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Banana fiber/low-density polyethylene recycled composites for third world eco-friendly construction applications – Waste for life project Sri Lanka

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Abstract

In the framework of the waste for life Sri Lanka project, low value industrial low-density polyethylene waste plastics and banana fibers made from agricultural waste are upcycled into affordable eco-friendly building products. This creates income for the local communities while mitigating waste disposal and reducing ecological problems. Within this context, a robust manufacturing method using compression molding was developed. Panels with varying fiber content were manufactured using unchopped and chopped fibers. Low-density polyethylene characterization using Fourier transform infrared spectroscopy and differential scanning calorimetry to compare plastic sources was conducted. To reduce cost, no fiber treatments or compatibilizers were used. An estimate of critical fiber length was found to be around 1.45 cm to 2.5 cm. A trend of increasing strength with fiber content (up to 40 wt.%) was achieved by using longer fibers than in the previous research. Handling and dispersion of the fibers were increased by chopping the fibers to 20 cm lengths, which led to an increase in tensile strength due to easier manufacturing. Cross-ply panels made with fibers chopped to a length of 20 cm were found to be strongest peaking at around 40 wt.% with a tensile strength of 32.8 MPa, a fourfold increase compared to a raw low-density polyethylene (0 wt.%) panel.

Keywords

Low-density polyethylene, banana fiber, waste for life, natural fiber composite, mechanical properties, recycled waste composite

Introduction

Waste for life Sri Lanka

As an increasing number of multinational corporations benefit through minimization of labour costs by outsourcing production to the Global South, local communities in these countries pay for such benefit through pollution and over production of waste. Such is the case of Sri Lanka where the insufficient garbage dumps have been collapsing. In 2001, the United Nations Environment Programme released a document concerning the state of the environment in Sri Lanka. The study reported that on the 6400 tons of waste produced daily, only 3500 tons are collected by local authorities.[1] The limited waste management resources are mainly focused in wealthier neighborhoods, resulting in the creation of open dumps in poor neighborhoods, where a variety of household or toxic items are discarded in the near vicinity of where they were

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produced.[2] Moreover, the amount of uncollected waste has an increasing trend and will only get harder to control over time.[3] From this lack of proper management has emerged an informal waste sector that only makes a small income, but plays a key role in reducing environmental problems as they collect discarded trash to sell to small-scale recyclers.

Waste for life is a not-for-profit organization which assists communities to create poverty reducing solutions to the waste problems that surround them. Their "twin goals are to reduce the damaging environmental impact of non-recycled plastic waste products and to promote self-sufficiency and economic security for at-risk populations who depend upon waste to survive."[4] They first assess the need of local communities and then conduct technical and economic feasibility studies for their projects. They have experience with such projects in Buenos Aires and Lesotho,[5,6] and now in Sri Lanka.[7]

The goal of WFL in Sri Lanka is to assist the informal waste sector that uses waste collection as their livelihood. One method to achieve this is by using salvaged low-density polyethylene (LDPE) plastic as well as banana fibers and transform them into low cost, recycled, and ecofriendly composites for housing applications. These simple, readily available and free base materials would provide local communities their own resources as well as mitigate waste disposal, thus reducing ecological problems.

Natural fiber composites

Natural fiber composites (NFCs) are made using fibers, from natural sources, which have high strength-to-weight ratios. They come from a renewable source, for which production requires little energy and entraps atmospheric CO_2 making them a sustainable choice.[8] However, NFCs have poor interfacial bonding between the hydrophilic banana fibers and hydrophobic thermoplastic matrix. As it is the case with many natural fibers, the high lignin and hemi-cellulose content as well as presence of pectin and waxy substances hinders the adhesion across the fiber/matrix phase boundary. A chemical alkaline delignification treatment has been shown to remove certain portion of those substances, cleaning the fibers and increasing the stress transfer capacities by increasing the interface strength.[9] This kind of chemical treatment or the addition of a compatibilizer is commonly used in the fabrication of NFCs. However, fiber treatments were not considered in this work since they can be costly, and their chemical nature can be harmful to the people who will be processing the banana fibers.

Due to the poor bonding of the two materials, the fiber's length has an impact on the composite's strength. The critical fiber length is the minimum length required to effectively strengthen and stiffen the material. It depends on the fiber diameter, its ultimate tensile strength (UTS), and on the fiber/matrix bond strength.[10] Thus, each fiber/matrix combination will have a different critical length. When loaded, the shear stress transferred through the interfacial bonding is what will load the fibers, which will undergo different tensile strains from the matrix due to their different moduli.[11] If the fiber is shorter than the critical length, failure will be dominated by end effects and there will be presence of interfacial shear debonding. Research has shown that the increase in untreated short fiber content will actually decrease the tensile strength most likely caused by fibers being below the required critical fiber length.[12,13] By treating the fibers, the interfacial bond strength is increased, therefore decreasing the critical fiber length. Thus, by treating the fibers, there is an increase in the tensile strength with increased short fiber content as shown by Prasad et al.[14] The same increasing strength trend can be achieved using longer fibers.

A strong matrix/fiber bond is a key factor in the manufacturing of the composite panels. For adhesion to occur, the LDPE matrix must be brought into intimate contact with the fibers.[15] This is achieved by heating the plastic to make it flow and approximating the behavior of a liquid. A good bond signifies that the matrix's flow over the fiber will envelop and fill every bump and cranny of the uneven fiber by displacing all air. A proper dispersion of the fibers within the matrix will increase fiber contact area and improve the bond.

Objectives

The current work aims to study banana fiber/LDPE composite panels using manufacturing methods that can be easily reproduced at a low cost in Sri Lanka. Using materials resembling available resources in Sri Lanka is important to make sure that the research is as relevant as possible. Hence, LDPE from Sri Lankan and Canadian sources were characterized to determine their similarity. Then, different manufacturing methods were explored to maximize UTS and tensile modulus. Different fiber lengths were used during the manufacturing process. This allowed to determine the impacts of fiber length on manufacturing (speed, dispersion) and mechanical properties. Long continuous fibers tend to form a bundle more than the short fiber. On the other hand, the short fiber-reinforced polymer composite faces different problems such as the fiber–fiber interaction and the critical length.[8] Chopping the fibers allows for easier handling and dispersion within the matrix. As LDPE is not strong enough to create structural parts, the aim was put on creating flat composite panels for roofing and cladding purposes.

Material and methods

Banana fibers

Banana fibers are a lignocellulic bast fiber that comes from the pseudo-stem of the banana plant.[16] The fibers were harvested and processed in Sri Lanka by the Yaal foundation – a group associated with banana farmers. They are made using waste from this industry using a semi-manual multifiber bundle decorticating machine that was donated by a German NGO. Natural fibers are not very abrasive to processing equipment and to the people handling them making them a perfect choice for our application. Characterizing the banana fibers' mechanical properties can be difficult, as natural fibers tend to vary greatly depending on yield, locality, maturity of the plant, location of fibers within the plant, and the varying weather conditions such as rainfall and sun exposure. The individual fibers also present a number of physical characteristics such as variation in microfibril angles, variable cross-section and numerous flaws such as links, dislocations, nodes and slip planes.[17,18] These can come from the plant's growth process or from the fiber extraction method used (retting process vs. mechanical extraction). As the trees were not grown primarily for their fibers, there is not much that can be done about these flaws.

Waste plastic characterization

An LDPE matrix was chosen due to its widespread presence and low processing temperatures. Industrial plastic stretch wrap recovered off the wrapped pallets by the freight receiving department of a local retail store (IKEA) in Montreal, Canada, was used. Waste plastic sourced from a textile company in Sri Lanka and the IKEA plastics were characterized with Fourier transform infrared spectroscopy (FTIR) and differential scanning calorimetry (DSC). Because not enough plastic material could be sourced from Sri Lanka, the characterization was done to assess the impacts of using plastics from a different origin.

First, a Spectrum Two FT-IR spectrometer made by Perkin Elmer analyzed the plastic samples over the range of 4000–500 cm^{-1} with a spectrum resolution of 4 cm^{-1}. This was to ensure that both are of the same nature (LDPE). Then, a TA Instruments DSC Q100 differential scanning calorimeter using a 20°C/min ramp from room temperature to 250°C was used to determine the melting temperatures of the plastics and establish a processing temperature. Both these tests do not ensure that the plastics will have the same rheology when being processed. However, since the aim is to provide a general methodology, rheology was not considered, as plastics from varied sources are expected to be used as a matrix. The local Sri Lankan manufacturers would have no way of determining the melt flow index or molecular weight of the materials they have at hand.

Critical fiber length

Assessing the impacts of the length of fibers is important to overcome the difficulties caused by the poor interfacial bonding. Chopping the fibers allow for better dispersion, but cutting them too short can also be detrimental. Knowing the critical fiber length (l_c) will provide a guideline for future works attempting to fabricate banana fiber/LDPE recycled composites. The critical fiber length is the minimum length required to effectively strengthen and stiffen the material. It can be calculated using

$$l_c = \frac{\sigma_f D}{2\tau}$$

where σ_f is the fiber's tensile strength, D is the fiber diameter, and τ is the interfacial shear bond strength at the fiber/matrix interface.[19] The critical fiber length was estimated using a combination of measured fiber diameter values (D) and literature values for σ_f and τ. The diameter of 75 fibers was measured using an optical microscope and then averaged. The fiber tensile strength was taken from literature to be 400 MPa–980 MPa.[16,20] The interfacial shear bond strength τ was approximated to be the shear yield strength of the plastic matrix. It assumes that the bond between fiber and matrix is perfect which is not the case here. Therefore, the found critical fiber length will be the lower bound on the fiber's critical length as τ will have a lower value in our panels. The matrix shear yield strength can be calculated using the Von Mises yield criterion

$$\tau_y = \frac{\sigma_y}{\sqrt{3}} = 0.577 \cdot \sigma_y$$

where τ_y is the matrix shear yield strength, and σ_y is the matrix yield strength. Hence, the critical fiber length can be estimated using the following equation

$$l_c = \frac{\sigma_f D}{2 \cdot 0.577 \cdot \sigma_y}$$

Manufacturing method

Compression molding

Compression molding is a simple and robust manufacturing method that can be used to create flat panels at a low-cost. Although panel property variability exists, the variability in the manufacturing process of the simple panels is quite low. The basic equipment is hard to break and can therefore be used for prolonged periods. Compression molding allows mixing the fiber with the matrix, applying heat and pressure all in one step. The simplicity of the manufacturing method makes compression molding a perfect fit for the purpose of this project.

Composite fabrication

Seven different types of panels were manufactured with different fiber contents. First, randomly oriented continuous fiber panels, where fibers were not cut and were kept at their full length of around 1 m as received from Sri Lanka. Then, panels made using randomly oriented fibers chopped to lengths of 20 cm, 10 cm, 5 cm, 2.5 cm, and 1 cm, respectively. Finally, a cross-ply panel using fibers chopped to 20 cm oriented in the 0° and 90° directions was made. All the panels were made using the same method, only the fiber length, weight percentages (wt.%) and orientations were changed. These panels will be referred to as continuous fibers, 1 cm chopped, 2.5 cm chopped, 5 cm chopped, 10 cm chopped, 20 cm chopped, and cross-ply panels in the rest of the paper. The 1 cm chopped and 2.5 cm chopped fiber panels were made to better understand the required critical fiber length to strengthen the material.

Manufacturing procedure

The banana fibers and plastic LDPE were first pre-pressed in a FZLC-B5–2 pneumatic double heated press that was made for t-shirt transfer printing. The press makes panels of 15.75″×23.6″ (40 cm × 60 cm). Before pre-pressing, the appropriate amount of fiber and plastic matrix is weighed, and then layered manually. The pre-press is used to debulk the material, making it easier to handle and insert into the final mold. First, a plastic sheet approximately sized to the pre-press (40cm x 60 cm) is laid down. Then, fibers are spread by hand evenly over the plastic, all while taking care of breaking up fiber clumps. Good fiber dispersion is important to maximize fiber/matrix contact when layering the raw recycled material. Then, this process is repeated to create the different layers of plastic and fibers. The number of layers will depend on the fiber wt.% of the panel. Hence, a panel with lower wt.% will contain more plastic layers containing smaller amounts of fibers between them. Finally, the layers are inserted between two Teflon baking sheets before inserting into the 140°C pre-press for 3 min. The pre-pressed sheet of a randomly oriented continuous fiber panel is shown in Figure 2(a). The prepressed composite panel was made to be cut into five sections considering the final 8″×9.5″ (20.32 cm × 24.13 cm) mold. Once cut, these sections were then layered into the final preheated mold with no waste as seen in Figure 2(b). It was pressed at 140°C at a pressure of 200 psi (1.379 MPa) for a 10-min period in a heated press as shown in Figure 2(c). The processing temperature was determined during the DSC tests that are presented in the results and was chosen to be past the LDPE's melting point. Then, the panel was left inside the mold to cool down to room temperature while keeping an applied pressure of 200 psi. A thermocouple was used to characterize temperature uniformity within the plate and ensure 140°C was reached. When the press' heating plates were set to 140°C, the center of the mold was only a few tenths of a degree cooler throughout the plate. An example of a final 38 wt.% panel is shown in Figure 1. After the panel was taken out of the mold, the excess plastic that flowed out (flashing) was cut. The final panel is then weighed. To calculate the fiber weight percentage of the final panel, the weight of the fibers (weighed earlier) is divided by the final weight of the panel. The presence of air voids was not considered in wt.% calculation.

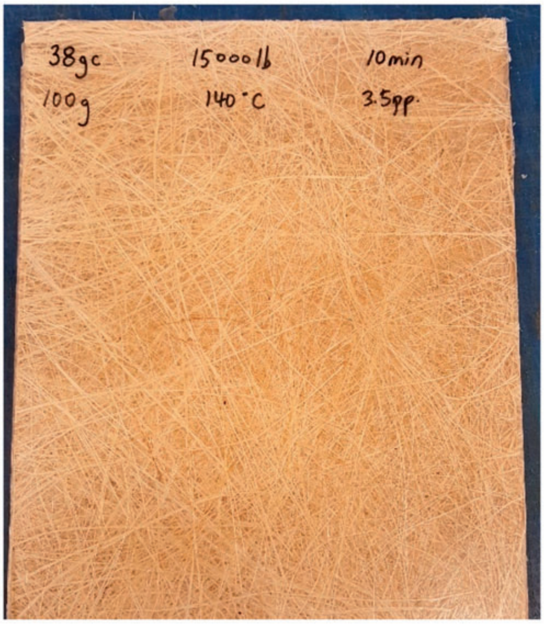

Figure 1. Final 38 wt.% banana fiber/LDPE panel.

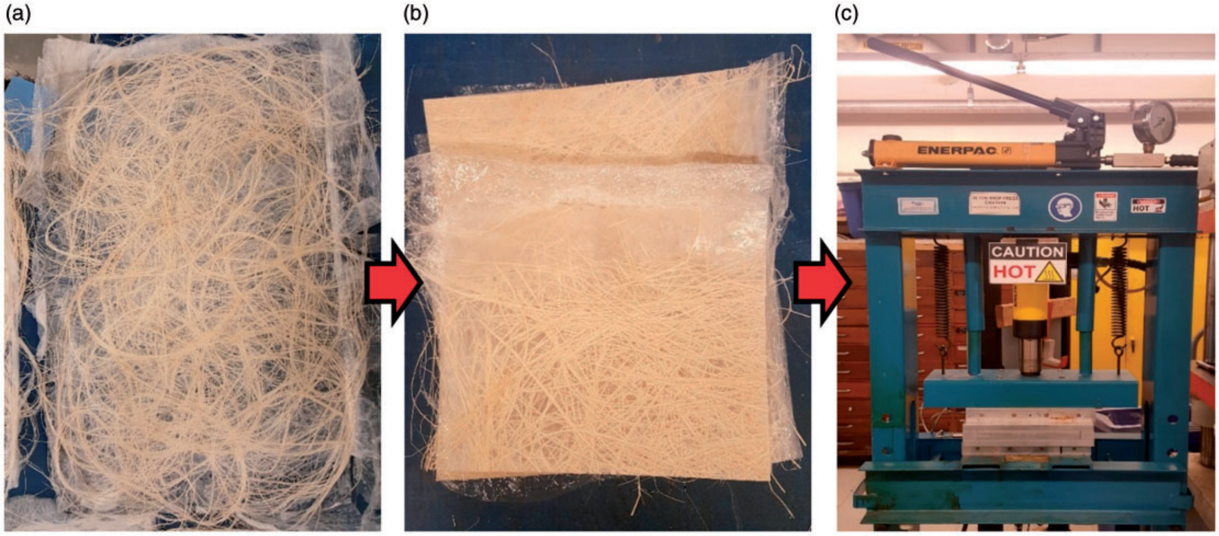

Figure 2. Simplified manufacturing procedure of a 25 wt.% continuous fiber panel. (a) Prepressed panel of randomly oriented continuous fiber panel. (b) Prepressed panel cut into final mold size. (c) Compression molding step.

Tensile testing

All tests were conducted using a 100 kN MTS testing machine. The tensile testing for the pure LDPE was conducted according to ASTM D638[21] using a crosshead displacement of 50 mm/min. Six specimens were cut according to Type I specimen specifications. The composite panels were tested according to ASTM D3039[22] using a crosshead displacement of 2 mm/min. Six specimens per panel type were tested. The tensile testing specimens were cut 8 inches (20.3 cm) long and 1.5 inches (3.8 cm) wide. A different test method for the raw plastic was used because of LDPE's high strain to failure. The LDPE panels could not meet the ASTM D3039 standards' requirements. Because the composite material is not homogeneous over a significant area, the specimen must be as large as possible.[23] It ensures that they contain a sufficient number of fibers in the testing gauge cross-section to be representative of the bulk material.[22] Therefore, they were cut to the maximum width of the grips to have a better approximation of the material properties. Strain was measured with an MTS 632.31E-24 axial extensometer with gage length of 20 mm.

Results and discussion

Characterization

FTIR. The FTIR spectra of both Sri Lankan and IKEA plastics are shown in Figure 3. It can be used to differentiate the different types of polyethylene. LDPE, high-density polyethylene (HDPE), and linear low-density polyethylene (LLDPE) are made from repeating methylene groups (CH_2) and can be differentiated by their different degrees of branching size and ramification. In all polyethylene types, characteristic doublets at 2919 cm^{-1} and 2851 cm^{-1} due to CH_2 asymmetric stretching, bending deformation doublets at 1473 cm^{-1} and 1463 cm^{-1}, and rocking deformation doublets at 731 cm^{-1} and 721 cm^{-1} are present. The three weaker bands at 1377 cm^{-1}, 1366 cm^{-1}, and 1351 cm^{-1} help to determine the type of polyethylene. When the peak at 1377 cm^{-1} is stronger than the 1366 cm^{-1} peak, as it is the case here, the polymer is LDPE. If the 1366 cm^{-1} peak is stronger, the polymer is LLDPE. If there is an absence of the 1377 cm^{-1} peak, it is HDPE. The 1351 cm^{-1} peak should be present in all cases. Thus, the FTIR confirms that both plastics are in fact LDPE. The presence of a slight peak around 1700 cm^{-1} in both plastics may be due to the addition of different antioxidant additives such as hindered amine stabilizers (HAS).[24] Each plastic most likely has a different additive as the 1700 cm^{-1} peaks do not look the same. The difference in strength of both signals is due to the difference in the film thicknesses that were not normalized. Using this characterization method, we can conclude that both plastics have similar chemical compositions.

DSC. DSC was used to determine the melting behavior of both Sri Lankan and IKEA plastics to fix a processing temperature. The thermograms of both materials from their second heating cycle are shown in Figure 4. The heat flow curves are very similar; however, the Sri Lankan plastic has a brief plateau at around 110°C, which is not present in the IKEA plastic. This may be due to the presence of an additive with a melting peak at 108°C that was also detected in the

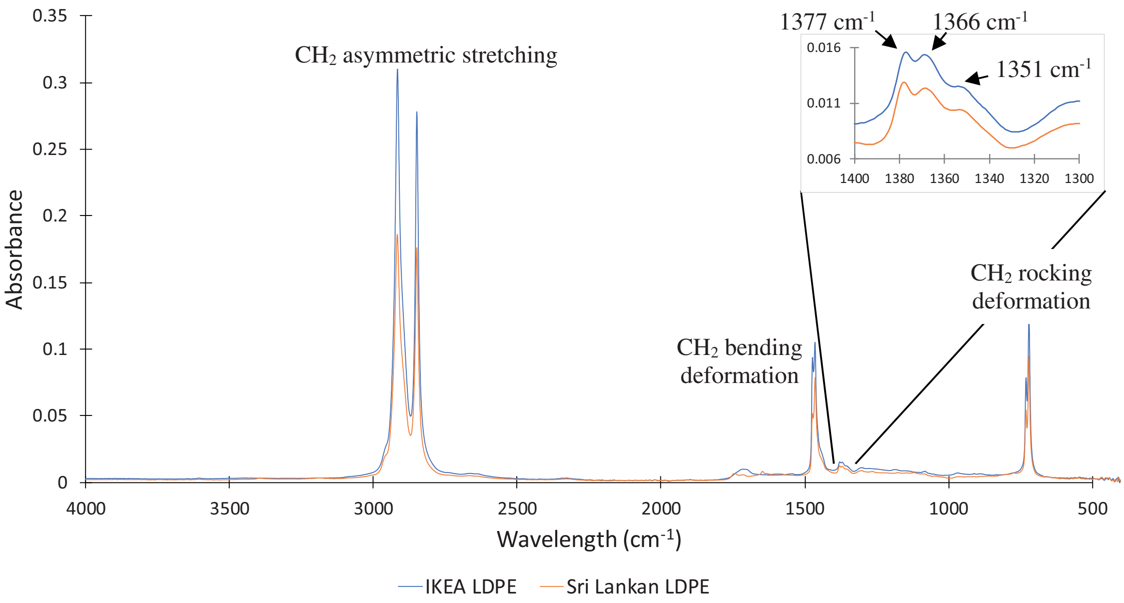

Figure 3. FTIR spectra comparing IKEA and Sri Lankan waste LDPE. LDPE: low-density polyethylene; FTIR: Fourier transform infrared spectroscopy.

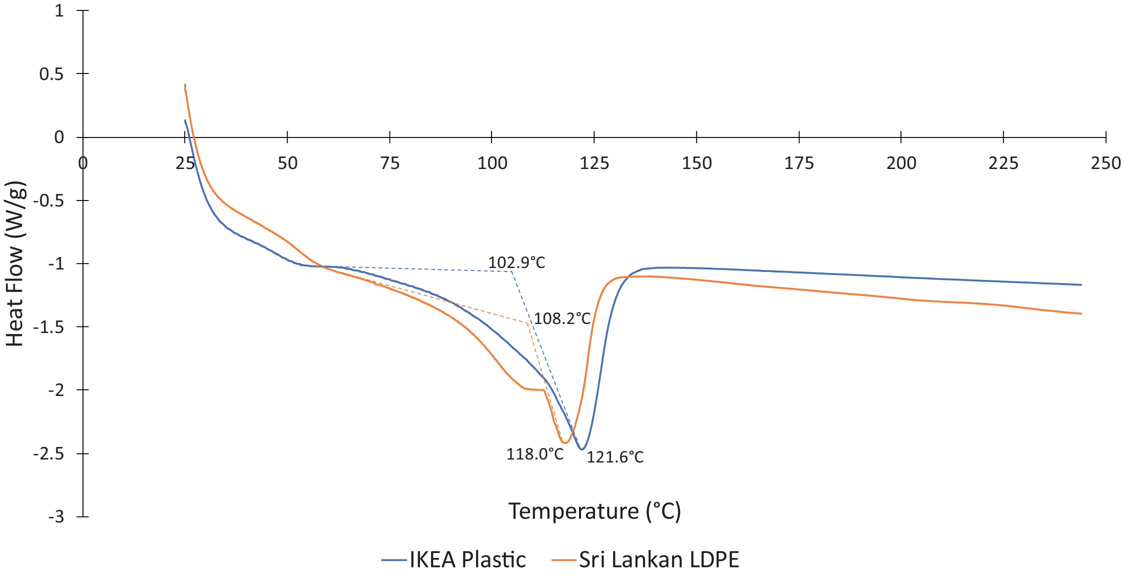

Figure 4. Thermograms comparing Sri Lankan waste plastic and Canadian waste plastic from IKEA.

FTIR analysis. The absence of this peak could confirm that each plastic contains different additives. The plastic from Sri Lanka has an onset melting temperature of 108.2°C, melting peak at 118.0°C and is fully melted by 132.5°C. The IKEA plastic has an onset melting temperature of 102.9°C, melting peak at 121.6°C and is fully melted by 136.5°C. A processing temperature of 140°C was chosen as it would fully melt the LDPE in both cases. A slightly higher temperature can be used to account for the possible variation between LDPE sources; however, the focus here was put on shortening the cycle time by minimizing heating and cooling of the mold.

Tensile test results

To have the greatest surface area of a single fiber adhered to the plastic matrix, the fibers were kept to their original length of approximately 1 m. After manufacturing these continuous fiber panels, it was realized that the unchopped fibers are very difficult to separate and disperse. The fibers were then chopped since their dispersion in the matrix was shown in literature to substantially influence mechanical properties.[8] This avoids the formation of bundles that would lower the fiber surface area adhering to the matrix. Also, each individual fiber can also be better separated. This minimizes fiber entanglement and resin-rich regions, thus reducing mechanically weak areas and increasing overall mechanical properties by increasing homogeneity. Fiber bundles and entanglement are to be avoided as they provide poor matrix impregnation. However, as the fibers are shortened, there is less matrix/fiber surface area for each fiber to have the tensile load transferred by shear. Since the panel test specimens were only a maximum of 25 cm long, the fibers were cut to 20 cm, 10 cm, and 5 cm lengths. This was to see if manufacturing with shorter fibers has an effect on tensile properties.

UTS and Young's modulus testing results for the different specimens mentioned above and in the manufacturing section are shown in Figures 5 and 6 along the with standard deviation ($n = 6$ for each dataset).

The LDPE plastic panels (0 wt.%) have an UTS of 8.1 MPa and can be used as a baseline. All the different types of composite panels show a maximum tensile strength at around 40 wt.%. The 10 cm chopped fiber panels and long continuous fiber panels behave similarly. They have a maximum UTS of 25.7 MPa and 25.4 MPa occurring at 43 wt.% and 43.5 wt.%, respectively. The 20 cm chopped fiber panels and cross-ply panels which both use fibers of 20 cm lengths have better properties. Their maximum tensile strengths are 30.5 MPa and 32.8 MPa, respectively. These occur at 36.5 wt.% and 43 wt.%. The 5 cm chopped panels had the weakest tensile strengths that were only slightly lower than longer fiber lengths. Its highest UTS of 19.75 MPa occurred at 46.8 wt.%. By looking at the 5 cm chopped fiber tensile strength trend, there is a possibility that the strength keeps increasing with added fibers. This is, however, unlikely when looking at the other data points and also at prior works in which a maximum is typically found around 40 to 45 wt.%.[16,25]

The panels that achieved the highest average UTS were made using fibers chopped to 20 cm lengths. In composite laminate theory, cross-ply panels should have better mechanical properties in the 0° and 90° direction compared with randomly orientated fibers. Hence, a single cross-ply panel was made at a fiber wt.% around the known maximum to see if this was also the case with our materials and manufacturing methods. No statistical difference was found between the 20 cm chopped and cross-ply panels. The additional step of aligning the fibers does not seem worthwhile here. The higher strength of panels using 20 cm fibers could possibly be explained by the testing method used. The testing gauge length between both grips of the tensile testing machine was 5″ (12.7 cm). Some fibers could have completely crossed the gauge going from one grip to another. Hence, these bridged fibers could have contributed to improve erroneously the tensile strength of the test specimens. This bridging effect should also exist

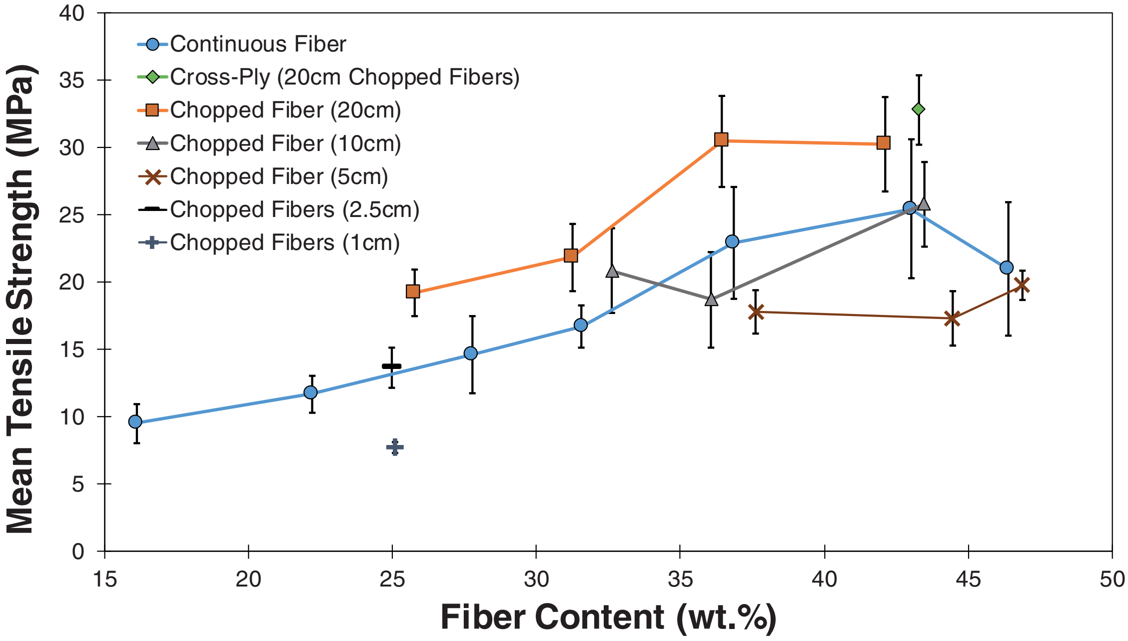

Figure 5. Tensile strength vs. fiber content of banana fiber/LDPE composite panels. LDPE: low-density polyethylene.

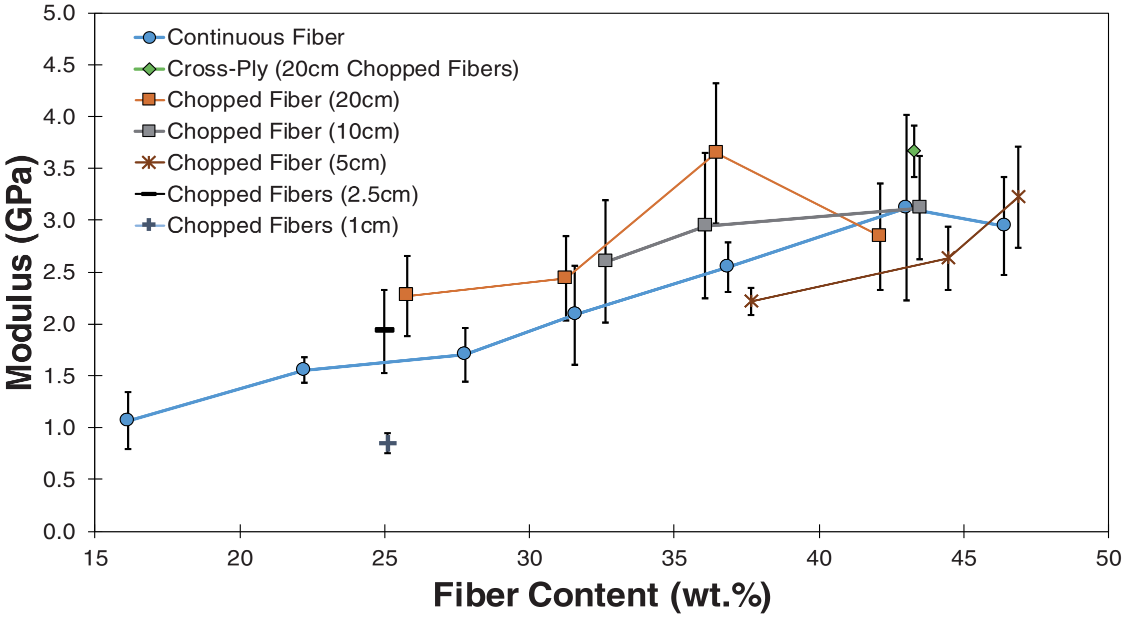

Figure 6. Young's modulus vs. fiber content of banana fiber/LDPE composite panels. LDPE: low-density polyethylene.

in the unchopped continuous fiber panels. The lower mechanical properties from the challenging manufacturing of unchopped fiber panels could have cancelled out the bridging effect that would have improved the tensile test data.

The tensile modulus also exhibits an increasing trend with a maximum at around 35 to 45 wt.%. However, due to the scatter, it is unclear if any of the panel types are the stiffest. The 43 wt.% cross-ply panel had the highest modulus of 3.66 GPa, whereas the 36.5 wt.% 20 cm chopped panel had a modulus of 3.65 GPa. The continuous fiber and 10 cm chopped fiber panels had a maximum modulus of 3.12 GPa at 43 wt.%. The 5 cm chopped fiber panels have their highest modulus at 46.8 wt.% with a value of 3.22 GPa.

There was an increase in standard deviation in the tensile data with a higher fiber loading. Standard deviations at each wt.% were averaged and then plotted against fiber loading. When aggregating over all samples, UTS standard deviation increases on average by 0.135 MPa per 10 wt.% with $R^2 = 0.84$ when using a linear fit. The R^2 value increases to 0.97 when ignoring samples over 45 wt.%. The modulus' standard deviation also shows an increasing trend with increased fiber content, but has a less clear trend. There is an average increase in standard deviation of 0.1 GPa per 10 wt.% increase with $R^2 = 0.66$ when using a linear fit. When looking at different fiber lengths at a specific wt.%, there seems to be a general increase in standard deviation with longer fibers. However, this is not a strong correlation and could be due to coincidence. Since the panels were made by hand, it is difficult to measure and control the dispersion of the fibers and matrix in the mold. This, however, does reflect the manufacturing conditions that would be present in Sri Lanka. Dispersion was only assessed during the layering of banana fibers and LDPE by looking for presence of clumps and subsequently by looking at the pre-pressed panels for resin-rich areas. Using shredded or sub-centimeter fibers should increase the homogeneity of the material and decrease variability, but this is not a viable solution here, as they would require fiber treatments to strengthen the material.

Chopped fibers, no matter what length (5 cm, 10 cm, 20 cm), are easier to separate than unchopped fibers. Shorter chopped fibers (5 cm, 10 cm) are harder to separate from each other, but could theoretically have a better dispersion. They take considerably longer to manufacture because of the arduous task of separating the individual fibers. Seeing as the 5 cm and 10 cm chopped panels had no significant strength improvements, the potential benefit of better dispersion of shorter chopped fibers do not seem to outweigh the tedious manufacturing difficulties. The longer chopped fibers can have lower dispersion due to the fibers forming entwined agglomerates. But, they are much quicker to manufacture as there are fewer fibers to separate for the same wt.% compared to shorter fibers. The 20 cm randomly oriented chopped fiber panels were almost as fast to manufacture as the unchopped fiber panels, but had the added advantage of easier dispersion. The improper dispersion of fibers in lower wt.% panels will have a much greater effect as there are much fewer fibers to compensate for improper fiber/matrix bonds.

This could create larger locally weak areas that reduce mechanical properties. In higher wt.% panels, dispersion issues will not be exhibited as prominently, as the sheer volume of fibers in surrounding areas can compensate for small local weaknesses.

Manufacturing of 20 cm chopped fiber panels is suggested as they offer the best compromise between time and mechanical properties for manufacturing large quantities of panels.

Critical fiber length

Using an optical microscope, the diameter of 75 fibers was measured. Their diameters ranged from 111 µm to 920 µm with the average diameter of the banana fibers being 292 µm. This is slightly wider than what is found in the literature (60 µm–250 µm).[16] There is a lot of variation in the fiber tensile strength. It was taken from literature to be 400 MPa–980 MPa.[16,20] Using a matrix yield stress of 7 MPa that was found from the plastic tensile tests, the critical fiber length was estimated to be 1.45 cm ($\sigma_f = 400$ MPa) to 3.54 cm ($\sigma_f = 980$ MPa). A sample calculation is shown below

$$l_c = \frac{\sigma_f \cdot D}{2 \cdot 0.577 \cdot \sigma_y} = \frac{400\,\mathrm{MPa} \cdot 292\,\mu\mathrm{m}}{2 \cdot 0.577 \cdot 7\,\mathrm{MPa}} = 1.45\,\mathrm{cm}$$

Both values are lower bounds of the critical length because a perfect matrix/fiber adhesion was assumed. Also, deviations from these values will exist in our composite panels since there are a lot of variations in fiber properties.

Two panels using 2.5 cm and 1 cm long fibers were made to verify the true critical fiber length. These 25 wt.% panels had a UTS of 13.65 MPa and 7.71 MPa, respectively, as shown in Figure 5. The 2.5 cm panel's UTS is well above raw LDPE (8.1 MPa). If the panel's tensile strength was below 8.1 MPa, then the added fibers would have acted as defects and weakened the material. Since the material was strengthened by the addition of the 2.5 cm fibers, these fibers were longer than l_c. This was not the case for the panel made with 1 cm fibers. Its UTS fell below that of raw LDPE, indicating its fibers are shorter than l_c. Therefore, the critical fiber length is above 1 cm and below 2.5 cm. This means that the theoretical lower bound of 1.45 cm is still a good estimate and l_c is found somewhere between 1.45 cm to 2.5 cm. These lengths correspond with the fibers in the weaker strength range that was found in the literature. This is consistent with the type of fibers that were used to make the panels. The fibers were made by decortication, which yields fibers with lower strength.[16]

Conclusions

In the present work, natural fiber composite panels using agricultural and plastic waste were made using compression molding. The work was carried out in support of the waste for life Sri Lanka project. The aim was to create manufacturing guidelines that can be used by the marginalized informal waste sector of third world countries. First, matrix characterization using FTIR and DSC showed that the plastic used was of the same nature (LDPE) and had similar processing temperatures to the waste plastic sourced from Sri Lanka. This was done to ensure that the processing method developed using the IKEA plastic could be used in Sri Lanka. Also, the impacts of different fiber lengths were evaluated. It was shown that by lengthening the fibers from the 2–10 mm short fiber lengths used by prior researchers[13,14,26] to a length past the fiber's critical length, an increasing tensile strength can be achieved by increasing the fiber content without the use of any treatments or compatibilizers. Avoiding extra chemical treatments is key to keeping low costs. Tensile testing showed that the tensile strength reached a maximum at around 40 wt.% with cross-ply panels having the strongest tensile strength (32.8 MPa). This is a four-fold increase over the 0 wt.% LDPE (8.1 MPa). A bridging effect may have skewed our 20 cm chopped fiber panel data. In addition, it was found that chopping the fibers allowed for easier dispersion and manufacturing. However, they should not be cut below the critical fiber length, which is estimated to be between 1.45 cm to 2.5 cm. Chopping the fibers to 20 cm length is suggested as it is the best way to disperse fibers properly and in an efficient manner over unchopped or shorter fiber lengths. Processing the panels for 10 min with a 200 psi (1.379 MPa) pressure at a temperature of 140°C is suggested.

This type of technology can be reproduced worldwide as the presence of plastic waste is widespread. Also, different types of natural fibers available locally could be used instead of banana fibers produced from agricultural waste. It was shown that construction materials can be successfully manufactured using local plastic and agricultural waste.

Declaration of conflicting interests

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