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ORIGINAL PAPER

Hybridized Biocomposites from Agro-Wastes: Mechanical, Physical and Thermal Characterization

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Abstract Agricultural wastes, oil palm trunk (OPT) veneer and oil palm empty fruit bunch (EFB) mat were used for the preparation of hybridized plywood using 250 and 450 g/m^2 of urea formaldehyde (UF) as gluing agent. The mechanical (flexural strength, flexural modulus, screw withdrawal, shear strength), physical (density, water absorption, thickness swelling and delamination) and thermal (TGA) properties of the biocomposites were studied. Images taken with a scanning electron micrograph (SEM) indicated an improvement in the fiber–matrix bonding for the laminated panel glued with 450 g/m^2 of UF.

Keywords Hybridized biocomposites · Thermogravimetric analysis · Scanning electron microscopy

Introduction

Agro-wastes from the oil palm industry such as oil palm trunks (OPT) and empty fruit bunches (EFB) have attracted much attention in the present day research to develop potential sources for new value added materials. African oil palm, *Elaeis guineensis*, is one of the most important plants in Malaysia. Malaysia is the world's largest producer and exporter of the oil, accounting for approximately 60% of the world's oil and fat production. The total area of oil palm plantations is close to 4.05 million hectares, which account for almost 50% of the land under cultivation in Malaysia. The oil consists of only 10% of the total biomass produced in the plantation. The residue biomass consists of huge amount of lignocellulosic materials such as oil palm fronds, trunks and EFB. The projection figures of these residues are as follows; 8.2 million tons of OPT, 26.2 million tons of oil palm fronds, and 15.8 million tons of EFB processed in oil palm mill [1]. Urea formaldehyde (UF) resins are the most important and common class of resin adhesives. The UF is the most frequently used and cure at relatively low temperatures will lead to reduce time in the press. UF resins tend to be the most widely used adhesives for bonding wood products due to the excellent adhesion to lignocellulosics, outstanding intrinsic cohesion, ease of handling and application, lack of color in the finished product, fast cure, high strength and low cost [2–4]. The other advantages of UF adhesives are their initial water solubility, hardness, nonflammability, good thermal properties, absence of color in cured polymers, and easily adaptability to a variety of curing conditions. The greater disadvantage of the amino resins is their bond deterioration, caused by water and moisture.

On the other hand, biomass from the oil palm industry has gaining commercial importance for the past 10 years. It generates a large amount of residues and in the number one source for natural fibers. Extensive research on the conversion of OPT, EFB and fronds into value added products such as particleboard, MDF, cement bonded particleboard, fiber reinforced plastics and plywood has been initiated with great commercial potentials [5]. Plywood is a flat panel built up from sheets of veneer called plies, joint under pressure by a bonding agent to produce a panel with an adhesive bond between plies as strong as or stronger than wood. Plywood is assembled from an odd number of layers with grain of adjacent layers perpendicular. Layers

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consist of a single ply or two or more plies laminated with parallel grain direction [6].

Earlier works done using plywood made from only OPT veneer did not achieve satisfactory properties. Therefore, the main objective of this study was to investigate the performance of the physical, mechanical and thermal properties of hybrid biocomposite made from OPT and EFB. Scanning electron microscopy (SEM) studies were carried out for morphological analysis on the biocomposite panels.

Experimental

Materials

UF was supplied by Hexion Specialty Chemicals Sdn Bhd, Kuala Lampur, Malaysia. OPT veneer Oil palm EFB fiber mats were supplied by Kin Heng Timbers Industries Sdn. Bhd., Perak, Malaysia and Ecofuture Bhd, Selangor, Malaysia, respectively.

Methods

Preparation of Hybridized Biocomposites

The OPT veneers (600 × 300 × 4.0 mm) and EFB (600 mm × 300 mm × 6.0 mm) samples were dried to approximately 10–12% moisture content. The determination of moisture content was carried out in accordance with BS EN 322:1993. The moisture content of the samples was measured by placing the samples in drying oven at 103 ± 2 °C, until a constant mass was achieved. The samples were then arranged into 5-ply plywood, consisting of alternating OPT veneers and EFB fiber mats. The layers were bonded together using a UF resin with either a low matrix spread level (250 g/m^2) and a high glue spread level (450 g/m^2). The layers were first cold pressed for 10 min and then hot pressed at a temperature of 120 °C for 25 min with a pressure of 200 bars (3000 psi).

Mechanical Testing

Flexural Test

The flexural tests were performed according to BS EN 310:1993, using an Instron Testing Machine Model 4204. Samples for flexural testing were cut into rectangular strips with dimensions of approximately 240 mm × 50 mm × 12 mm. The exact lengths, widths and thicknesses of the samples were measured and recorded. Samples were tested at a crosshead speed of 10 mm/min over a span of 240 mm. All of the specimens were conditioned at ambient temperature (25 ± 3 °C) and at relative humidity of 30% (±2%) before testing.

Screw Withdrawal Test

The screw withdrawal tests were performed using an Instron Testing Machine Model 4204. The length, width and thickness were measured and recorded. The tests were carried out in accordance to BS EN 320:1993. The screw withdrawal tests were carried out on samples with dimensions of 75 mm × 75 mm × 12 mm. The test pieces were conditioned to constant mass in an atmosphere with a mean relative humidity of 65 ± 5% and a temperature of 20 ± 2 °C. For this test, a steel screw, nominal size 4.2 mm × 38 mm was used. The screw was inserted into the hole to the full thickness of the board. The testing machine was set to a crosshead speed of approximately (10 ± 1) mm/min and until maximum load was achieved.

Shear Test

Shear tests were performed according to BS EN 314-1:2004, using an Instron Testing Machine Model 4204. The shear tests were performed on rectangular strips with dimensions of approximately 135 mm × 25 mm × 12 mm. The length, width and thickness of each sample was measured and recorded. Samples were tested at a crosshead speed of 1.5 mm/min. All of the specimens were conditioned at ambient temperature (25 ± 3 °C) and a relative humidity of 30% (±2%) before testing.

Prior to shear tests, UF plywood was subjected to a water interior treatment (INT). Before the water treatment, the length and width of the shear area were measured with accuracy to within ±0.1 mm. The shear tests were carried out on wet test pieces, allowing for the use of a wiping based process. The shear test pieces were arranged in the centre of the clamping devices in such a way to allow the load to be transmitted from the testing machine, through the ends of the test pieces and to the shear area without any transverse loads. Slipping is only allowed in the initial stage of the loading. The clamp is positioned on the sample faces. The load was applied at a constant moving rate, designed to induce rupture within 30 ± 10 s. Samples were tested at a crosshead speed of 1.5 mm/min.

Physical Testing

Four different physical tests were conducted in this study to test the properties viz. density, water absorption, thickness swelling and delamination.

Density

The densities of the plywood were determined by measuring the mass and volume of each sample. Each test sample was weighed with an accuracy of 0.01 g. The mass of each sample was obtained by calculating the arithmetic mean of the mass of all of the test samples taken from the same board. Accurate determination of test sample dimensions was made using a sliding caliper, in accordance with BS EN 325:1993. The volumes of the samples were obtained using the measured dimensions. The density, D was then calculated using the formula in Eq. 1,

$$D = \frac{m}{v}\left(\frac{\mathrm{g}}{\mathrm{cm}^3}\right) \quad (1)$$

where, m is the mass and v is the volume of the bio-composite sample.

Water Absorption and Thickness Swelling

To test water absorption and thickness swelling, samples were soaked in water for 7 days. The rate of water absorption initially increased with immersion time, until eventual stabilization. The absorbed water in the samples (A) and the thickness swelling of the samples (G) was calculated as a percentage according to the procedure given in BS EN 317:1993. The amount of absorbed water was calculated using the Eq. 2

$$A(\%) = \left(\frac{M_1 - M_2}{M_2}\right) \times 100 \quad (2)$$

where M_2 is the weight before the test and M_1 is the measured weight (grams).The thickness swelling was calculated using the Eq. 3

$$G(\%) = \left(\frac{A_1 - A_2}{A_2}\right) \times 100 \quad (3)$$

where A_2 is the thickness before the test and A_1 is the thickness (mm) after the test.

Delamination Test

The delamination test was done following the standard BS EN 391:2002. It measured the perimeter of failed glue line over the total perimeter of glue line available. The delamination results are evaluated using Eq. 4

$$D = \frac{P_{\mathrm{glF}}}{P_{\mathrm{gl}} \times N} \times 100 \quad (4)$$

where D is delamination, P_{glF} is the perimeter of failed glue line and P_{gl} is the perimeter of glue line, and N is the number of glue lines.

Ten replications of biocomposite panels were constructed with OPT veneers and oil palm EFB layers, using UF resin. Samples were made in dimensions of 50 × 150 mm and were pre-treated. Test pieces were impregnated with water (vacuum at 70–85 kPa for 5 min, pressure at 500–600 kPa for 1 h, vacuum at 70–85 kPa for 5 min, pressure at 500–600 kPa for 1 h), drying at 60–70 °C for 21–22 h.

Thermogravimetric Analysis (TGA)

Thermal stability of the plywood panels was investigated using TGA. Thermograms were obtained with a Perkin Elmer (TGA-6) instrument with a heating rate of 20 °C/min, over a temperature range of 25–900 °C. All TGA runs were performed under a nitrogen atmosphere.

Scanning Electron Microscopy (SEM)

A SEM (Leo Supra, 50 VP, Carl Ziess, SMT, Germany) was used to analyze the morphology of the plywood materials. A thin section of the sample was mounted on an aluminum stub using conductive silver paint and the sample was sputter-coated with gold. The SEM micrographs were obtained under conventional secondary electron imaging conditions using an acceleration voltage of 15 kV.

Results and Discussion

Flexural Properties

The flexural strength and flexural modulus of hybrid biocomposite is given in Fig. 1. The higher flexural properties in hybrid composites are due to the presence of higher density as compared to that of OPT plywood. The comparative densities are given in Table 1. Reddy and Yang [7] mentioned that the properties such as density, tensile strength, modulus, moisture regain and crystallinity is related to the composition and internal structure of the fibers.

The hybrid biocomposite obtained by using a higher spread level (450 g/m^2), the flexural properties of the plywood and hybrid biocomposite were higher than those of plywood using a lower adhesive spread level (250 g/m^2), for UF resin. The higher spread level caused the adhesive that was spread on the surface of the OPT and EFB to enter the pores, where it harden and anchored. This may be the result of an inadequate amount of adhesive being used to form adhesion between the surfaces for plywood and hybrid biocomposite at a 250 g/m^2 spread

Fig. 1 Flexural strength and flexural modulus for OPT and hybrid biocomposites with different glue spread level using UF

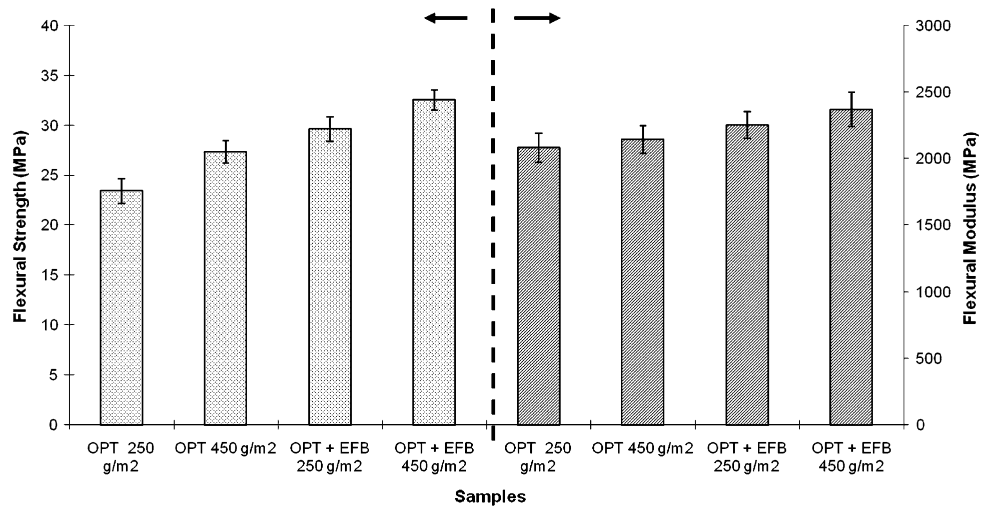

Table 1 Physical properties of OPT plywood and hybrid biocomposites

Adhesive	Sample	Physical properties		
		Density (g/cm^3)	Water absorption (%) (after 7 days)	Thickness swelling (%) (after 7 days)
UF	OPT (250 g/m^2)	0.6226 (0.05)	57.4502 (4.4)	11.6830 (1.2)
	OPT (450 g/m^2)	0.6340 (0.02)	56.2346 (3.9)	11.1478 (1.2)
	OPT + EFB (250 g/m^2)	0.6746 (0.04)	50.6156 (3.2)	9.8529 (1.2)
	OPT + EFB (450 g/m^2)	0.7350 (0.08)	36.6305 (4.2)	7.4189 (1.4)

level. Besides, the results shown in Fig. 1, as expected, the flexural modulus was generally higher for the plywood using a higher glue spread level for both adhesives used. This behavior can be explained by the better fiber-adhesive contact for plywood at a higher glue spread level. The flexural strength and modulus of plywood hybrid with oil palm EFB possesses higher bending strength and modulus than OPT plywood. This is because the oil palm EFB exhibited higher cellulose content than OPT.

Although the strength of fibers cannot be exactly correlated to the cellulose content and microfibrillar angle, generally, fibers with higher cellulose content, higher degree of polymerization of cellulose and lower microfibrillar angle give better mechanical properties [7]. The higher cellulose content will lead to the higher hydroxyl bonding between oil palm EFB with UF and give better compatibility.

Screw Withdrawal Properties

Figure 2 indicates that hybrid biocomposites presented higher resistance values for face screw withdrawal compared to OPT plywood. The results showed that there is a good correlation relationship between screw withdrawal strength and the density.

The resistance of a screw shank to direct withdrawal from a piece of wood depends on the density of the raw material, the diameter of the screw, and the depth of penetration. In this testing, the screw diameter and depth of penetration are uniform, therefore density played the important role for the screw withdrawal in this experiment [8]. The limiting length to cause a tension failure decreases as the density of the plywood increases since the withdrawal strength of the plywood increases with density as mentioned by Chai et al. [9]. Celebi and Kilic [8] found that there was a linear relationship between withdrawal strength of screw and the specific gravity, and increases in withdrawal strength of screw were determined for increased specific gravity values. The correlation between screw withdrawal strength and density for UF plywood is shown in Table 2.

The glue spread also affects the screw withdrawal properties of the plywood. Table 2 shows that plywood using glue spread 450 g/m^2 give higher screw withdrawal compared to the plywood using 250 g/m^2 glue spread. The glue spread is important to get the high quality bonding that accurate weight and even distribution are basics to a high quality bonding. Withdrawal strength is affected by the factors such as glue layer thickness. Values of screw withdrawal improved as the resin amount is increased [10, 11].

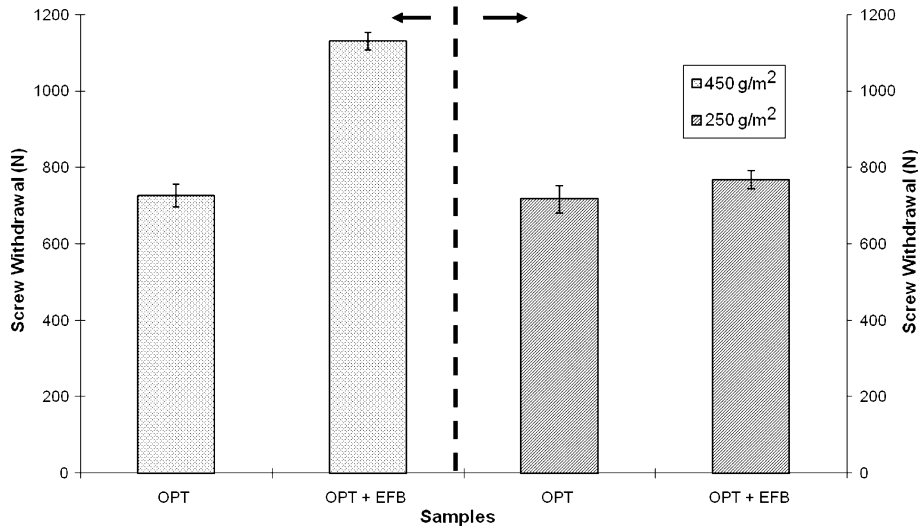

Fig. 2 Screw withdrawals of OPT and hybrid biocomposites with different glue spread level using UF

Table 2 Relationship between screw withdrawal strength and density for UF plywood

	OPT + UF	OP + EFB + UF
450 g/m^2	726 N	1130 N
Density	0.634	0.735
250 g/m^2	717 N	768 N
Density	0.623	0.675

Screw withdrawal in Newton (N)

Shear Properties

The shear strength of the samples using UF is shown in Fig. 3. It can be seen that the shear strength of hybrid biocomposites with EFB was lower compared to the shear strength of OPT plywood. A factor contributed to the poor performance of hybrid biocomposite is its fiber size.

It was noted that the fibers produced from oil palm EFB are much finer thus a good resin distribution is needed to ensure sufficient resin–fiber contact. Besides, low bond strength was related to poor wettability and adhesion by using oil palm EFB as raw materials because surface roughness also have significant effect on the shear strength of plywood [12]. Aydin [13] also reported that the roughness of a veneer surface affects the wettability of the surface hence the gluability and the good wettability will lead to good bonding strength.

According to Fig. 3, it can clearly be seen that the bond strength of plywood panels decreased when using a glue spread of 250 g/m^2; the highest mean bond strengths were found in the OPT plywood using UF with a glue spread of 450 g/m^2. This can be related to the fact that smaller size fibers will cause more resin absorption which due to larger surface area. As surface area increases, the proportion of glue decreases in relation to the surface area [14]. Therefore, the higher amount of resin is needed to ensure sufficient resin–fiber contact. Hence, the shear strength increased with the increasing of the resin glue spread. Besides, accurate weight and even distribution are basics to a high quality bonding. So that, the uses of higher amount of glue improved the bonding strength of the plywood.

The results showed that, as expected, the shear strength was higher for the samples without pretreatment compared with those that underwent pretreatment for INT test. This test is appropriate for a normal interior climate. With pretreatment, the samples experienced a drastic change in condition, which probably caused more moisture to penetrate into the plywood and weaken the samples. Figure 4 shows the shear strength from INT pretreatment for plywood using UF.

The shear strength was higher in the dry test than in INT pretreatment. The plywood using glue spread of 450 g/m^2 demonstrated higher glue bond strengths than plywood using a glue spread of 250 g/m^2. The difference in glue bond properties might be due to different resin penetrations into veneer. Hence, less moisture penetrate into the samples with higher glue spread because more glue will bulk into the cell wall.

Physical Properties

Density

Table 1 shows the density of plywood and hybrid biocomposites with different glue spreads of 250 and 450 g/m^2 using UF. It was observed that the density of plywood also increased by the effects of adhesives glue spread and the raw material used for the manufacture of plywood. The most important characteristic property of plywood strength is density. From Table 1 and Figs. 1, 2, 1, and 4,

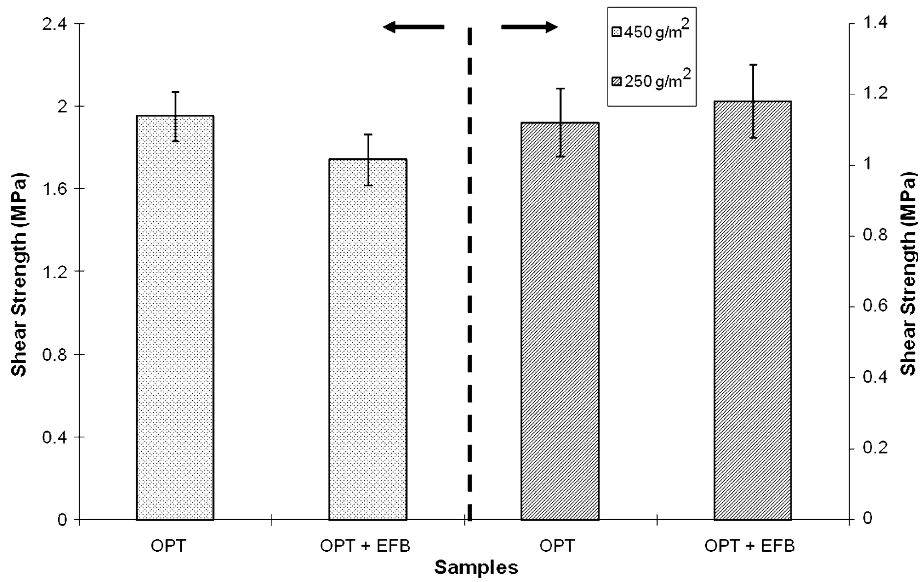

Fig. 3 Shear strength of OPT and hybrid biocomposite with different glue spread level using UF

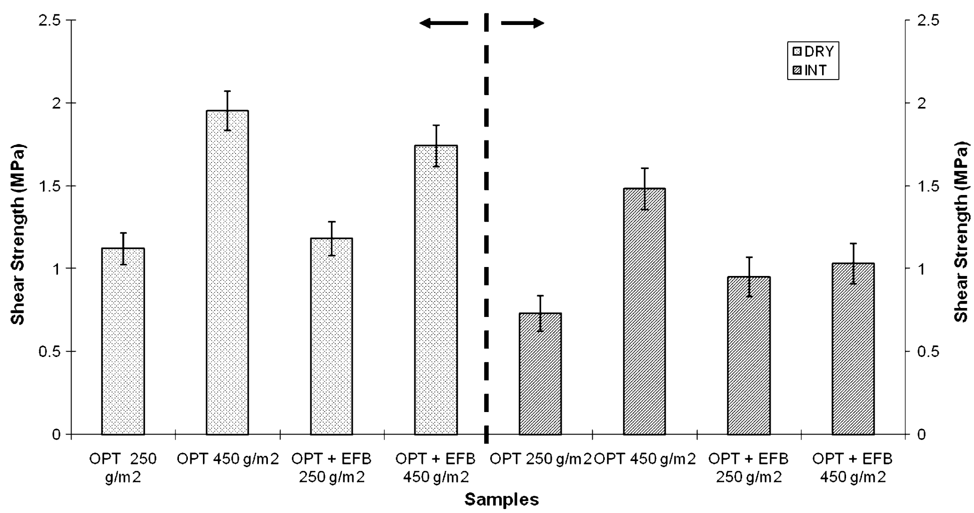

Fig. 4 Comparison of shear strength between dry and INT treatment test of OPT and hybrid biocomposites with different glue spread level using UF

the strength of plywood increased with the increasing of the density. Results showed that hybridization of OPT with oil palm EFB plywood using UF resin as an adhesive have higher densities than the plywood made from OPT using the same resin. This may be due to the difference in the density of the raw materials that ultimately affects the plywood panel density. The difference of veneer density may be due to which part of veneer was obtained from the trunk because OPT consists of two main structures.

The first one is vascular bundles with thick walled cells and high density while the other one is parenchyma tissues with thin walled cells, low density, more porous and starch. Vascular bundles are scattered in parenchyma tissues as matrix, with a reduced concentration from the outer to the inner part. Density gradient between trunk's outer part (0.4 g/cm^3) and center part (0.15 g/cm^3). The density of the OPT also varies greatly within species because of number of factors. These include location in a tree, location within the range of the species, site condition and genetic sources [15]. While the density of EFB is 0.7–1.15 g/cm^3. Apparently that the plywood manufactured from layers of OPT will have a lower density than the hybrid biocomposite with EFB.

Additionally, the amounts of resin consumption (glue spread) also contribute to the density of the plywood panels. The sample using UF with a spread level of 450 g/m^2 showed higher density compared to the samples with different glue spread levels. This is due to the enhanced interfacial adhesion between the UF and the plywood panels attributed to their hydrophilic qualities may be explained in part by the presence of the free methylol groups. The free methylol groups appear to possess an unusually good affinity toward cellulosic materials [16].

Water Absorption

From Table 1, the percentage for both of OPT plywood and hybrid biocomposite using higher glue spread level (450 g/m^2) indicated lower water absorption than using lower glue spread level (250 g/m^2). This is may be due to the higher compatibility between the hydrophilic fiber of OPT and oil palm EFB with UF adhesives using higher adhesives spread level compared to using lower adhesives spread level. The weak compatibility between fiber surface and adhesive could lead to the formation of void structures within the composites which facilitates the water absorption and the very fine capillaries in the wood/glueline system also play a role [17]. Besides, the cured thermosetting resin glues are not hygroscopic, therefore the plywood panel using higher amount of glue will absorb less water than plywood panel using lower amount of glue which decreased the water absorption of the plywood panel.

In addition, it was observed that the highest water absorption was determined in OPT plywood while the lowest water absorption was determined in hybrid biocomposite. This is because OPT contains higher parenchyma which leads to the higher water absorption. This can be explained by the greater affinity of the parenchyma to absorb water as compared to the fiber bundles due to the presence of higher OH groups which enhance the water absorption [18]. The polar hydroxyl groups in the parenchyma molecular structures are able to form hydrogen bonds with water molecules and the higher contents of hydrogen group will also increase the possibility of water being absorbed and form the hydrogen bonds.

Thickness Swelling

Thickness swelling depends on the type of wood-based panel used. These factors are much lower in the case of plywood than in the case of other wood based products.

The differences in swelling stress during immersion in water are related to the conditions during pressing of the individual type of wood-based panel used. Plywood exhibit greater dimensional stability compared to most other wood-based building products because plywood, compared to other wood based products is compressed at a lower temperature and a lower pressure, less wood damage occurs and so less swelling and a lower swelling stress occurs [19]. Swelling stress was greater in the case of the larger samples, and even the time needed to achieve this stress was longer.

From Table 1, the percentage for both of OPT plywood and hybrid biocomposites using higher glue spread level (450 g/m^2) indicated lower thickness swelling than using lower glue spread level (250 g/m^2). This is due to OPT has poor dimensional stability due to the diffusion of water through the cell walls that consequently leading to the movement of the trunk. Hence, by using higher glue spread level (450 g/m^2), bulking the cell wall with polymers may minimize the movement and improve the properties of OPT veneer compared using lower glue spread level (250 g/m^2).

The OPT plywood made with UF adhesives exhibited a higher degree of thickness swelling than hybrid biocomposite because OPT consists of numerous vascular bundles embedded in the parenchyma ground tissue. The parenchyma behaves like a sponge and hold high moisture leads to higher thickness swelling in OPT plywood. Besides, thickness swelling increased with the increase of moisture content and decreased with the decrease of moisture content. Plywood panels change dimensions with changing moisture content because the cell wall polymers contain hydroxyl and other oxygen-containing groups that attract moisture through hydrogen bonding. This test also showed that the thickness swelling of the composites increases with an increase in the period of water exposure. The increase in water exposure time allows a significant amount of water to be absorbed, resulting in fiber swelling. This can be related to the poor dimensional stability of UF due to the bond deterioration takes place upon exposure to water and moisture due to the hydrolysis of their aminomethylenic bond, whereas fibres are hydrophilic in nature because of an abundance of hydroxyl groups.

Delamination Test

The performance of plywood panels depends on the bonding strength between the resin and the substrate. Any failure in the glue bond weakens the mechanical strength. In addition, good durability is associated with the absence of delamination in the plywood samples. Delamination assessment on ten specimens from both OPT plywood and hybrid biocomposite with different glue spread level revealed that all of the plywood panels obtained a slight delamination.

It was observed that both OPT plywood and hybrid biocomposite using UF specimens delaminated at the glue line and cracks occurred on the edges of the samples. Table 3 shows that samples of OPT plywood with glue spread level 300 g/m^2 using UF exhibited 3.2% delamination; and

Table 3 Delamination of samples affected by delamination test for OPT plywood and hybrid biocomposite

Samples	Delamination (%)
OPT 450	0.7
OPT 250	3.2
OPT + EFB (450 g/m^2)	1.15
OPT + EFB (250 g/m^2)	3.4

samples of hybrid biocomposite with glue spread 250 g/m^2 using UF exhibited 3.4% delamination. While, OPT plywood and hybrid biocomposite with spread level 450 g/m^2 exhibit lower delamination with 0.7 and 1.15% delamination, respectively.

Thermogravimetric Analysis (TGA)

TGA was used to study the degradation. In TGA loss of mass is measured, whereas the degradation of polymeric materials begins frequently with enthalpy changes [20]. From Fig. 5, the hybrid panels with different glue spreads of UF showed better thermal resistance than the OPT panels.

The initial degradation step in the case of a hybrid panel with a resin spread level of 450 g/m^2 occurred at 207 °C, while the other panels showed lower initial degradation temperature, as shown in Table 4.

The hybrid biocomposites with a spread level of 450 g/m^2 of UF had final degradation temperature of 372 °C and an ash content of 24.6%, which are comparable with the other panels glued with UF. Overall, hybrid biocomposite panel glued with UF with a spread level of 450 g/m^2 showed better thermal stability than the other panels.

Scanning Electron Microscopy (SEM)

The micrographs obtained from SEM are given in Fig. 6a, it was observed that the adhesive has filled up the available space in the glue line, and some glue also is able to penetrate through the vessel lumen adjacent to the glue line.

This probably happened during the glue spreading and the adhesive could fill up the lumen void surface with using higher glue spread level (450 g/m^2), which probably improved the adhesion. The adhesives also can be seen penetrate between OPT and oil palm EFB fibers.

A view of oil palm EFB in cross section is shown in Fig. 6b. The adhesive can be seen filling up the available space in the glue line, and some glue is able to penetrate through the vessel lumen.

This probably happened also during the glue spreading and the adhesive could fill up the lumen void surface, which probably improved the adhesion. However, there are some spaces which not filled up with adhesives using lower glue spread level (250 g/m^2) and can lead to poor adhesion.

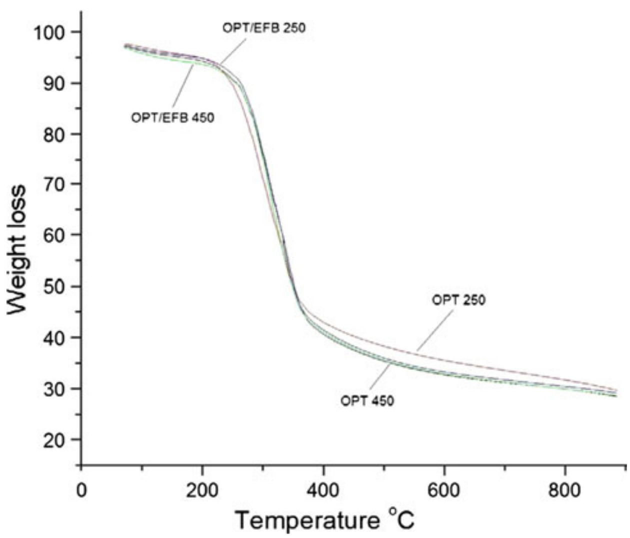

Fig. 5 Thermograms of OPT and hybrid biocomposite panels glued with UF

Table 4 The degradation temperature and ash content from thermograms of panels glued with UF

Samples	T_i (°C)	T_f (°C)	Ash (%)
OPT (450 g/m^2)	188.68	366.59	23.25
OPT (250 g/m^2)	197.68	363.88	24.31
OPT + EFB (450 g/m^2)	207.15	372.59	24.62
OPT + EFB (250 g/m^2)	204.15	369.59	23.35

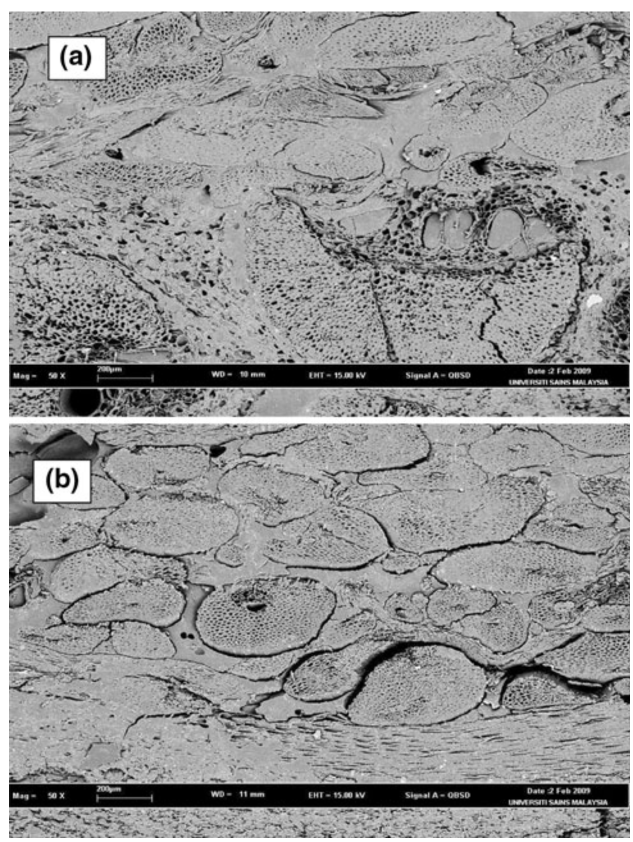

Fig. 6 SEM of hybrid biocomposite with **a** 450 g/m^2 (50×), **b** 250 g/m^2 (50×)

This is maybe due to lower glue spread level and the glue cannot spread the fiber well.

Normally, the failure during the shear test was observed to occur due to OPT failure rather than glue line failure. The glue line of the OPT panels can be a combination of surfaces of parenchyma or vascular bundles. As can be seen in Fig. 7a, the glue line occurred in between the parenchyma and fibers in the vascular bundles of the adjacent veneer. This probably affects the strength because both surfaces were not homogenous. The fiber in the vascular bundles has a high density surface, while the parenchyma surface has a very low density surface. Surfaces with higher density will probably have higher strength compared to surfaces with lower density. OPT failure probably occurs in this weak zone of lower density in the OPT.

The adhesives were able to penetrate into a few cells above and below the glue line and filled up the lumen void area in the OPT veneer surfaces, as can be seen in Fig. 7b. However, the Fig. 7b also showed that less adhesives filling up the spaces and parenchyma cells of the OPT veneer porous surfaces. This is maybe due to the inadequate amount of adhesives used with low adhesives spread level (250 g/m^2) and this will lead to the poor adhesion between the surfaces of the OPT veneer.

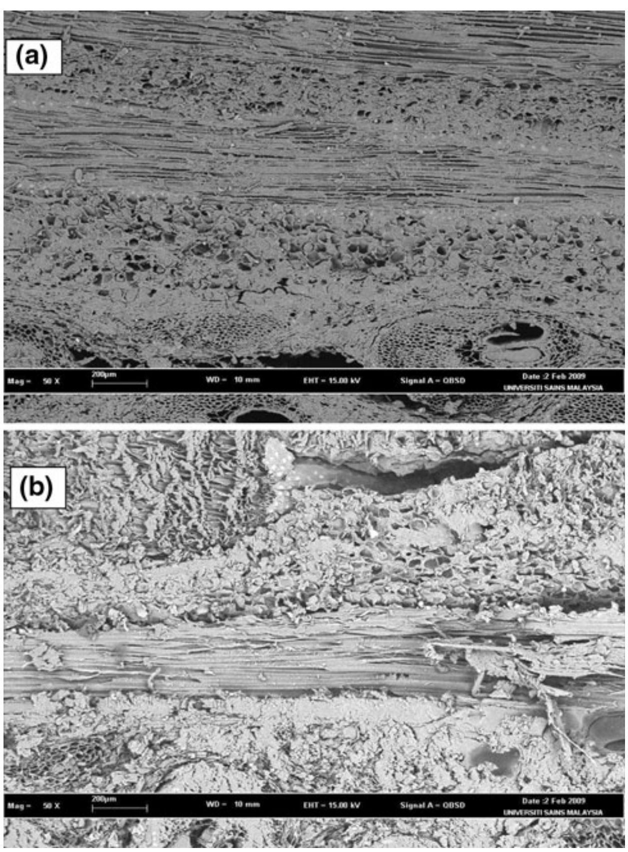

Fig. 7 SEM of OPT plywood with **a** 450 g/m^2 (50×), **b** 250 g/m^2 (50×)

Conclusion

We conclude that hybrid biocomposite improves some properties of plywood, such as flexural strength, screw withdrawal and shear strength. Hybrid biocomposite showed better physical properties such as thickness swelling and water absorption than OPT plywood. The plywood constructed with OPT and hybridization oil palm EFB with OPT presented slightly delamination. In addition, hybrid biocomposite made using a glue spread level of 450 g/m^2 have better properties than plywood using a glue spread level of 250 g/m^2. The thermal and morphological analysis of the hybrid biocomposites glued with UF confirmed that the panels have good thermal resistance and good adhesion, with a well-dispersed glue line. Therfore, EFB can be used to substitute raw materials to produce plywood.

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