Recycled Polypropylene–Oil Palm Biomass: The Effect on Mechanical and Physical Properties

H. P. S. ABDUL KHALIL,* B. T. POH, A. M. ISSAM AND M. JAWAID
Bio-Resource, Paper and Coating Technology, School of Industrial Technology
Universiti Sains Malaysia, Penang 11800, Malaysia

R. RIDZUAN
Malaysia Palm Oil Board (MPOB), Biomass Technology Centre
Engineering and Processing Division, Jalan Sekolah, Pekan Bangi Lama
Kajang 43000, Selangor, Malaysia

ABSTRACT: In this study, 25-year-old oil palm biomass (OPB) fiber–polypropylene (PP) composites are prepared by five different fiber loadings (10, 20, 30, 40, and 50%). The types of OPB used are oil palm empty fruit bunches, oil palm frond, and oil palm trunk. Transmission electron microscopy has confirmed that the cell wall structures of the various oil palm fibers have different cell wall thicknesses and exhibit the same ultrastructure as that of wood. The fibers consist of middle lamella, primary, and thick secondary walls with different thicknesses for different types of fibers. The secondary wall is differentiated into a S1 layer, a unique multi-lamellae S2 layer, and a S3 layer. OPB fibers are compounded with PP using a Brabender DSK 42/7 twin screw extruder. The mechanical features such as tensile, flexural and impact properties of the OPB–PP composite are studied. The melt flow index (MFI) of the composite materials is also studied. Generally, the results show that lower fiber loading (10%) exhibits the highest tensile strength and MFI properties as compared to higher fiber loading (50%). Evidence of a fiber–matrix interphase is analyzed using scanning electron microscopy.

KEY WORDS: polypropylene (PP), oil palm biomass (OPB), 25-year-old oil palm tree, mechanical properties, composites.

INTRODUCTION

Oil palms (ELAEIS guineenis) were first introduced into Malaysia for planting in 1870. Oil palm trees generally have an economical life span of about 25 years, and these trees contribute to a high amount of agricultural waste in our country. Oil palm biomass (OPB) can be used as an alternative material for bio-composites, pulp, and paper industries. With the present limited supply of raw materials from forests and rubber tree plantations, OPB in the form of empty fruit bunches (EFB), oil palm trunk (OPT), oil palm frond (OPF), and others can be further processed for the manufacture of valuable products. OPB fibers offer excellent specific properties and have potential as...
outstanding reinforcing fillers in plastics. High volume fillings are possible with natural fibers due to their non-abrasive nature and lower densities [1–3].

Oil palm is a commercial crop in Malaysia. The oil palm tree is ≈7–13 m in height and 45–65 cm in diameter, measuring 1.5 m above the ground level. It has been found to be an important source of fiber for composites and other industrial applications. The Malaysian oil palm industry not only produces crude palm oil as the main product, but also generates abundant and readily available amounts of biomass residues in the form of EFB, OPT, and OPF. It was estimated that over 100 million tons of OPB is generated annually. In this study, 25-year-old OPB has been used as a fiber material [4,5].

OPB is an agricultural by-product periodically left in the field during the replanting, pruning, and milling processes. This by-product is largely unutilized after a 25-year economic life of the tree and causes severe environmental pollution problems [6,7]. Extensive studies have been carried out using OPB as a fiber material because of its low cost, abundance in nature, low energy, low density, and biodegradability [8,9]. However, the OPB used in previous studies was taken from a diverse range of years, parts, portions, and locations. In this study, a 25-year-old OPB was selected as raw material, i.e., OPT, OPF, and EFB.

Owing to the presence of hydroxyl groups, OPB fibers are hydrophilic in nature, limiting the compatibility with hydrophobic matrices as well as causing dimensional instability when exposed to moisture. They are also susceptible to decomposition by fungi, bacteria, and insects, have high inflammability, and have a degradable surface when exposed to light (photo-sensitivity). These attributes restrict their use in many applications [10,11].

However, these disadvantages have been overcome as lignocellulosics began to be used as filler in thermoplastic composites [12,13]. The properties of composites come directly from their structure; there is a thorough mixture of the filler and plastic. The matrix effectively coats the particle as a thin layer [14]. The combination of plastic and lignocellulosic filler has caused the escalating cost of raw material and energy in lightweight high performance material products. In this study, polypropylene (PP) was used as it can accept various types of fillers and reinforcements, such as glass fibers, glass sphere, talc, asbestos, mica, wallastonite, calcium carbonate, and silica [15]. PP belongs to the polyolefin family and has a linear structure that can be melted and remolded a few times. PP has a high softening point and its mechanical properties are constant at ambient temperature. It also has dimensional consistency, impact resistance, and a high strength-to-weight ratio [16]. The objectives of this study are to determine the effect of different filler loadings (10, 20, 30, 40, and 50%) and different parts of OPB (EFB, OPT, and OPF) on the mechanical and physical properties of the composites.

Recently, many studies have focused on the use of OPB as filler in reinforcing thermoplastics such as PP [17,18]. In general, it has been reported that the incorporation of OPB fiber into PP matrix has, to a certain extent, reduced both the tensile and impact strengths of the composite [18].

In spite of the many published works [16–20] on oil palm fibers filled in thermoplastic composites, sources that include the cell wall structure and the use of oil palm fibers comprehensively are quite scarce, disperse, and inadequate. To date, no research reported has evaluated the PP-based composite containing various parts of oil palm fibers specifically from 25-year-old oil palm trees.

With more advanced technology, OPB may supplement the natural forest and rubber plantation resources by helping to fulfill the demand for product differentiation, a growing trend among customers worldwide. In addition, OPB is a by-product of the oil palm industry, so there is no additional cost in planting the trees for the wood-based industry.
In fact, as OPB is an environmentally friendly product, it will provide an advantage for manufacturers in marketing the biomass-based products as compared to deforestation in making wood-based products [21].

**MATERIALS AND METHODS**

**Oil Palm Biomass Fiber**

Various oil palm fibers, i.e., oil palm trunk (OPT), oil palm frond (OPF), and empty fruit bunches (EFB), were obtained from Seng Heng Plantation Sdn. Bhd., Juru, Pulau Pinang. Only OPB fiber from 25-year-old oil palm trees and certain parts of OPB were taken. The OPB was chopped to a length of 1 cm and then was oven dried at 105°C for 24 h in order to achieve a moisture content of <5%.

**Chemical Composition and Transmission Electron Microscopy of Cell Wall Structure**

The chemical composition of the cellulose, hemicellulose, lignin, and extractive contents were determined as reported in an earlier study [22]. For cell wall structure analysis, the fiber was chosen randomly, then dehydrated in an ethanol series, and embedded in epoxy resin (Epon), which was polymerized for 24 h at 60°C. A transverse section (1μm) was cut from the embedded material, using a Sorvall ultra microtome (MT). The section was viewed under a transmission electron microscope (TEM), Phillips Model CM 12.

**PP Matrix**

Homopolymer PP WH 101 (Melt index 8 g/10 min, density 0.90 g/cm³) was supplied by The Polyolefin Company (TPC), Singapore. A commercial grade talc-filled PP known as CALP 30 (30%PP/Talc) was supplied by CALP Corporation. No coupling agents or bonding agents were used in this preliminary experiment. The properties of the PP matrix are given in Table 1.

**Preparation of Composite**

Prior to compounding, mixing of PP and OPB fiber was performed at SIRIM Technology Centre, Shah Alam, Selangor, Malaysia. Mixing was done in a Brabender W 50E mixer at a temperature of 190°C and a blade speed of 50 rpm. The compounding of PP and OPB fiber was carried out in a Brabender DSK 42/7 twin screw extruder. The processing temperatures used were in the range of 170–190°C. Composite samples with 10, 20, 30, 40, and 50% fiber loadings were prepared and compounded. The mixtures were fed into the hopper of the extruder, extruded, cooled, and granulated. The compounded samples were prepared as test specimens by an injection molding technique. The machine used was a 20-ton Battenfeld BA 200 CD Plus machine, with a UNILOG 4000 closed loop control system, at an injection pressure of 140 bars.

**Mechanical Tests**

The tensile, flexural, and impact properties of OPB–PP composites were studied. The tensile properties were determined using an Instron Universal Testing Machine.
Model 1114. The tensile test was carried out by using rectangular strips of 150\( \times 20 \times 10 \text{ mm}^3 \). The width and thickness of the specimens were measured and recorded. Specimens were tested at a cross-head speed of 3 mm/min and a gage length of 60 mm, according to ASTM D 638 [21]. A minimum of 10 samples were tested and an average value was recorded.

Flexural tests were conducted using the same machine according to ASTM D 790 [23]. The width and thickness of the specimens were measured and recorded. Specimens were tested at a crosshead speed of 3 mm/min with a 10 kN load cell. Rectangular strips of 160\( \times 20 \times 10 \text{ mm}^3 \) were carefully sanded using a fine graded sandpaper to remove small cracks. The flexural strength and flexural modulus were calculated from this test.

The Izod impact test was performed on a Ceast 6456 Izod pendulum impact tester. Notching (45\(^\circ\)) was carried out on the impact specimens using a Davenport notch apparatus. The test was conducted based on ASTM D 256-93 on a Zwick model 5101 with a pendulum weight of 4 J [21]. The works of fracture values were calculated. All the specimens were conditioned at ambient temperature (25\( \pm 3^\circ\)C) and a relative humidity of 30\( \pm 2\)% before testing.

**Physical Properties**

The physical properties basically measure the morphologies and bulk properties of the composite. The melt flow index (MFI) of the sample was determined according to ASTM D 1238 (230\(^\circ\)C per 2.16 kg) by using a Zwick D 7900 melt flow indexer [23]. An average of 10 runs was taken for each sample. The samples were conditioned at 27\(^\circ\)C and 65\% RH for 24 h, in accordance with ISO 291 standard on conditioning and testing atmospheres, prior to testing.

Studies on the morphology of the composites were carried out by using a scanning electron microscope (SEM). SEM micrographs of the fracture surfaces of tensile specimens were taken. The samples were coated with a thin gold–palladium layer using a Sputter Coater Polaron SC 515 to avoid electrical charge accumulation during examination. Then, images of the fractured samples were taken using a digital video camera JVC 3-CCD, which was connected to a computer, and the images were analyzed using Image Analysis Pro software.

<table>
<thead>
<tr>
<th>Property</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>g/cm(^3)</td>
<td>0.90</td>
</tr>
<tr>
<td>Tensile strength, 73(^\circ)F</td>
<td>psi</td>
<td>4500</td>
</tr>
<tr>
<td>Tensile modulus of elasticity, 73(^\circ)F</td>
<td>psi</td>
<td>16,500–100,000</td>
</tr>
<tr>
<td>Elongation, 73(^\circ)F</td>
<td>%</td>
<td>200–700</td>
</tr>
<tr>
<td>Flexural modulus of elasticity, 73(^\circ)F</td>
<td>psi</td>
<td>17,000–100,000</td>
</tr>
<tr>
<td>Shear strength, 73(^\circ)F</td>
<td>psi</td>
<td>5710</td>
</tr>
<tr>
<td>Compressive strength</td>
<td>psi</td>
<td>6720</td>
</tr>
<tr>
<td>Hardness, Rockwell, 73(^\circ)F</td>
<td>–</td>
<td>80–120</td>
</tr>
<tr>
<td>Melt index</td>
<td>g/min</td>
<td>8</td>
</tr>
<tr>
<td>Melting point</td>
<td>(^\circ)F</td>
<td>335</td>
</tr>
<tr>
<td>Continuous service temp., air, max.</td>
<td>(^\circ)F</td>
<td>180</td>
</tr>
<tr>
<td>Dielectric strength</td>
<td>V/mil</td>
<td>500–660</td>
</tr>
<tr>
<td>Volume resistivity</td>
<td>ohm-cm</td>
<td>10(17)</td>
</tr>
<tr>
<td>Dielectric constant, 60 Hz</td>
<td>–</td>
<td>2.3</td>
</tr>
<tr>
<td>Water absorption, immersion – 24 h</td>
<td>%</td>
<td>0.03</td>
</tr>
</tbody>
</table>
RESULTS AND DISCUSSION

Relationship of Cell Wall Architecture in Composites

Figure 1(a)–(f) shows the anatomy and cell wall structure of oil palm trunk (OPT), oil palm frond (OPF), and empty fruit bunches (EFB). In general, the fibers have different anatomies and various cell wall layers consisting of primary (P) and secondary (S₁–S₃) walls as determined from TEM analysis. The middle lamella (ML), which glues the cell together, showed a clear transition to the adjacent primary wall layers. Oil palm fibers showed a great variability in the thickness of the S₂ layer, which is the main factor contributing to the strength of the individual fibers. In this study, OPT shows the thickest S₂ layer compared to that of EFB and OPF. The fiber strength is dependent on the cellulose microfibril that is aligned parallel to the fiber axis on the S₂ layer. The thicker S₂ layer results in stronger fibers, hence influencing the composites [22]. The fibers act as reinforcement or filler in the composite, depending on the stress transferred from the matrix to the fibers or filler.

Figure 1. TEM of ultrathin section of various types of plant fibers. (a) OPT; (b) OPF; and (c) EFB. Transverse sections of different types of agro fibers at low magnification after being stained with toluidine blue. (d) OPT; (e) OPF; and (f) EFB. F: fiber; P: parenchyma, Mx: metaxylem, Ph: phloem.
Table 2 shows the differences in chemical composition between the various types of oil palm fibers (OPT, OPF, and EFB). Extractive content was the highest in OPT fibers (4.9%) compared to other fibers. Extractive content is expected to play the most important role in dimensional stability because a high extractive content (especially oil and wax) will reduce the hygroscopic fiber property. However, OPT fibers show the highest percentage of holocellulose (72.6%) and $\alpha$-cellulose content (46.2%). The amount of cellulose in fibers will affect their use in various applications. In fiber and composites technology, the strength of a fiber, and hence the strength of the composite, depends on the content of cellulose. Generally, EFB fibers showed the highest percentage of lignin (24.9%), followed by OPF (22.4%) and OPT (19.7%). A higher lignin content indicates that this material can undergo extrusion of compounding (matrix and fiber) more easily.

**Tensile Properties of OPB–PP Composites**

Tensile property is one of the most important single indications of the strength of a material. Figures 2 and 3 show the variation of tensile properties of OPB–PP composites. The effects of fiber type and fiber loading upon the tensile properties of the composites were determined for a range of fiber contents from 10% to 50% (by weight). In general, both tensile strength and modulus were higher for OPT as compared to OPF and EFB.

**Table 2. Chemical compositions between the various types of oil palm fibers (OPT, OPF, and EFB).**

<table>
<thead>
<tr>
<th>Oil palm biomass fiber</th>
<th>Chemical composition (%)</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cellulose</td>
<td>Hemicellulose</td>
<td>Lignin</td>
<td>Extractives</td>
</tr>
<tr>
<td>Empty fruit bunch (EFB)</td>
<td>47.9</td>
<td>17.1</td>
<td>24.9</td>
<td>3.7</td>
</tr>
<tr>
<td>Oil palm frond (OPF)</td>
<td>42.2</td>
<td>26.4</td>
<td>22.3</td>
<td>3.3</td>
</tr>
<tr>
<td>Oil palm trunk (OPT)</td>
<td>29.2</td>
<td>16.5</td>
<td>18.8</td>
<td>3.9</td>
</tr>
</tbody>
</table>

![Figure 2. Effect of fiber material and fiber loading on tensile strength of OPB–PP composites.](image-url)
The result for the tensile strength is illustrated in Figure 2. The figure clearly shows that tensile strength decreased as fiber loading was increased. Higher fiber loading did not improve the strength of the composites; in contrast, it reduced these properties. This phenomenon was due to poor adhesion between the PP matrix and OPB fibers, which was evident by the extensive fiber pull-out of the OPB fiber, leading to a weak interfacial bond and resulting in an inefficient stress transfer between the PP matrix and OPB fibers. In addition, at higher fiber loading, more voids were formed, initiating crack formation and propagation in the composite, when compared with low fiber loading. This resulted in a higher probability of phase separation and agglomeration of fibers. This reduces the effective aspect ratio and hence, the strength of the composite. In general, the highest tensile strength of 29.55 MPa was gained by composites with 10% fiber loading of OPT fiber, followed by EFB (28.5 MPa) and OPF (27.0 MPa). Composites with 50% fiber loading displayed the lowest value of tensile strength: OPT (25.6 MPa), EFB (25.0 MPa), and OPF (22.4 MPa).

Different behavior was observed with the tensile modulus compared to the tensile strength. Figure 3 clearly shows that the tensile modulus was significantly improved by increasing the fiber loading. At high fiber loading, the increased population of fiber leads to agglomeration, which affects the stiffness of the composites. Fibers with a higher stiffness than that of the matrix can increase the modulus of the composite, as the modulus was a measure of the material stiffness. It was noted that the most prominent effect of the fibers is an increase in the modulus of the resultant composites [14]. The overall increase in the modulus demonstrated the ability of the OPB fibers to impart greater stiffness to the composite. This was in agreement with other lignocellulosic filled thermoplastics [12–14]. Therefore, the fibers were able to contribute to the effective stress transfer between fibers and the matrix. In general, it is noted that the increase of fiber loading increased the tensile modulus of the composites and thus increased the stiffness with an associated decrease in the elongation at break. Composites at 50% fiber loading showed the highest value of tensile modulus with OPT (3.30 GPa), followed by EFB (2.60 GPa) and OPF (2.50 GPa).

![Figure 3. Effect of fiber material and fiber loading on tensile modulus of OPB–PP composites.](image)
Flexural Properties of OPB–PP Composites

The three-point bending test was used to determine the flexural properties of the composite. Flexural strength and modulus of the OPB–PP composites are shown in Figures 4 and 5, respectively. The flexural strength of the composites determined the ability of the composites to withstand bending forces applied perpendicular to its longitudinal axis or the maximum stress in the outer layer of the test specimen at rupture.

**Figure 4.** Effect of fiber material and fiber loading on flexural strength of OPB–PP composites.

**Figure 5.** Effect of fiber material and fiber loading on flexural modulus of OPB–PP composites.
In flexural loading, the composites were subjected to compression, tension, and shear stresses. In three-point flexural tests, failure occurred due to bending and shearing. In general, flexural strength increased with an increase in OPB fiber loading up to 50%. Figure 4 shows that at 10% fiber loading, values of 14.33, 14.27, and 14.15 MPa were obtained for EFB, OPF, and OPT fibers, respectively. High fiber loadings (50%), resulted in higher values of 17.9, 17.55, and 17.44 MPa for EFB, OPF, and OPT fibers, respectively. This figure also shows that the flexural strength is lower at 10% as compared to 20–50% fiber loading. This was due to very poor fiber dispersion, which leads to poor performance. The lower flexural strength of OPT fiber composites as compared to EFB and OPF fibers showed that the composites were not capable of withstanding higher stress. This may be attributed to the low interaction and poor distribution of the fiber in the matrix. A unique feature of flexural strength, exhibited when the fiber was incorporated into the brittle matrix, is that the matrix still remains in the external phase of the composites. Hence, the flexural strength was still controlled predominantly by the resin domain. It was also noted that the stiffness and flexural modulus values increased as the fiber loading increased [7].

As highlighted by several researchers, the quality of the interfacial bonding was determined by several factors, such as the nature of plant fiber and the matrix as well as their composition, the fiber aspect ratio and the types of incorporation procedures and processing employed. Fibers with a non-uniform cross section and aspect ratio will normally reduce the composite strength. Poor wetting was expected due to poor compatibility between the polar plant fibers and non-polar polyester matrix, giving rise to weak interfacial regions [13–15].

As expected, the modulus which indicates material stiffness increases steadily with increasing fiber loading for the OPB composites at all fiber loadings as shown in Figure 5. The higher flexural modulus implied that the incorporation of OPB fiber in a PP matrix imparts greater stiffness to the composites. At 50% fiber loading, EFB, OPF, and OPT composites showed the highest values of flexural modulus of 2.702, 2.45, and 2.648 GPa, respectively. The increase in the flexural modulus at higher fiber loading was in agreement with similar trends observed in other studies of natural fiber composites [16,17]. This may be attributed to the increased deformability of a rigid interface between the fiber and the matrix material. In general, EFB fiber composites exhibited slightly higher values of flexural modulus as compared to the OPF and OPT fiber composites. This may due to factors affecting the composite modulus such as fiber modulus, fiber loading, and fiber aspect ratio (the ratio of the major to the minor dimension of a fiber). High modulus composites require fibers of high modulus, high aspect ratios, and preferably high fiber loading [18].

Impact Properties of OPT–PP Composites

Impact strength determined the ability of the material to resist fracture under stress applied at high speed. The impact properties of composite materials were directly related to their overall toughness, which was highly influenced by the interfacial bond strength and the matrix as well as fiber properties. The effect of fiber loading and fiber type on the impact strength of OPB fiber composites is shown in Figure 6. In general, impact strength increased with an increase in OPB fiber loading up to 50%. Figure 6 shows that at 10% fiber loading, values of 28.48, 26.88, and 27.11 J/m were obtained for EFB, OPF, and OPT fibers, respectively. However, high fiber loadings (50%), resulted in higher values of 36.29, 34.30, and 35.03 J/m for EFB, OPF, and OPT, respectively. The higher impact strength of
EFB fiber composites as compared to OPF and OPT fibers may be attributed to the larger fiber diameter and higher lignin content of EFB fiber as compared to OPF and OPT fibers.

**Elongation at Break of OPT–PP Composites**

Figure 7 shows the elongation at break of various oil palm fibers. In general, the elongation at break decreased as the filler/fiber loading increased. This was due to the decrease in plastic in the composites. Elongation at break followed in the order: virgin PP (highest) 10% > 20% > 30% > 40% > 50% (lowest) fiber loading. This was expected due to higher fiber loading, lower plastic content in composites, and hence a lower elongation at break. This phenomenon was similar to that observed in an earlier study [24]. With regard to different fiber content, OPT shows the highest elongation at break (6.2%), followed by EFB (5.9%) and OPF (5.8%). This was due to the higher cellulose content and thicker cell wall structure of OPT fiber. The S₂ layer has influenced the elongation at break of composites.

**Melt Flow Index Properties of OPT–PP Composites**

Figure 8 shows the MFI properties of the composites for various fiber loadings and fiber types. In general, the MFI decreased as fiber loading increased. This was due to the presence of fiber, which increases the viscosity of the composite. As can be seen in Figure 9, composites prepared from EFB fiber showed the highest MFI values as compared to that of OPF and OPT fibers. This phenomenon was due to physical characteristics of EFB that enable it to deform more easily than OPF and OPT fibers. Figure 9 also shows that EFB lignin content (24.9%) is greatest as compared to OPF (22.4%) and OPT (19.7%), indicating that this material can easily undergo extrusion.
of compounding. Lower fiber loading (10%) also allowed the PP matrix to flow easily as compared to higher fiber loadings (20, 30, 40, and 50%).

**SEM Micrograph of OPT–PP Composites**

Based on SEM analysis of impact failure surfaces, it is clear that at 10 and 50% filler loading, excessive voids and porosity occurred within the composite materials leading to poor homogeneity. The extensive fiber pull-out was also observed. This clearly provides
a supportive evidence for the poor mechanical and physical properties of the OPB composites. This phenomenon was due to hydrogen bonds formed between the fiber and PP matrix, which caused the fiber to agglomerate into bundles and thereby, were unevenly distributed throughout the matrix.

Based on fiber–matrix bonding of various oil palm fibers (OPT, EFB, and OPF, respectively). Poor fiber–matrix bonding was observed in all the fibers. However, OPT fiber composites exhibited slightly better fiber–matrix bonding as compared to that of OPF and OPT fiber composites. This indicates the poor stress transfer between the fiber and matrix. The poor bonding quality between fibers and polymer matrix, observed during experiment, creates weak interfacial regions, which results in debonding and fractional pull-out of fiber bundles.

Owing to the abundance of hydroxyl groups associated with the cellullosic component of the fibers, oil (3%), wax and other substances on the fibers, the fiber layers show poor wetting by the non-polar matrix in polymer composites [5,6]. However, the properties can be altered by modifying the chemistry of the fibers. Chemical modification (brought about by anhydrides, isocyanates, epoxides, and compatibilizers) of lignocellulosics has been shown to improve fiber–matrix bonding. Effective compatibilization between matrix and natural fiber happens when maleated polymer forms an ester bond with the fiber and the polymer chain from the maleated polymer simultaneously penetrates into the fiber [26,27].

**CONCLUSIONS**

(1) Based on the electron micrographs, it can be stated that the cell wall structure of EFB, OPT, and OPF has the same ultrastructure as that of wood fiber and is composed of primary (P) and secondary walls (S1, S2, and S3).

(2) Extractive content was the highest in OPT fiber (4.9%) when compared to the other fibers. However, OPT fiber shows the highest percentage of holocellulose (72.6%) and
α-cellulose content (46.2%). Generally, EFB fiber showed the highest percentage of lignin (24.9%), followed by OPF (22.4%) and OPT (19.7%).

(3) OPB composites with higher fiber loading (50%) exhibit a higher tensile modulus, flexural strength, flexural modulus, impact strength and melt flow index. However, at 10% fiber loading, the tensile strength and elongation at break show stronger properties.

(4) In water absorption, OPT (5.2%) showed the highest water uptake followed by EFB (4.0%) and OPF (2.9%).

(5) Based on SEM analysis, the composite materials showed poor fiber–matrix bonding. However, OPT fiber composites exhibited slightly better fiber–matrix bonding as compared to the OPF and OPT fiber composites.

ACKNOWLEDGMENT

The researchers would like to thank the Ministry of Science, Technology and Innovation (MOSTI) and the Universiti Sains Malaysia, Penang for providing the research grant E-Science Fund (RM-9) 03-01-05-SF0334 or 305/PTEKIND/613323 that has made this work possible.

REFERENCES


