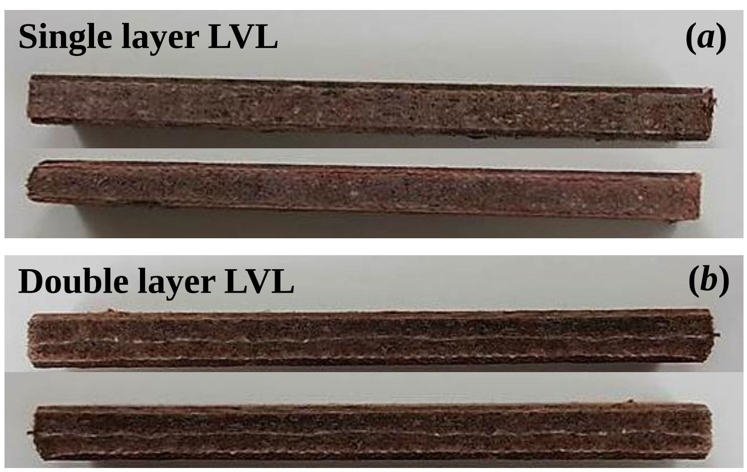

Fig. 5. Photographs of sandwich structure engineered wood reinforced with fiber glass products with; (a) single (1XLVL) and (b) double (2XLVL) layer core made from 50EF/50BG fibers

For the HDT at 1820 kPa load, there was an approximately three-fold increase for the sandwich structure compared with the wood foam core. By doubling the core, a marginally elevated HDT was observed. The similar trend on increasing of HDT, by transforming the core into the sandwich structure, were seen on the system made from the hybridization with engineered fibers. However, the extents of the HDT enhancement of the sandwich wood derived from the hybrid cores, especially for the CF hybrid, were less obvious than in the non-hybrid cores. There are two explanations for the enhancement of the lightweight sandwich engineered wood using the EF/BG wood cores foam. First, it was stronger, with good core/skin interfacial adhesion of the teak veneer and prepreg glass skins; secondly, it was soft but robust, with excellent energy dispersion cores. At the same thickness, more layers represented thinner cores. With the same engineered fiber length, the excess length or "spring effect" dominated, reflecting the higher internal residual stress and lower mechanical properties of the CF hybrid cores. At the same time, the degree of elaboration of KF was diminished due to the excess fiber length and fiber curvature forming the load compacted spring effect. Thus, the 2XLVL sandwich structure fabricated with only EF/BG was the best candidate.

In comparison, between the identical sandwich structures, for example the 1XLVL samples where the core was made from 50EF/50BG, 35EF/35BG/30FG and so on, it is found that the structural properties are controlled by the properties of the core. Within the 1XLVL structures, the specimen manufactured from 35EF/35BG/30CF showed the lowest measured properties, but the KF-reinforced core showed exceptional mechanical properties. The excess length and high elastic modulus of the long length CF, generating the internal residual stress or "spring back effect", was taken into consideration for their properties incompetency.

Table 8. Mechanical Properties and HDT of Sandwich Engineered Wood Based EF/BG Foam Samples

Woods	Sample Thickness (mm)	Impact Strength (kJ/m^2)		Flexural Properties			HDT (°C)
		Notched	Unnotched	Strength (MPa)	Modulus (GPa)	Max. Def. (mm)[a]	
50EF/50BG	5.22 ± 0.04	2.02 ± 0.22	2.05 ± 0.21	6.56 ± 1.05	0.70 ± 0.13	2.58 ± 0.63	33.7 ± 2.4
1XLVL	4.78 ± 0.06	14.74 ± 1.51	23.31 ± 2.29	20.55 ± 6.64	2.63 ± 2.03	5.97 ± 6.96	90.0 ± 5.4
2XLVL	4.81 ± 0.10	21.00 ± 1.99	29.14 ± 2.65	58.06 ± 11.51	4.55 ± 1.08	5.47 ± 2.33	96.4 ± 13.9
35EF/35BG/30FG	5.37 ± 0.04	2.66 ± 0.18	4.51 ± 0.43	8.08 ± 0.43	0.82 ± 0.04	3.13 ± 0.32	39.4 ± 3.7
1XLVL	5.01 ± 0.15	18.65 ± 1.46	25.11 ± 0.60	29.48 ± 2.50	4.37 ± 0.55	2.56 ± 0.73	63.5 ± 10.1
2XLVL	5.08 ± 0.30	20.46 ± 1.42	30.74 ± 1.36	33.28 ± 2.48	3.72 ± 0.69	2.97 ± 0.60	66.1 ± 5.8
35EF/35BG/30CF	5.66 ± 0.05	2.78 ± 0.19	4.19 ± 1.49	8.88 ± 0.74	1.07 ± 0.11	3.19 ± 0.24	42.9 ± 2.7
1XLVL	6.05 ± 0.16	12.91 ± 0.51	15.38 ± 1.03	13.43 ± 1.84	1.95 ± 0.50	4.43 ± 1.56	53.2 ± 0.2
2XLVL	5.72 ± 0.28	19.05 ± 2.01	23.77 ± 1.31	26.09 ± 2.22	2.39 ± 0.43	4.48 ± 0.94	56.1 ± 2.4
35EF/35BG/30KF	5.12 ± 0.11	9.74 ± 0.64	11.79 ± 0.77	10.70 ± 1.44	0.92 ± 0.06	4.19 ± 0.38	41.1 ± 2.4
1XLVL	5.13 ± 0.20	22.26 ± 0.96	26.79 ± 1.65	46.06 ± 6.56	3.18 ± 0.95	4.94 ± 0.84	67.3 ± 4.3
2XLVL	5.10 ± 0.19	24.04 ± 2.18	28.32 ± 2.82	50.60 ± 5.43	2.92 ± 0.78	4.67 ± 0.82	78.8 ± 6.2

[a] Maximum Deformation at Break

The dimensional stability of the sandwich products made from EF/BG and the hybrid foam cores immersed in water for 1 day or 7 days are shown in Table 9. The results reveal that the % WA_i of the EF/BG lightweight sandwich was decreased at both timepoints. A further decrease was noticed when the core layers were doubled. A similar trend was found for the % TS_i values. However, it seems that the expansion is independent of the core layer. For the dimension stability of the sandwich structure after vacuum drying, the % $TS_{dried,i}$ was found at the relatively high level. Introducing 30% of the engineered fibers into the EF/BG core by hybridization, the % WA_i of the moisten sandwich woods is again diminished compared with the core, regardless of the immersion time. However, the % expansion of the immersed sandwich wood panel was noticeably increased, especially for the 1XLVL and for the CF hybrid system. Moreover, the thickness retaining, high % of $TS_{dried,i}$, were found for the hybrid sandwich structures, irrespective of the immersion time. Thus, to improve the dimension stability of the lightweight sandwich wood panel, teak veneers and reinforced prepreg fiber glass layers act as moisture barriers that prevent water penetration of the wood foam core. In addition, the foam core of the sandwich structure containing hydrophobic of short synthetic fibers would also resist moisture absorption. However, the “spring effect” of the long length synthetic fibers has the greatest influence on thickness swelling during water immersion and also after removal of the adsorbed moisture. The longest fiber length and the highest modulus of elasticity CF is the apparent example of this phenomenon.

The properties, mechanical and durability, of the EF/BG and its 30% hybrid lightweight cores were enhanced by utilizing the sandwich wood core production process. The length of the reinforcement engineered fibers, with respect to the thickness of the manufactured wood cores, must be carefully considered. Reinforcing with the extra-long high modulus fiber forms high internal residual stress, due to the “load compacted spring effect” on the core. After subjection to force or hydrostatic loading, the sample will be easily deformed or fail.

Table 9. Durability Properties of the EF/BG Sandwich Engineered Woods and Their Hybrid Systems

Woods	% Water Absorption (WA_i)		% Thickness Swelling (TS_i)		% Thickness Swelling After Drying ($TS_{dried, i}$)	
	1 Day	7 Days	1 Day	7 Days	1 Day	7 Days
50EF/50BG	97.6 ± 11.2	106.0 ± 17.7	16.9 ± 2.4	16.9 ± 1.6	3.1 ± 1.2	1.6 ± 2.0
1XLVL	80.6 ± 19.3	74.5 ± 6.7	14.1 ± 2.3	12.4 ± 9.2	5.9 ± 3.4	1.4 ± 3.7
2XLVL	52.7 ± 4.2	50.4 ± 4.5	12.5 ± 1.6	12.6 ± 0.7	2.2 ± 1.6	1.9 ± 0.3
35EF/35BG/30FG	75.2 ± 10.1	77.2 ± 12.8	11.4 ± 0.1	10.7 ± 1.1	0.7 ± 0.3	-1.1 ± 0.8
1XLVL	67.2 ± 15.7	74.1 ± 9.4	10.2 ± 1.3	11.8 ± 5.7	3.3 ± 2.4	3.3 ± 1.6
2XLVL	55.1 ± 3.1	48.9 ± 5.0	11.7 ± 0.8	9.41 ± 4.7	1.9 ± 1.0	2.5 ± 0.4
35EF/35BG/30CF	88.5 ± 9.9	97.7 ±13.6	12.1 ± 1.1	7.9 ± 0.8	1.5 ± 0.5	0.6 ± 0.7
1XLVL	88.4 ± 7.1	91.9 ± 14.2	7.6 ± 1.1	12.1 ± 2.7	5.6 ± 1.6	5.3 ± 1.8
2XLVL	56.1 ± 18.4	67.3 ± 7.3	12.1 ± 1.1	9.3 ± 1.8	3.9 ± 0.3	5.1 ± 1.1
35EF/35BG/30KF	86.0 ± 6.9	74.9 ± 9.9	11.7 ± 6.8	9.7 ± 1.0	0.4 ± 0.2	-0.9 ± 0.6
1XLVL	52.0 ± 5.5	48.2 ± 5.0	11.9 ± 6.6	11.5 ± 2.1	1.5 ± 1.6	3.2 ± 1.1
2XLVL	55.4 ± 1.7	54.0 ± 8.4	10.3 ± 1.0	9.2 ± 0.9	3.0 ± 2.1	2.9 ± 0.7

CONCLUSIONS

1. Combining the thermal degradation blowing agent, OBSH, at 3 phr, with the low boiling point foaming agent, ethyl acetate (EA), in the manufacturing the EF wood foam enhanced the properties of the wood foam product.
2. Incorporation of RF or BG into the EF decreased its mechanical properties due to their L/D ratio and high non-compacted bulk density of RF and BG. The high hydrophilicity of BG increased the % water uptake and decreased the dimensional stability of the wood foam core.
3. The mechanical performance of the natural fiber core was enhanced by the randomized unidirectional GF, CF, and KF synthetic fibers. However, the hybrid cores

manufactured from the engineered fiber having its length longer than the sample thickness, exhibited a weakened mechanical and durability properties. Especially, the fiber with high modulus such as CF. The generated internal residual stress, “spring effect”, was responsible for this defect.

4. The mechanical and durability properties were superior in the lightweight sandwich engineered wood reinforced with fiber glass derived from the EF/BG and its 30% hybrid lightweight cores. Nevertheless, utilizing the length of the engineered fibers must be carefully considered. Employing the extra-long and high modulus of elasticity fiber, with respect to the thickness of the sandwich structure, had a negative influence on the properties. The high internal residual stress generated from “load compacted spring effect” of the core was the prime suspect for the inferiority.

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