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Developing a Compression-moulded Composite Partitioning Panel from Banana Fibres and Polylactic acid (PLA)

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Abstract

Green construction materials developed using renewable resources have become the focus of concurrent research owing to increasing environmental considerations and legislations. However, most of the available literature focus only on load-bearing construction elements. Consequently, little attention has been paid towards non-load-bearing construction elements such as partitioning materials. The present work aims to address this gap by investigating the viability of using the biodegradable bioplastic PLA in combination with yarns spun using banana fibres to manufacture a composite panel intended for temporary partitioning materials used in the construction industry. Pre-tensioned banana yarns were used as the reinforcement while PLA was used as the matrix. The composite panels were manufactured using the compression moulding technique. The effect of process parameters such as moulding temperature and pressure, the effects of the degree of pre-tension and the amount of reinforcing yarn on the performance of the panels were investigated. The optimum moulding conditions were found to be 180oC moulding temperature and 15 tons of moulding pressure. Yarn pre-tensioning exhibited a positive effect on the performance of the composite panels. However, increasing the reinforcing yarn percentage caused a degradation of flexural performance of the composite. Finally, the performance was compared against the most widely used partitioning material currently, medium-density fibreboard (MDF). The novel composite panel manufactured at optimum conditions exhibited 52% higher impact strength and 55% higher flexural strength when compared to MDF. The composite panel presented herein has the potential to replace MDF as a better performing material manufactured using renewable resources.

Keywords

Construction material, PLA, banana yarn/fibre, composite panel, partitioning material

1. Introduction

With the rapid growth of world population and overall improvement of living standards during last two decades, the demand for construction materials and energy consumption have also seen a steep rise (Gavali & Ralegaonkar, 2020). The construction sector is considered as one of the most energy-consuming, greenhouse gas-emitting and solid waste generating industries (Tiskatine et al., 2018). It has been shown that construction activities are responsible for consuming about 40% of natural resources such as stone, sand, wood and water (Mateus et al., 2013). 50% of total waste accumulated in landfills, as well as 30% of total carbon emissions (Vasconcelos et al., 2013). In attempts to alleviate these negative impacts to the environment, numerous strategies have been introduced to the construction industry (Commission, n.d.). where 'green buildings' is a new basic requirement in the Construction Products Regulation (CPR) (Marques et al., 2017). Consequently, novel material development for the construction industry using renewable resources has been the focus of numerous contemporary research (Kim et al., 2019, Marques et al., 2020, Darwish et al., 2019, Dissanayake et al., 2021a, Dissanayake & Weerasinghe, 2021, Dissanayake & Weerasinghe, 2021).

However, it can be observed that the main focus of concurrent research has been more towards load-bearing construction materials than their counterparts, even though the amount of non-load-bearing construction materials is significant (Passer et al., 2012). It has also been shown that non-load bearing construction materials such as internal partitioning walls account for 41% of the environmental impacts, from the usage of the raw material (Passer et al., 2012). Medium-density fibreboards (MDFs) is the most commonly used partitioning material currently. MDF is a composite made of wood and formaldehyde and is cheaper than most of the other conventional partitioning materials. However, MDFs have inherent disadvantages. MDFs are made out of trees. MDF exhibits high water absorption which results in swelling of the material at affected areas, and tend to crack or split under extreme stress. Moreover, the use of urea formaldehyde in its production could cause irritation to lungs and eyes. MDF dust has also been reported as a health concern (Thetkathuek et al., 2016). Therefore, a better class of substitutive materials is required in place of MDFs. However, the reported literature in this niche research area is relatively scarce and constitutes the premise of the present study. The means of developing a composite panel intended to be used as a partitioning material is presented.

Application of fibres in construction and building materials receives great attention due to their inherent properties such as, strength, lightweight, physical performance and less thermal conductivity (Binici et al., 2012, Barbero-Barrera et al., 2016). In particular, natural fibres such as jute, sisal, flax, hemp and banana have been used as substitutive materials replacing synthetic fibres (Komal et al., 2020, Kiruthika, 2017, Asumani and Paskaramoorthy, 2020, Takagi, 2019, Cho et al., 2007). The present work aims to develop a composite material using fully renewable resources; PLA and banana fibres. Banana fibre is a commonly used natural fibre and PLA is a biodegradable, thermoplastic material produced from starch-rich plants such as corn and sugar cane. PLA is renewable material that is widely used in composite applications (Katogi et al., 2012, Ben et al., 2007). However, PLA inherently possesses weak mechanical properties, especially, low impact strength (Komal et al., 2020). This hinders the potential of renewable PLA being used in commercial applications such as construction and building materials which demand superior mechanical properties from raw materials. This can be overcome by using banana yarns/fibres as a reinforcing material in combination with PLA as the matrix material, in a composite system.

Dissanayake et al. (Dissanayake et al., 2018) used the compression moulding technique to produce a thermal insulation composite panel using post-industrial textile waste intended to be used as a construction material. Nylon/Spandex fabric and polyurethane shreds were used to produce the panels where the nylon polymer acted as a binding agent upon being melted. Dissanayake et al. (Dissanayake et al., 2021) produced an environmentally friendly sound insulation material for the construction and building sector, also from post-industrial textile waste where natural rubber was used as a binding material. The compression moulding technique was used to manufacture the composite panel. Compression moulding is known to be less complicated and is relatively a fast method of manufacturing a rigid composite panel, which is advantageous in manufacturing a construction material required in bulk quantities. Therefore, compression moulding technique is selected as the method of manufacturing the composite panels in the present work. Moreover, banana fibres/yarns in particular are selected as the reinforcing material due to the abundant availability, ease of manufacturing and most importantly, renewability. Banana is the most planted tree in Sri Lanka (469 842 tons/year, 49,168 hectare) and its fibres have been used in yarn manufacturing (Mumthas et al., 2019, Balakrishnan et al., 2019).

Dissanayake et al. (Dissanayake et al., 2021) and Dissanayake et al. (Dissanayake et al., 2018) reported that the compression moulding parameters such as moulding temperature and moulding pressure are critical parameters in developing a suitable compression-moulded panel. Therefore, the effects of varying moulding conditions on the performance of the panel were investigated in detail in the present study. Moreover, the effects of degree of pre-tension of the reinforcing banana yarns and the amount of banana yarns present in the composite on the performance of the panel were also investigated. The performance of the panels was determined by testing the composite panels for their impact strength (ASTM D256) and flexural strength (ASTM D790). The optimum moulding conditions, reinforcement yarn pre-tension and amount of reinforcement yarns are presented.

2. Materials and Methods

2.1 Materials

Banana yarns were used as the reinforcement while PLA was used as the matrix material for all the composite panels prepared in the present study. Yarns were manufactured using Cavendish AAA banana tree (‘*Musa acuminata*’) stems.

As the matrix of the composite, Poly-Lactic Acid (PLA) was used. PLA filaments were sourced from Unitech Trading (Pvt) Ltd, Colombo, Sri Lanka in the filament form with a diameter of 1.75 mm. A general-purpose silicon emulsion was used as the mould release agent. A pre-tensioning apparatus was manufactured using metal rods to hold and tension the reinforcing yarns.

2.2 Methods

Preparation of banana yarns

The pseudo stems of the banana trees were initially cut approximately one metre pieces. These pseudo stems were fed to a decorticator in order to extract banana fibres with an approximate length of one metre. This is shown in Fig 2 (a) and (b).

Fig 2. (a) Inserting banana pseudo stem to the decorticator, (b) extracted banana fibers and (c) hand-spun banana yarns

Subsequently, these fibres were hand-spun in order to produce 100% banana yarns as shown in Fig 2 (c). These yarns were subsequently used for the manufacture of the composite panels. The composition of the banana yarns were investigated using a Fourier-transform infrared spectroscopy (FTIR) test. The strength was also characterised in accordance with ASTM D2256 (Standard Test Method for Tensile Properties of Yarns by the Single-Strand Method) standard. A thermal analysis of the banana yarns was also carried out using a thermogravimetric analysis (TGA). The yarn count was measured according to ISO 2060 standard.

Composite Fabrication

Two types of composite panels were prepared in the present study, unidirectional and bidirectional. In the unidirectional panels, pre-tensioned banana yarns were laid unidirectionally, while pre-tensioned banana yarns were laid bidirectionally for the bidirectional panels. For bidirectional panels, the two yarn sets were laid orthogonal to each other. The metal frame with unidirectional and bidirectional yarn lays are shown in Fig 1.

Tensioning of the yarns was achieved by a custom-made metal frame and known weights as shown in Fig 3.

A square-shaped mould with dimensions 101 mm x 101 mm x 4mm was used and is shown in Fig 4 (c). Mould parameters were selected such that 100 mm x 10 mm x 4mm specimens could be prepared in order to perform flexural and impact strength tests. Banana yarns were laid with different tensions using the metal frame and known weights. PLA filaments were crushed into pieces of approximately 2 mm in length and placed inside a mould as shown in Fig 4 (a) and (b).

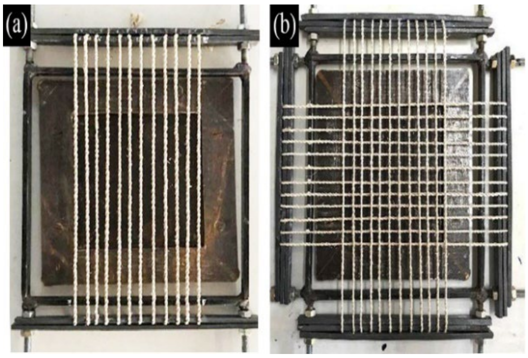

Fig 1. Tensioned yarns laid (a) unidirectionally and (b) bidirectionally

Fig 3. Yarn tensioning frame

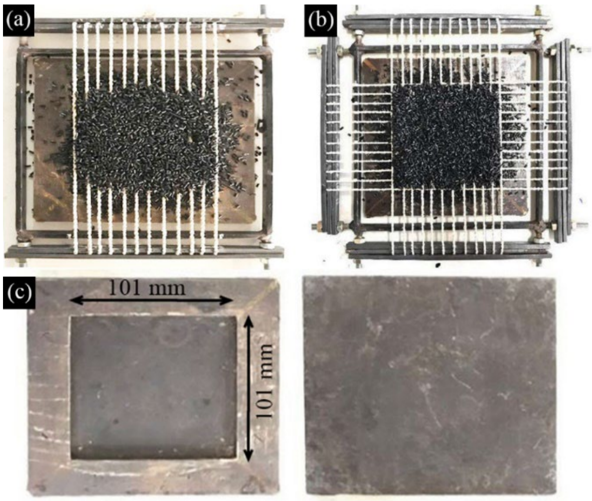

Fig 4. Crushed PLA placed inside the mould with (a) unidirectional yarn lay-up and (b) bidirectional yarn lay-up and (c) the empty mould.

Before placing the PLA, the releasing agent was applied on the inner surface of the mould. Here, the yarn reinforcements were placed in-line with the mould such that the reinforcements lie in the mid-plane of the composite panel and the composite panels were then prepared under a range of different moulding temperatures and pressures. Reinforcement yarn weight percentage, moulding pressure, moulding temperature, and pre-tensioning force were varied to prepare a total of fourteen different samples as summarised in Table 1.

Table 1. Sample matrix

Yarn lay-up	Controlled parameter	Value
Unidirectional	Yarn weight percentage (%)	2, 4, 6
	Moulding pressure (ton)	5, 10, 15, 20
	Moulding temperature (°C)	180, 190, 200
	Pre-tension of reinforcing yarn (N)	5, 7.5, 10, 12.5, 15
Bidirectional	Yarn weight percentage (%)	3, 6, 9
	Moulding pressure (ton)	5, 10, 15, 20
	Moulding temperature (°C)	180, 190, 200
	Pre-tension of reinforcing yarn (N)	5, 7.5, 10, 12.5, 15

The employed value ranges were selected by considering the available resources and the required quality of the final product. Weight percentage of the yarn was calculated according to Eq. 1.

$$W = \frac{W_1}{W_2} \times 100 \qquad (1)$$

Here, 'W' is the yarn weight percentage, 'W_1' is the weight of the composite after manufacturing (g) and 'W_2' is the weight of yarns laid in the cavity of the mould (g). 'W_2' was calculated according to Eq. 2.

$$W_2 = L \times \lambda \qquad (2)$$

Here, 'L' is the length of yarn laid in mould cavity (cm) and 'λ' is the linear density of the yarn (gcm^{-1}).

Testing composite panels

Each of the samples was tested for flexural and impact strength. All the results were taken after averaging four values of impact strength or flexural strength. Flexural strength was calculated in accordance with the ASTM D790 (Standard Test Methods for Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulating Materials) standard, using Eq. 3.

$$\sigma = \frac{3\,P\,L}{2\,b\,d^2} \qquad (3)$$

Where, 'σ' is the stress of outer fibres at mid-point (MPa), 'P' is the load at a given point of the load-deflection curve (N), 'L' is the support span (mm), 'b' is the width of the beam tested (mm) and 'd' is the depth of the beam tested (mm). Moreover, impact strength of the samples was calculated in accordance with ASTM D256 (Standard Test Methods for Determining the Izod Pendulum Impact Resistance of Plastics) standard, Izod Impact Testing (Notched Izod).

3. Results and discussion

3.1 Chemical and mechanical properties of the banana yarns

The TGA test results of the banana yarn are shown in Fig 5. The blue curve of the TGA of banana yarn indicates the mass of a banana yarn as a function of temperature as the temperature of the sample is increased in a controlled atmosphere. The green curve of the TGA of banana yarn indicates the first derivative of the weight loss curve (blue curve) and the red curve indicates the heat flow during testing. It can be observed that 5.5% weight percentage of banana yarn is lost, when sample is heating from around 25 ^{0}C to 120 ^{0}C due to the vaporisation of water. Another 1.5% weight percentage of banana yarn is lost, when the yarn is further heated from 125 ^{0}C to 200 ^{0}C due to loss of low molecular weight compounds. Moreover, the results also reveal that banana yarn starts to thermally decompose around 125^{0}C.

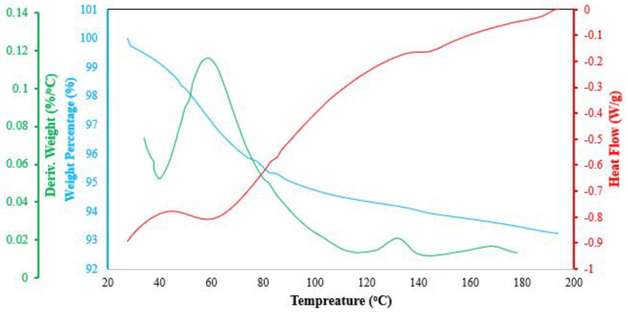

Fig 5. TGA results for the banana yarns

The produced banana yarns were also tested for their strength in accordance with ASTM D2256. The yarn count was measured (in accordance with ISO 2060) to be 1175 Tex. Fig 7 shows the typical force-elongation behaviour of a banana yarn. The ultimate tensile strength of the banana yarn was observed to be 102.5N. Therefore, the pre-tension used for reinforcing yarns was varied from 5N to 15N, which is approximately 5% and 15% of the average ultimate tensile strength of the banana yarn. The yarn showed approximately 16% strain at failure. Therefore, it can be assumed that the banana yarns could provide sufficient reinforcement for a non-load bearing application such as a partitioning panel.

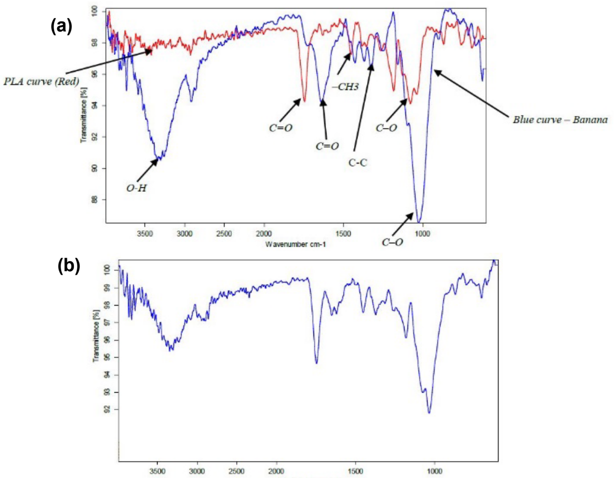

Fig 6. (a) FTIR curves of banana and PLA and (b) the composite panel

The FTRI spectra of banana yarns and PLA and the composite panel are given in Fig 6 (a) and (b), respectively. PLA usually shows characteristic stretching frequencies for C=O, –CH3 asymmetric, –CH3 symmetric, and C–O, at 1746, 2995, 2946 and 1080 cm^{-1} wavenumbers, respectively. Bending frequencies for –CH3 asymmetric and –CH3 symmetric have been identified at 1452 and 1361 cm^{-1}, respectively (Ramachandran et al., 2016). Banana yarns shows the relative intensities of bands at 3400 cm^{-1} (O-H stretching), 2900 cm^{-1} (C-H stretching), 1036 cm^{-1} (C-O stretching), 1725 cm^{-1} (C=O stretching), 1150 cm^{-1} (C–O–C and C–O stretch) and 1500–1600 cm^{-1} (C-C aromatic skeletal vibrations) (Milani et al., 2016). Sharp peaks around the abovementioned wavenumbers can be observed in Fig 6 (a). Moreover, it can also be observed in Fig 6 (b) that the same sharp peaks are available approximately around the same wavenumbers. This implies that the chemical composition of PLA/Banana yarns remained unchanged upon manufacturing of the composite panel.

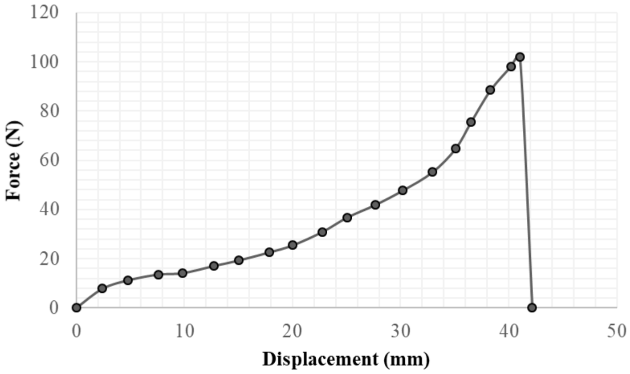

Fig 7. Force-elongation curve for the banana yarn

3.2 Effects of moulding conditions on the impact strength

As discussed in Section 2.2.2, a series of composite panels were prepared under different moulding conditions: moulding temperatures and pressures. Each sample was tested for its impact and flexural strengths and was compared to those of MDF boards. The MDF boards exhibited an impact strength of 5.62 kJ/m^2 and a flexural strength of 34.92 MPa.

The variation of impact strength of the unidirectional and bidirectional panels with moulding temperature is illustrated in Fig 8 (a) and (b), respectively. Moreover, the variation of flexural strength of the unidirectional and bidirectional panels with moulding temperature is illustrated in Fig 8 (c) and (d), respectively. The impact tests were carried out both along and across the reinforcement yarns for the unidirectional panels, in order to evaluate any anisotropic properties. It was observed that the impact strength properties of the unidirectional panels is highly anisotropic. The impact strength is far superior along the reinforcement yarn direction than across it. This is anticipated since the impact strength along the reinforcement yarn is supported by the reinforcing yarns in contrast to the impact strength across the reinforcing yarns where the strength is governed by the strength of the PLA matrix. However, the directional effect is absent on the bidirectional panels since the composite panel is reinforced in both directions. It was observed that the impact strength decreased with moulding temperature for both unidirectional and bidirectional composite panels. The reduction is approximately the same for both composite panels and stands at ca. 20%, when the moulding temperature was increased from 180ºC to 200 ºC. However, it was also observed that the across-yarn impact strength of the unidirectional composites remained approximately constant when the moulding temperature was increased. The flexural strength of the panels also followed a similar trend. Moreover, it is observed that both the impact and flexural strengths are superior to the MDF boards at all temperatures, with the exception of impact strength across reinforcing yarns (unidirectional panels). It was observed that the lowest moulding temperature yielded the highest flexural strength. Therefore, the optimum moulding temperature was selected to be 180ºC, considering both the impact and flexural strengths of the materials. At a moulding temperature of 180ºC, both the impact and flexural strengths are well above the strengths of the MDF boards (except across yarn unidirectional panel).

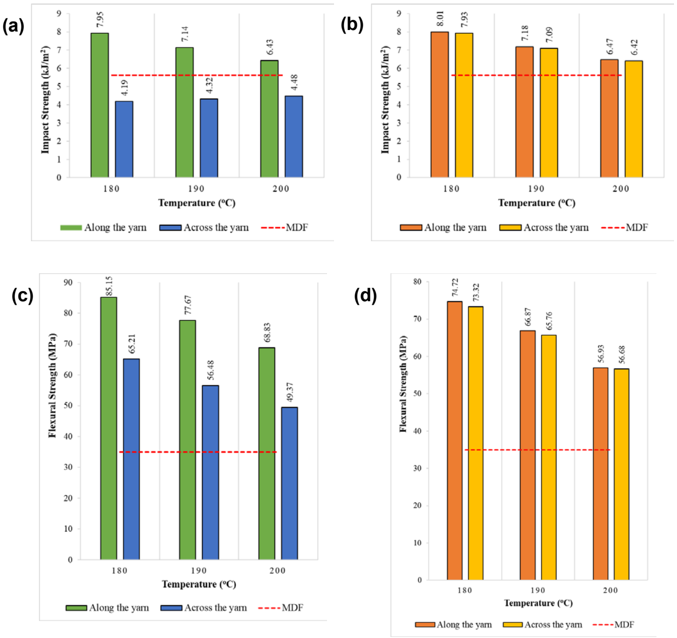

Fig 8. The effect of moulding temperature on the impact strength of (a) unidirectional composite panels, (b) bidirectional composite panels and the flexural strength of (c) unidirectional composite panels and (d) bidirectional composite panels

Similarly, the variation of impact strength of the unidirectional and bidirectional panels with moulding pressure is illustrated in Fig 9 (a) and (b), respectively. A strong material anisotropy can be observed when the moulding pressure is varied in the unidirectional composite panel, similar to the anisotropy observed when the moulding temperature was varied. However, instead of a strictly decreasing trend, a parabolic distribution of impact strength variation can be observed. The impact strength exhibited a maximum at a moulding pressure of 15 tonnes for both unidirectional and bidirectional composites. Moreover, the impact strength of the unidirectional panels remained approximately the same when tested across the reinforcing yarns. This is anticipated and occurs due to the reinforcement being present only along one direction as explained above. The impact strengths of the bidirectional panels were observed to be approximately the same in both perpendicular directions. Similar to the impact strength, the flexural strength followed a similar parabolic trend. However, the flexural strength of the unidirectional panels also exhibited a parabolic fluctuation in contrast to the impact strength distribution. It was also observed that the maximum flexural strength was approximately 6% higher in the unidirectional composite at 15-ton moulding pressure. This difference is apparent for all the different moulding pressures. This is due to the premature failure of the bidirectional panel due to the presence of yarn intersections. For bidirectional panels, due to the overlapping of orthogonal reinforcing yarns, yarn intersections are present. Matrix cracking initiated from such intersections thereby causing failure. Since unidirectional composites did not have such intersections, they exhibited a higher flexural strength.

It is also observed that the impact and flexural strengths are superior to the MDF boards at almost all the moulding pressures, with the exception of across yarn impact strengths of unidirectional panels. It can be concluded that the optimum moulding pressure is approximately 15 tonnes for both unidirectional and bidirectional panels, considering both the impact and flexural strengths of the composite panels. At a moulding pressure of 15 tonnes, both the impact and flexural strengths are well above the strengths of the MDF boards (except across yarn unidirectional panel).

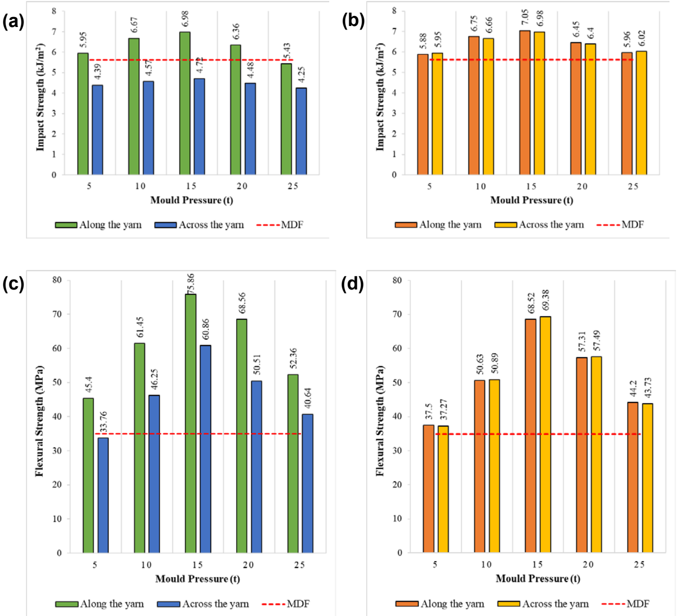

Fig 9. The effect of moulding pressure on the impact strength of (a) unidirectional composite panels, (b) bidirectional composite panels and the flexural strength of (c) unidirectional composite panels and (d) bidirectional composite panels

4. Effects of reinforcement yarn conditions on the impact strength

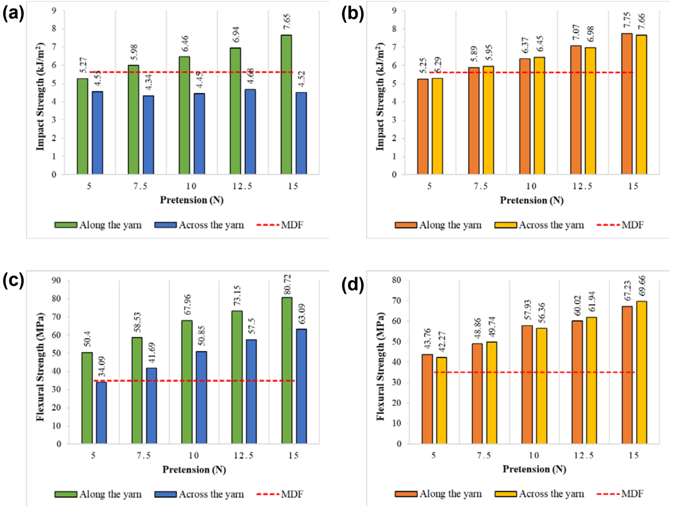

Fig 10. The effect of reinforcing yarn pre-tension on the impact strength of (a) unidirectional composite panels, (b) bidirectional composite panels and the flexural strength of (c) unidirectional composite panels and (d) bidirectional composite panels

The variation of impact strength of the unidirectional and bidirectional panels with reinforcing yarn pre-tension is illustrated in Fig 10 (a) and (b), respectively. Material anisotropy continues to appear in the unidirectional panels. When the reinforcing yarn pre-tension is increased up to 15N, the impact strength difference between the along and across yarn directions is approximately 41%. The impact strength across the yarns in unidirectional composites remains approximately the same, similar to the earlier occurrences, since the strength is governed only by the strength of the PLA matrix. However, the bidirectional panels exhibit approximately the same impact strength regardless of the direction. Both the panels exhibit a strictly increasing trend in impact strength when the reinforcement yarn pre-tension was increased from 5N to 15N. It was observed that the impact strength was increased by more than 30% when the pre-tension was increased up to 30%. Furthermore, the flexural strength also followed the increasing trend when the reinforcing yarn pre-tension was increased. Similar to the cases of moulding conditions, it can be observed that the flexural strength across the reinforcement yarns in unidirectional composites also followed an increasing trend. For the unidirectional composite panels, the flexural strength was increased by 38% along the reinforcement yarn and 46% across the reinforcement yarn. For the bidirectional composite panels, the flexural strength was improved by approximately 40%, considering both directions. Therefore, the optimum reinforcement yarn pre-tension was concluded to be 15N. Even though the strictly increasing trend suggests using a higher pre-tension would yield better results, it should be noted that the maximum yarn pre-tension possible was limited by the designed frame used in the present work. Moreover, the higher the pre-tension, the higher the strain the reinforcing yarns undergo. Since the banana yarns used exhibited a limited strain of 16% to failure, using a pre-tension of approximately 15N is justified, which occurs at less than 5% strain.

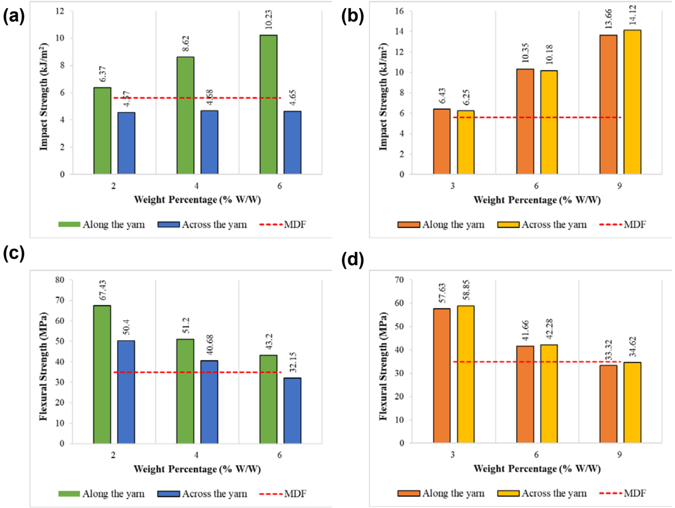

Fig 11. The effect of reinforcing yarn weight percentage on the impact strength of (a) unidirectional composite panels, (b) bidirectional composite panels and the flexural strength of (c) unidirectional composite panels and (d) bidirectional composite panels

In contrast to all the other variables, the reinforcement yarn percentage exhibited opposing trends in impact and flexural strengths. It was observed that the impact strength of both types of composite panels showed an increasing trend whereas the flexural strength showed a decreasing trend, when the yarn weight percentage was increased. The impact strength exhibited a similar strictly increasing trend when the reinforcing yarn weight percentage was increased, for both unidirectional and bidirectional composite panels. While the across yarn impact strength did not exhibit an increasing trend, the along yarn impact strength exhibited an increase of approximately 38%. However, it was observed that the impact strength of the bidirectional composite panels was increased by approximately 56% when the yarn weight percentage was increased to 6%. Similar to the other cases, the bidirectional panels did not exhibit noticeable material anisotropy in terms of both impact and flexural strength. However, the flexural strength exhibited a strictly decreasing trend when the reinforcing yarn weight percentage was increased for both types of panels. The flexural strength was reduced by 36% for unidirectional composites while the strength was reduced by 40% for the bidirectional composites. This is also explained by the nature of failure of the panels explained above.

Consequently, when choosing the optimum weight percentage of reinforcing banana yarns, it is a tradeoff between the impact strength and flexural strength. For instances where high flexural strengths are required, a lower reinforcing yarn weight percentage can be used. Similarly, for instances where the impact strength is a concern, a higher weight percentage of reinforcing yarns can be used. The optimum weight percentage in this case is taken as 6% (4% for unidirectional panels) considering both impact and flexural strengths.

In summary, the optimum process parameters can be tabulated as given in Table 2, to produce a composite partitioning material by the compression moulding technique. The unidirectional panels cannot be recommended for commercial use given their inferior performance when tested across the reinforcing yarns. On the other hand, bidirectional panels exhibit far superior performance than MDF boards.

Table 2. Optimum process parameters to manufacture the composite panel.

Variable	Optimum value
Reinforcement yarn lay-up	Bidirectional
Moulding temperature	180°C
Moulding pressure	15 tonnes
Pre-tension of the reinforcing banana yarns	15 N
Weight percentage of the reinforcing banana yarns	6%

A bidirectional composite panel was moulded as per the conditions given in Table 3. The composite panel was then tested for its impact and flexural strengths. This composite panel exhibited an impact strength of 11.56 kJ/m² and a flexural strength of 76.81 MPa. When compared to MDF, the impact strength is 51.5% higher while the flexral strength is 54.6% higher in the composite panel.

5. Conclusions

Based on the experimental work carried out in the present work, the following conclusions can be drawn.

1. A composite partitioning material can be manufactured using banana yarns/fibres and the bioplastic PLA, which are renewable resources, using the compression moulding technique. The optimum moulding conditions are 180°C moulding temperature and 15 tonnes of moulding pressure.
2. Bidirectional reinforcement yarn layup better reinforces the composite panels than unidirectional layup. Flexural strength is higher for unidirectional composite panels along the reinforcing yarn. However, the impact strength is poor when tested across the reinforcing yarns.
3. Pre-tensioning of the reinforcing yarns show an improvement of both flexural and impact strengths. The higher the pre-tension, the better the properties.
4. With increasing weight percentage of reinforcing yarns the impact strength improved while the flexural strength deteriorated. A weight percentage of 6% (bidirectional panel) yielded desirable properties. With 6% reinforcing yarns, the impact strength was 45% more and flexural strength was 17% more than MDF.
5. At the optimum production conditions, the PLA-banana yarn composite panel exhibits 52% higher impact strength and 55% higher flexural strength than MDF.

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