Mechanical Behaviour of a Green Composite from Biopolymers Reinforced with Sisal Fibres

Bruno Dorneles de Castro [a], Mohamad Fotouhi [b], Luciano Machado Gomes Vieira [c], Paulo Eustáquio de Faria [c], Juan Carlos Campos Rubio [a,c]

[a] Engineering School, Federal University of Minas Gerais (UFMG), Brazil*

[b] School of Engineering, University of Glasgow, Glasgow, G12 8QQ, United Kingdom

[c] School of Engineering of São Carlos (EESC), University of São Paulo (USP), São Carlos, Brazil

ABSTRACT

In recent years, green composites based on thermoplastic matrices from renewable sources, and reinforced with natural fibres, have gained significant importance in different industrial applications, due to lower environmental impacts and production costs than traditional composites. This work investigates the manufacturing process, fibre/matrix integration and mechanical properties of a novel environmentally friendly green composite with a recyclable biobased polymer from a renewable source and a biodegradable natural fibre. Untreated woven sisal fibres reinforced post-consumer green polyethylene composites were evaluated in terms of flexural, tensile and impact properties. Traditional and green high-density polyethylene (HDPE), originated from sugarcane ethanol, were utilised as matrices of the investigated composites. Woven sisal fibres were arranged in two different stacking sequences, i.e. [0°/90°] and [± 45°], being incorporated into the HDPE with a mass percentage proportion of 30/70 (fibre/matrix). A low-cost manufacturing process based on the hot compression moulding was used to produce the composites. The results were analysed by a factorial design to identify the effects of polyethylene type and the use of woven sisal fibres, considering the [0°/90°] and [± 45°] orientations. Thermal gravimetric analysis was used to verify the thermal stability of the sisal fibre. The topographic surface of sisal fibres was observed by scanning electron microscopy. The results showed that the use of green polyethylene reinforced with untreated woven sisal fibres achieved higher flexural modulus (35%), flexural strength (13%), tensile strength (39%) and ultimate strain (68%) than traditional polyethylene without reinforcement. The green composite presented promising mechanical results to replace materials from non-renewable sources and can reduce manufacturing costs of the final product. These composite materials can be efficient for structural applications such as insulated panels, drywall and partitions for furniture.

Keywords: Green polyethylene, Woven sisal fibres, Green composites

1. Introduction

Natural fibre reinforced polymer composites have received great attention in recent years due to the considerations of developing environmentally friendly materials. These composites have been used in many applications by civil construction and automotive industries, where the weight and density are influential factors in the performance of the final products and there is a great concern about their life cycle [1].

The use of natural fibres as reinforcement in polymeric based composites have been widely investigated. These natural fibres have many advantages such as low density, low cost, carbon neutrality, recyclability and sustainability. Replacing synthetic fibres with natural fibres, as the reinforcing element in composites, has been investigated in recent years to produce green composites. In developing countries, the production of natural fibres can improve the life quality and survivability of many communities, due to their environmentally friendly properties [2].

Green plastics, originated from renewable sources, are being studied as composite matrices to reduce the environmental pollution generated by the extraction and processing of petroleum [3]. A recently developed green polyethylenecan contribute to the reduction of greenhouse gases, being one of the solutions to complex sustainability problems. It is produced from ethanol that is derived from sugarcane, which is a renewable raw material that captures and fixes carbon dioxide during its production. In addition, green plastics can also be reinforced with fibres that can result in materials with higher mechanical strength [4].

The life cycle of a green composite (see Fig. 1) begins with the use of raw materials from renewable sources, such as sugarcane and sisal, to produce the constituent materials. The ethanol from sugarcane is dehydrated, obtaining the green ethene, which is polymerized and transformed into a green PE, widely used in plastic bags [5]. In the same sustainable context, sisal fibres are extracted from the plant leaf and can be woven in various orientations, resulting in a natural and biodegradable constituent [6]. The resulting green composite is an environmentally friendly material, produced by a rapid and low-cost manufacturing process, which contributes to the reduction of carbon dioxide in the atmosphere.

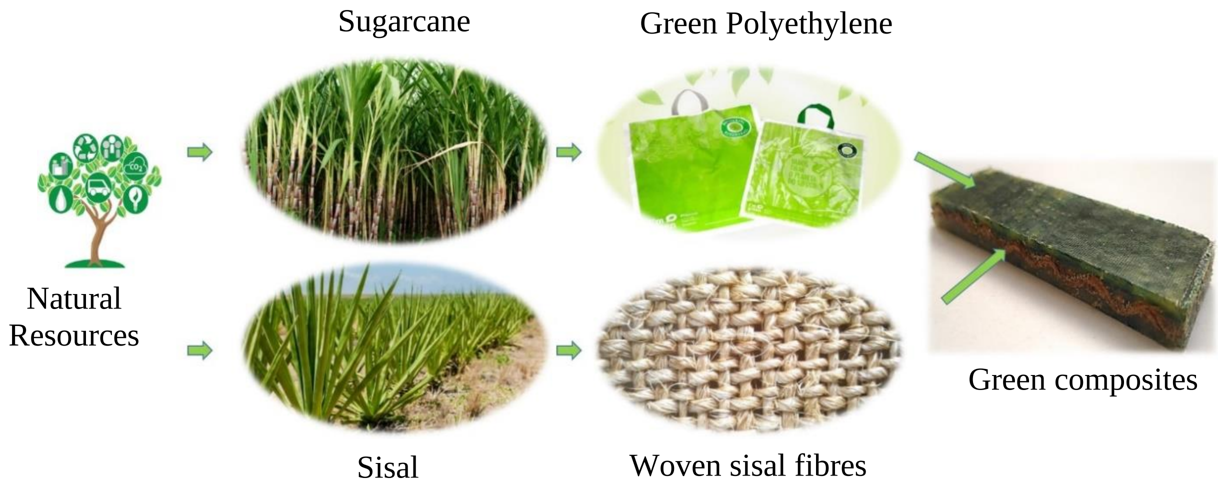

Fig. 1. The life cycle of a green composite.

The mechanical behavior of natural fibres reinforced polymer composites can be influenced by several physical and chemical factors, such as properties of constituent materials, fibre and matrix content, fibre length and orientation, physical profile of the contact surface, interlaminar shear strength and interfacial chemical bonding [7]. Consequently, the failure mode of these materials depends on the combination of these factors and the overall system response when a given load is applied to a specific region of the composites.

Many studies have evaluated the mechanical behaviour of green composites by flexural, tensile and impact tests [8, 9]. Robledo-Ortiz et al. [1] studied rotomoulded composites with green polyethylene and natural fibres of agave tequilana and coir treated with maleated polyethylene, as sustainable materials to replace petroleum-based polymer composites, and found improvements in tensile modulus (34%) and tensile strength (12%), at 30% wt fibre content, highlighting also the possibility of reducing production costs with the use of fibres. Guilhen et al. [10] investigated the mechanical properties of bleached cellulose fbres reinforced green polyethylene composites produced by a co-rotating intermeshing twin-screw extruder, obtaining improvement in tensile and flexural properties in case of 30% wt of fibres. Garcia-Garcia et al. [5] used different compatibilisers on green composites, manufactured with green polyethylene and peanut shell, finding good results in tensile and flexural modulus using a polypropylene-graft-maleic anhydride compatibiliser.

Mechanical tests allow the understanding of the mechanical properties of the material and can be the basis of the study of the failure mode resulting from the stress imposed. According to Hughes [11], failures in fibres may occur due to the damage caused in their cellulose molecules, which are essential in the mechanical strength of these materials. Besides, plastic deformation and cracks propagation in various directions in polyethylene may also occur, depending on the applied stress and the chemical bonds between phases [12].

The matrix-fibre interface influences the mechanical properties of composites, and so it has been widely studied by researchers. The use of compatibilisers has been investigated to improve the interfacial bonding between the fibres and matrix, showing significant effects on the mechanical properties of these composites [13]. Fávaro et al. [14] investigated the mechanical properties of post-consumer polyethylene with mercerised and acetylated sisal fibres (5–10 mm in length), mixed in a lab-made mono-screw extruder, founding improvements on fexural and impact properties.

On the other hand, chemical treatments in lignocellulosic fibres, such as sisal, fax and coir, can cause strong damage to the structure of these fibres, reducing their mechanical properties. In addition, the use of these chemical agents does not contribute to the sustainable concept of these materials, due to the complexity of degradation of the chemical structure of these agents [15].

This study investigates the mechanical behaviour of a novel untreated woven sisal fbre-reinforced post-consumer green polyethylene composite, combining two specific environmentally friendly materials: a post-consumer polyethylene matrix made of sugarcane (green HDPE), which is a recyclable biobased polymer made from renewable source, and untreated natural woven sisal fibres. No chemical treatments were used on the fbres, minimising the potential impacts of these chemical agents to the environment. A low-cost and simple composite manufacturing process was detailed and a factorial design with six treatments was performed. The results indicate that the investigated green composite can be used as an efficient and sustainable alternative to replace the traditional composites in different types of structural applications.

2. Materials and methods

Table 1 summarises the designed and conducted experiments in this paper. Six treatments were investigated based on two factors. Two types of PE were defined: the traditional PE and the green PE. The traditional PE represents the plastic generated from the use of petroleum (non-renewable source) and the green PE represents the plastic generated by a renewable source, from sugarcane ethanol. The reinforcement factor had three levels: without reinforcement and reinforced by woven sisal fibres with two different configurations, i.e. [0°/90°] and [± 45°].

Flexural, tensile and Charpy impact tests were carried out in a room temperature of 25 °C and an average relative humidity level was at 65 %. Five specimens for each experimental condition plus a replica were evaluated.

Table 1
Experimental conditions

Experimental conditions	**Reinforcement type**
Traditional HDPE	Without reinforcement
Traditional/90	Woven sisal fibres in [0° / 90°]
Traditional/45	Woven sisal fibres in [± 45°]
Green HDPE	Without reinforcement
Green/90	Woven sisal fibres in [0° / 90°]
Green/45	Woven sisal fibres in [± 45°]

2.1. Materials

Traditional high-density PE (HDPE) films, supplied by the PACK FORT, and green PE biopolymer films, supplied by the UNISOLD and produced by the BRASKEM petrochemical company, were used in this work. This biopolymer was industrially prepared from ethene produced from ethanol, originated a result of fermentation and distillation processes of sugarcane [9].

Woven sisal fibres were used to manufacture the composites. Woven sisal fibres (Fig. 2), with yarns type 530/1, were supplied by APAEB Sisal (Brazil). It should be noted that all the raw materials were used as supplied, with some simple cleaning for removal of dirt and surface impurities. No further treatment or modification was done in their molecular structure.

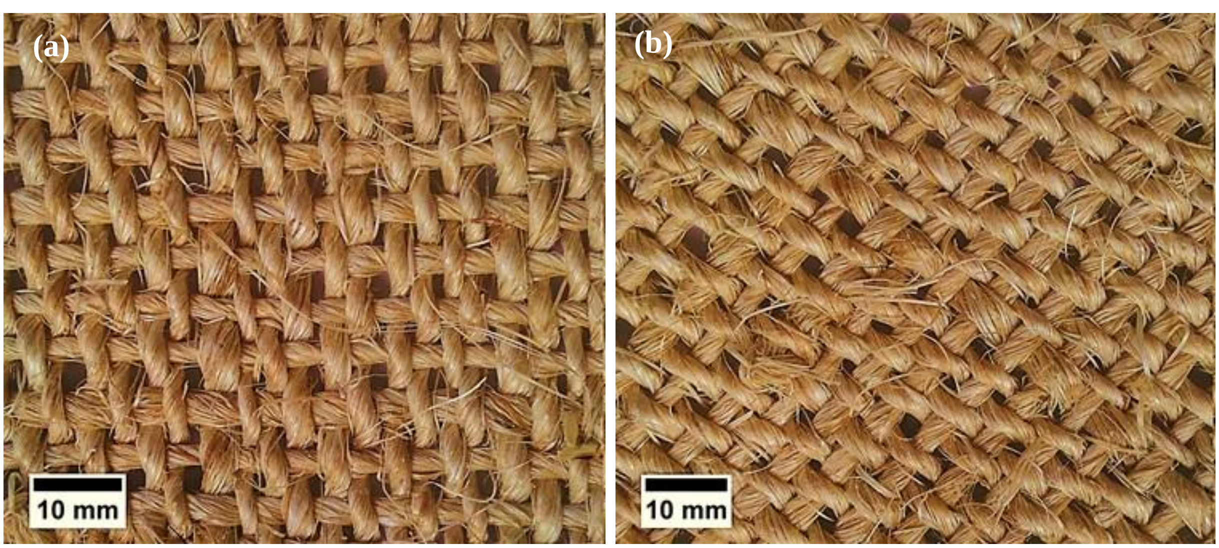

Fig. 2. Woven sisal fibres (a) [0°/90°] and (b) [±45°].

2.2. Composites Manufacturing

The composite samples were manufactured in the Laboratory of the Innovation and Technology in Materials (GITEM), Federal University of Minas Gerais. A single layer of cleaned woven sisal fibres was stacked by the PE films and the laminate was cured in a compression mould with a controlled heating (185°C). The woven sisal fibres had a biaxial configuration and they were investigated in two orientations in the composites, i.e. [0°/90°] and [± 45º]. The woven sisal fibres had a length of 190 mm and a width of 140 mm, weighing approximately 34g. The PE weight was 79g for each plate.

A compression machine (Fig. 3) was constructed for the compression and compaction of the composites in a proportion of 30% fibre / 70% matrix [13]. The pressure used was 12.39 KPa. A k-type thermocouple, which was attached to a multimeter Icel model MD-5660C, was used to measure the mean temperature near the plates. The temperature was controlled to reach approximately 185 ± 5 °C. This temperature was based on the results of thermal gravimetric analysis (TGA) in the sisal fibres and in experiments conducted by other researchers at different temperatures [13]. The average heating rate measured in the experiments was 12.5 °C/min. Once the temperature was set for the heating of the machine, the resistors were switched off and the plates were kept inside the machine to cool down until 100 °C. The specimens were in a solid form at 100 °C. After that, the specimens were removed from the machine and kept at room temperature (25 °C). The curing cycle is shown in Fig. 3.

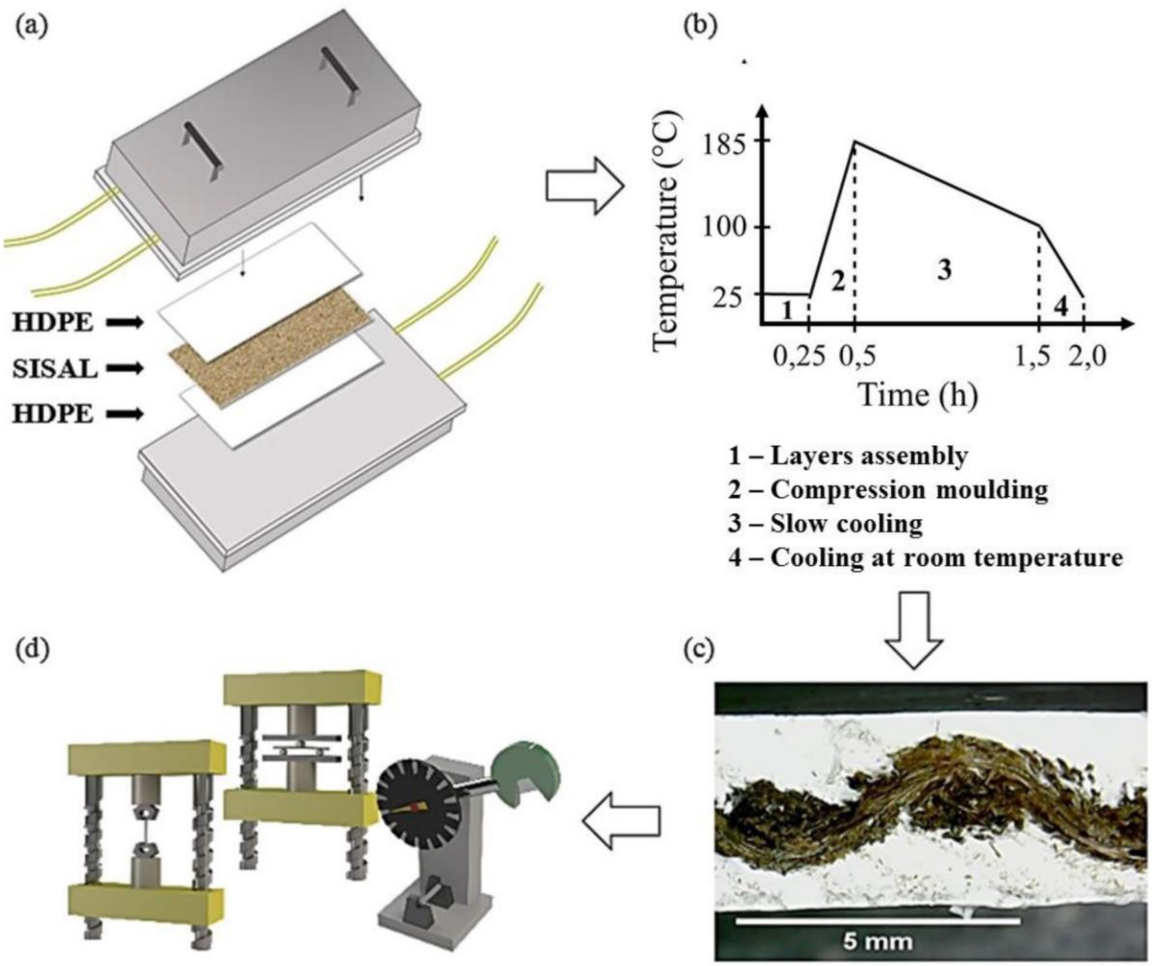

Fig. 3. Manufacturing procedures of the composites: (a) materials and compression machine, (b) the curing process, (c) manufactured composites and (d) mechanical tests.

2.3. Thermal, Morphological and Mechanical Characterization

The surface of the fibre was examined using a scanning electron microscope (SEM), Hitachi TM-3000, with an accelerating voltage of 15 kV. Thermal gravimetric analysis (TGA) was performed in a sisal fibre using a Perkin Elmer DTG-60H Thermal Analyzer. The test occurred under controlled atmosphere (Nitrogen), with a heating rate of 3°C/min, ranging from 25 °C to 360 °C. Three-point flexural tests were performed using a universal test machine of Shimadzu, model AG-X Plus, in accordance with [17], with specimens' dimensions as 78 mm in length and 12.7 mm in width, and 3 mm/min cross-head feed rate. The flexural modulus, flexural strength and displacement were measured for each experimental condition. The tensile tests were also carried out using a Shimadzu test machine, model AG-X Plus, and in accordance with [18], specimens' dimensions as 160 mm in length, 19 mm in width and cross-head feed rate of 2 mm/min. The tensile modulus, tensile strength and ultimate strain were evaluated. Charpy impact tests were performed using an XJJ-50 Series machine, with a pendulum of 15 J and low-velocity speed at 3.8 m/s, to measure the energy absorbed. The impact was performed according to [19] in the lateral section of the specimens, which had dimensions of 80 mm in length and 10 mm in width.

3. Results and discussion

3.1. Scanning Electron Microscopy (SEM)

For this study, the sisal woven passed through a washing process in order to reduce impurities on its surface to improve the fibre/matrix interface. After drying at room temperature, the washed fibres were used to manufacture the composite. Fig. 4 shows optical images of the pure sisal fibre, the fibre's surface presents impurities composed by parenchyma, lignin, hemicellulose and waxes, these impurities influence adhesion between the fibre and polymer. It was only done by washing the fibres to avoid toxic chemical agent commonly used in treatment of natural fibres [14]. No treatment with chemical agents was performed, due to degradation in the fibres and especially the environment caused by these agents [16, 20].

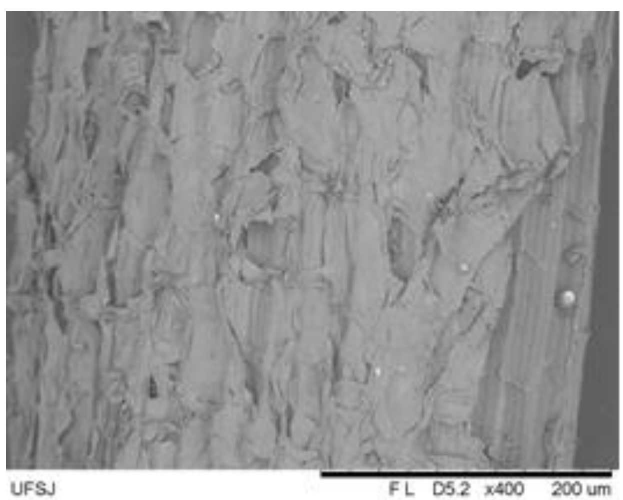

Fig. 4. Optical microscopy of the neat sisal fibres.

3.2. Thermal Gravimetric Analysis (TGA)

Fig. 5 shows the TGA results of the utilised sisal fibre. An initial weight loss around the temperature range 20-225 °C occurred that is related to the surface water evaporation. In temperature range 230-350 °C, the fibres began to degrade, implying a significant loss in their weight and mechanical properties [21].

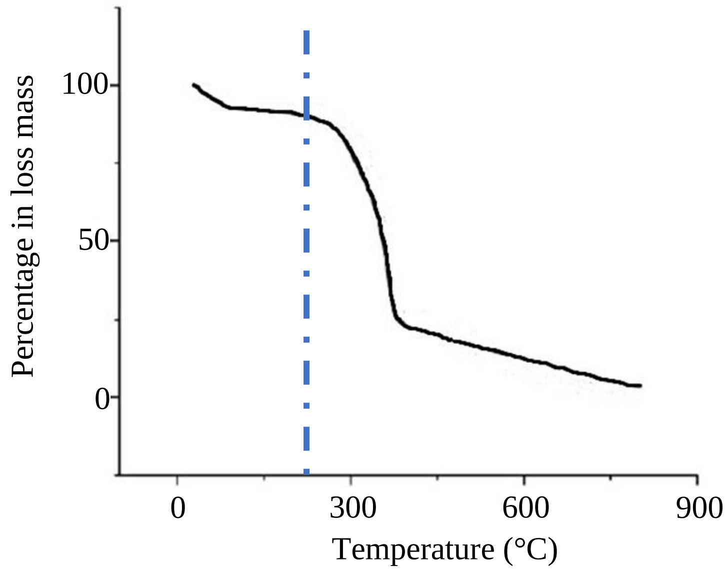

Fig. 5. Thermal gravimetric analysis of the utilised sisal fibre.

From the TGA, it was possible to find the working temperature range for the sisal fibres, which is before they begin to degrade (the blue dashed line in Fig. 5, approximately 200 °C). This is an important manufacturing parameter, especially for high temperature applications. A temperature selection is, therefore, a necessity for the manufacturing of composites to avoid degradation by the high temperature in the sisal fibre.

3.3. Mechanical Tests

Analysis of Variance (ANOVA) was adopted to verify if the effect of the main factors and interaction of factors are statistically significant. A p-value lower or equal to 0.05 indicates a significant effect provided by the main factors, or the presence of the interaction of factors on the response variables, considering a confidence interval of 95%. The main factor is only interpreted individually when there is no evidence that it interacts with the other factors [22]. Table 2 presents the results of ANOVA for the mean values of the mechanical properties for each experimental condition. The assumptions of the normal probability of residuals and the homogeneity of variances were checked and confirmed. ANOVA was used to verify the influence of the resin and fibre types and the interaction between them on the response variable, as a support to the conclusions found in the descriptive statistics, verifying whether the means of each experimental condition are different or not. Values of adjusted R^2 are greater than 90%, showing that the models explain a considerable variation of data. Minitab 17 software was used to perform statistical analysis based on ANOVA.

Table 2
Analysis of Variance (ANOVA)

Factors	**P-*value***						
	Flexural Modulus (GPa)	**Flexural Strength (MPa)**	**Displace-ment (mm)**	**Tensile Modulus (GPa)**	**Tensile Strength (MPa)**	**Ultimate Strain (%)**	**Energy absorbed (J)**
Polyethylene type	*0.000*	*0.000*	*0.000*	0.115	*0.000*	*0.000*	0.957
Reinforcement type	*0.000*	*0.000*	*0.000*	*0.000*	*0.000*	*0.000*	*0.000*
Polyethylene* Reinforcement type	0.132	*0.000*	*0.030*	*0.000*	0.219	*0.000*	*0.000*
R^2 (Adjusted)	92.06 %	93.31 %	93.25 %	92.39 %	92.74 %	91.56 %	91.02 %

3.3.1. Flexural Tests

The type of matrix and the reinforcement orientation significantly influenced the flexural properties presented from the tests, with p-value lower than 0.05, including the interaction between these factors in the case of flexural strength and displacement (Table 2). Mechanical properties obtained from the flexural tests are presented in Table 3. In general, green composites presented higher values for the flexural properties than composites with traditional HDPE, and composites with woven sisal fibres in orientation [± 45°] showed better results than those with orientation [0°/90°]. The heterogeneity of the composite structure, considering the gaps between the yarns, the wettability of the fibres and slight variations of the temperature in heat zones with polymers in melting process, may have influenced these results. In addition, flexural involve a complex stress state, with tensile, compression and shear stresses present simultaneously in the specimen. When the fibres are oriented at [± 45°], the applied load is resolved into longitudinal and transverse components, thus developing shear flow in the matrix [23]. According to [24], shear stresses are common in these materials under flexural tests and they influence the results. When the interfacial bonding is poor the delamination size can increase linearly, and it is only affected by the applied stress. When the ultimate limit is exceeded, the layers are debonded and the global stiffness is reduced [25].

Table 3

Flexural tests

Experimental conditions	Flexural Modulus (GPa)	Flexural Strength (MPa)	Displacement (mm)
Traditional HDPE	0.63 ± 0.03	16.27 ± 1.11	9.81 ± 0.85
Traditional/90	0.53 ± 0.02	14.20 ± 0.35	11.94 ± 0.35
Traditional/45	0.72 ± 0.02	14.45 ± 0.80	11.66 ± 0.42
Green HDPE	0.72 ± 0.04	22.67 ± 0.45	11.46 ± 0.19
Green/90	0.65 ± 0.02	14.62 ± 0.92	12.36 ± 0.46
Green/45	0.85 ± 0.03	18.44 ± 0.61	13.27 ± 0.73

Fig. 6 shows examples of force-displacement curves for the composites, that evidence the elastic region of these materials, with lines more inclined in case of reinforcements in the [± 45°] orientation. In these tests, shear failure can be assumed as the predominant mode, when the load-displacement curve decreases gradually to zero [24]. Considering the shear modulus of this type of reinforcement, when fibres are at +45° and -45°, there is a higher incidence of fibre performance than at 0° and 90°, due to the fact that fibres oriented to 90° (upright to the test) do not behave in the same proportion as a 45°, which tends to increase its rigidity under flexural stress. Chianelli-Junior et al. [26] found a similar result in his study of the flexural behaviour of composites with post-consumer HDPE and sisal fibres, attributing it to the weak interfacial adhesion of these composites.

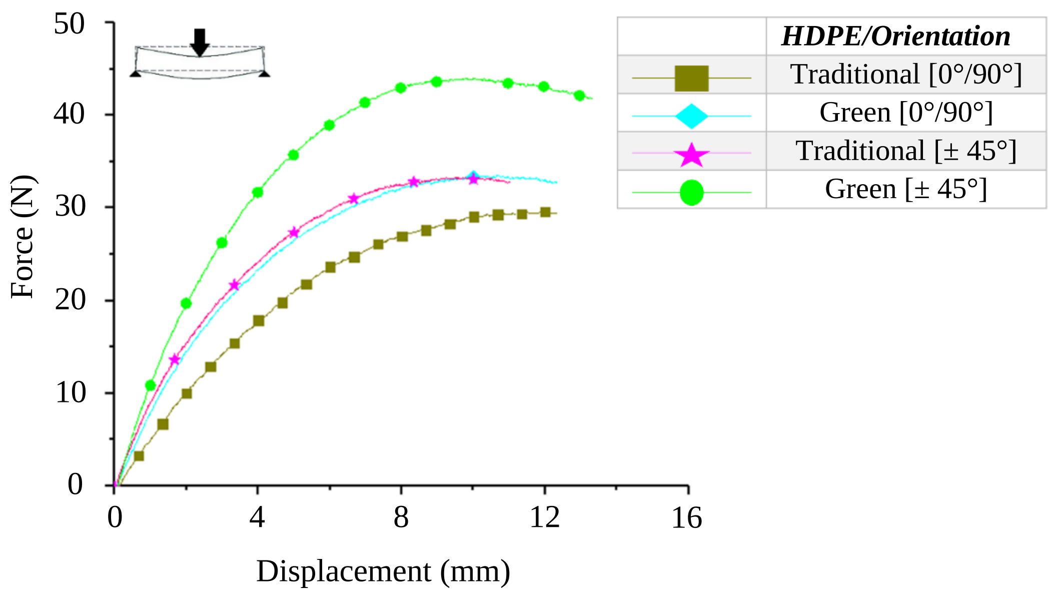

Fig. 6. Flexural tests: force-displacement curves of composites.

3.3.2. Tensile Tests

The statistical ANOVA showed a significant influence of the tensile modulus and ultimate strain in the tensile tests, with p-value less than 0.05 (Table 2). Table 4 shows the tensile modulus, tensile strength and tensile ultimate strain values. The tensile tests results showed that woven sisal fibres in orientation [± 45°] reinforced composites had lower tensile modulus than the non-reinforced HDPE in both types of HDPE. These composites presented a high level of interlaminar tension in tensile stresses, reducing stiffness in the tensile stress. This mechanism can be explained by interfibre / interlaminar failure theory proposed by Daniel et al. [27], which is based on the assumption that the failure of composite materials is governed by the limiting microscopic strain in the interfibre/interlaminar region of the layer. A compression dominated failure is governed by the microscopic shear strain, a shear dominated failure is governed by the tensile strain, and failure by combined tension / shear is dominated by the tensile strains [28].

Table 4
Tensile tests

Experimental conditions	Tensile Modulus (GPa)	Tensile Strength (MPa)	Ultimate Strain (%)
Traditional HDPE	0.72 ± 0.02	14.43 ± 0.40	11.73 ± 0.75
Traditional/90	0.63 ± 0.02	16.86 ± 0.75	15.57 ± 0.49
Traditional/45	0.55 ± 0.02	10.26 ± 0.83	19.88 ± 1.27
Green HDPE	0.67 ± 0.01	19.12 ± 0.92	19.83 ± 0.67
Green/90	0.65 ± 0.01	20.12 ± 1.26	19.69 ± 0.94
Green/45	0.63 ± 0.01	13.69 ± 0.88	19.42 ± 1.51

Regarding the reinforcement, composites with woven sisal fibres in orientation [0°/90°] presented higher tensile strength than those with orientation [±45°], as can be seen in Fig. 7, with examples of stress-strain curves for each composite. Tensile tests were performed in the 0° direction, so fibres in alignment with that direction provide better results in tensile strength, improving the performance of composites reinforced with woven sisal fibres in [0°/90°]. Jawaid et al. [29] investigated the tensile properties of woven jute fibres reinforced polymeric composites and emphasized that the tensile strength of fibres reinforced composites is influenced by the strength and modulus of fibres. The authors reported that woven fibres exhibit low deformation at the break and hence these composites exhibit high strength. It may be due to the stretching nature of woven fibres and strands break at different times as each fibre can stretch independently and break individually when reaching their failure stress. In tensile tests, composites with woven sisal fibres in orientation [±45°] present multi-axial states of stress, involving combined transverse and shear loadings, which may have a strong effect on the failure behavior of the material, reducing the tensile strength of these composites [28]. In addition, Fig. 7 also shows a higher stiffness of the green PE composites with both types of reinforcement, evidencing the significant influence of different factors interaction in the tensile modulus as verified by the ANOVA.

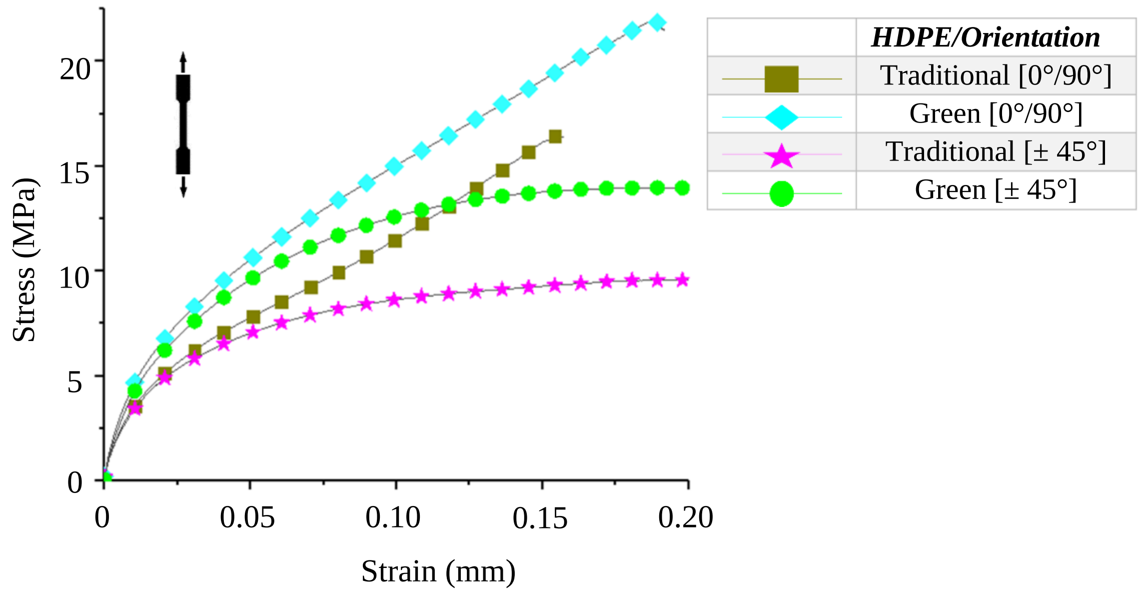

Fig. 7. Typical stress-strain curves for composites.

3.3.3. Charpy Impact Tests

The results from Charpy impact tests showed that the interaction of different factors affecting the absorbed energy significantly, based on the ANOVA and p-value less than 0.05 as exhibited in Table 2. The behaviour in impact resistance of the composites with woven sisal fibres in orientation [0°/90°] has been more effective than the orientation [± 45°] (Table 5). This was observed in both the green and traditional composites. Some internal defects inside the composites emerged from the manufacturing process, such as voids, delamination, and resin-poor or resin-rich regions, which had notable effects on the mechanical properties of the composites [30].

Table 5

Charpy impact tests

Experimental conditions	Energy absorbed (J)
Traditional HDPE	2.57 ± 0.29
Traditional/90	3.45 ± 0.36
Traditional/45	1.52 ± 0.18
Green HDPE	3.99 ± 0.16
Green/90	2.44 ± 0.23
Green/45	1.39 ± 0.16

Considering the Charpy impact tests, the applied load transferred by shear to fibres was greater than the interfacial bond strength, causing debonding. In this context, the fibre length did influence the energy dissipation. Long fibres had a larger absorption capacity by avoiding damages like fibre pull-out and fibre breakage [31]. The woven sisal fibres in orientation [0°/90°] had larger yarns in the transverse direction of the impact than those in orientation [± 45°], which provided higher energy absorption and higher impact resistance (Fig. 8).

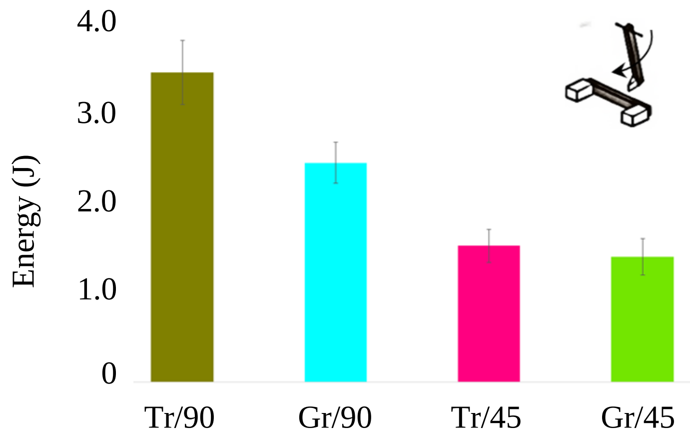

Fig. 8. Absorbed Charpy impact energy for each condition.

3.4. Fracture analysis of the composites

Fig. 9 and Fig. 10 show the failures of the composites, with woven sisal fibres in orientation [0°/90°] and [± 45°], respectively. In the flexural tests, fibre-matrix debonding were evident in the specimens, being the predominant failure mechanism. This failure is a typical problem of poor fibre-matrix adhesion, which may be due to the hydrophilic nature of sisal fibres and the hydrophobic nature of PE, not allowing the wetting of the fibres by the matrix and avoiding coupling of the phases. In addition, delamination (red arrow) and fibre pull-outs (yellow arrow) were also detected, as shown in composites with woven sisal fibres in orientation [± 45°] (Fig. 10a and 10b), indicating the weak interfacial bond. Chaudhary et al. [32] investigated the flexural properties of sunnhemp fibre-reinforced waste PE bag composites, and reported a similar behavior, attributing it to the poor fibre-matrix adhesion that caused microcrack formation at the interface and a non-uniform stress transfer between the fibre and the matrix. Moreover, there are stretching zones in the composites with woven sisal fibres in orientation [0°/90°] and [± 45°] (Fig. 9a, 9b and Fig. 10b), with an evident plastic deformation (blue arrow) of the matrix phase. Thermoplastics, such as PE, can be reprocessed through melting and molding processes. According to the heating and cooling conditions, the polymer chains can be reconfigured, which modifies their strength and stiffness. In addition, when plastic deformation (blue arrow) of these materials occurred, a change in their color was observed in the composites with woven sisal fibres in orientation [0°/90°] (Fig. 9b) due to the molecular interactions or molecular conformations [33].

Similar to the flexural tests, the presence of plastic deformation was also be observed in the composites with woven sisal fibres in orientation [0°/90°] and [± 45°], under the tensile tests (Fig. 9c, 9d and Fig. 10d). They also presented delamination and fibre pull-outs, as can be seen in Fig. 10c and 10d. The problems in the interfacial adhesion did not allow the transfer of loads between different phases of the composites. Thus, after the interfacial shear strength was exceeded, the tension resulting from the tensile stress was concentrated on the PE plastic deformation and on the tensile strength of the oriented fibres in the test direction (90°), which explains the better performance of the composites reinforced with woven sisal fibres in [0°/90°], compared to orientation [± 45°]. Habibi et al. [34] also reported a similar behaviour, i.e. observing delamination in tensile tests for lignocellulosic fibres reinforced with PE, indicating that lignocellulosic fibres were not well wetted by the matrix, creating a gap around the fibres.

In Charpy impact tests, the woven fibres reinforced with traditional PE, and orientation [0°/90°], failed with a notable plastic deformation (Fig. 9e). Composites with green PE with woven sisal fibres in orientation [0°/90°] and [± 45°] (Fig. 9f and Fig. 10f) showed a matrix breakage (orange arrow) without the evident zone of stretching. This difference in the plastic deformation in the failure of the PE can be explained by the different conformations and molecular interactions resulting from the reprocessing of the material and additives already existing in these plastic materials. In addition, breakages and pull-outs of fibres (Fig. 9e, 9f and Fig. 10e, 10f) could be observed, reaffirming the weak interfacial bond presented in the composites. The occurrence of fibre pull-out and fracture may be related to the energy dissipated in the impact, as the fibres of greater length in the [0°/90°], compared with the [± 45°], may allow a better energy propagation. Theses longitudinal fibres of the composites, oriented transversely to the direction of the impact pendulum, may realize friction in the matrix and dampen a greater amount of energy. According to Mulinari et al. [35], brittle behavior of fibres can limit the plasticity behavior of the composites because of mechanical friction process, resulting in the fibre pull-out from the matrix. Zhao et al. [36] measured impact properties of sisal fibres reinforced PE composites, and reported that in the impact event, fibre pull-out, fracture of fibres and the matrix are the most common modes of energy dissipation when the interfacial bond is weak.

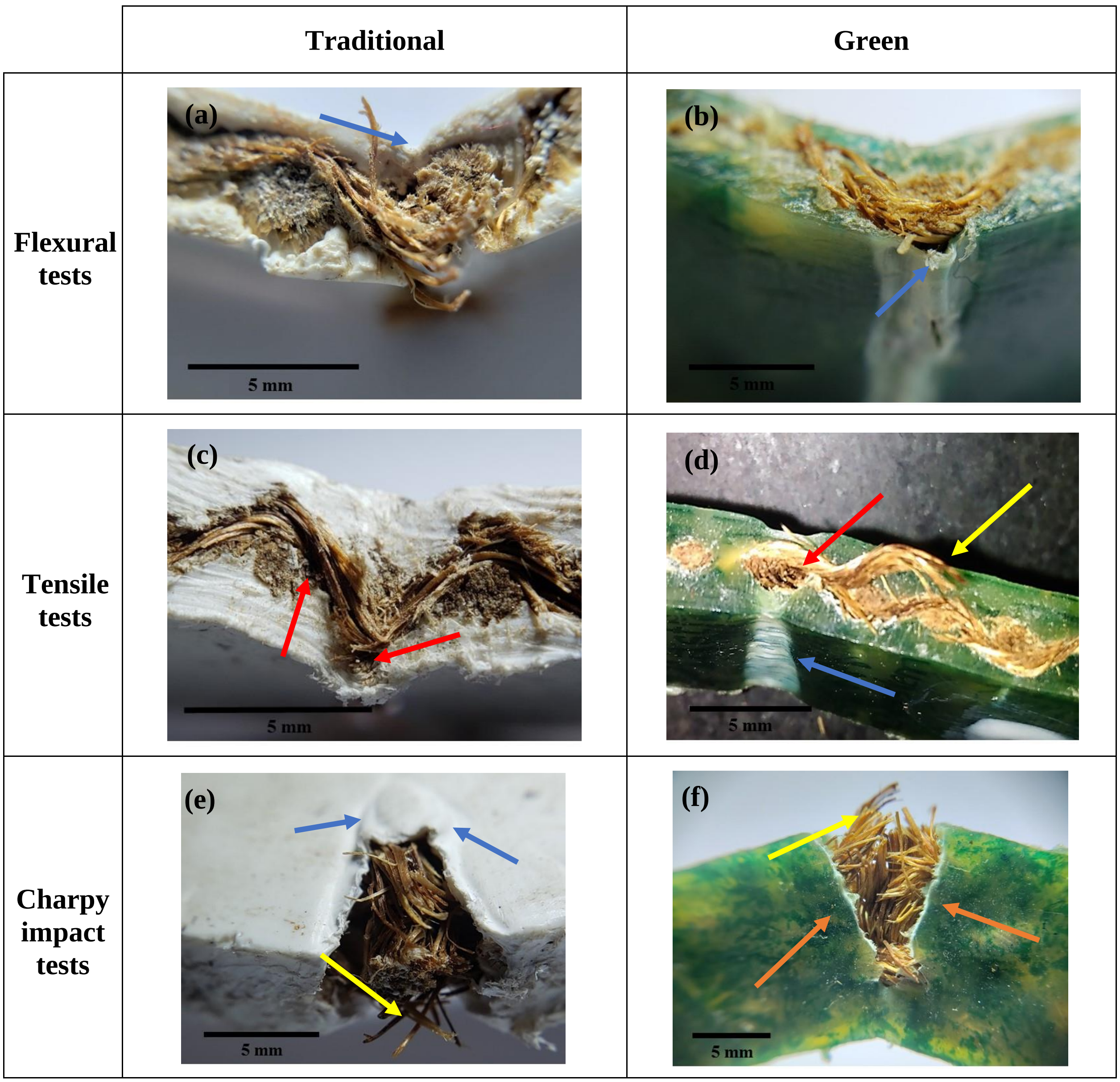

Fig. 9. Fractures analysis of the composites with woven sisal fibres at [0°/90°].

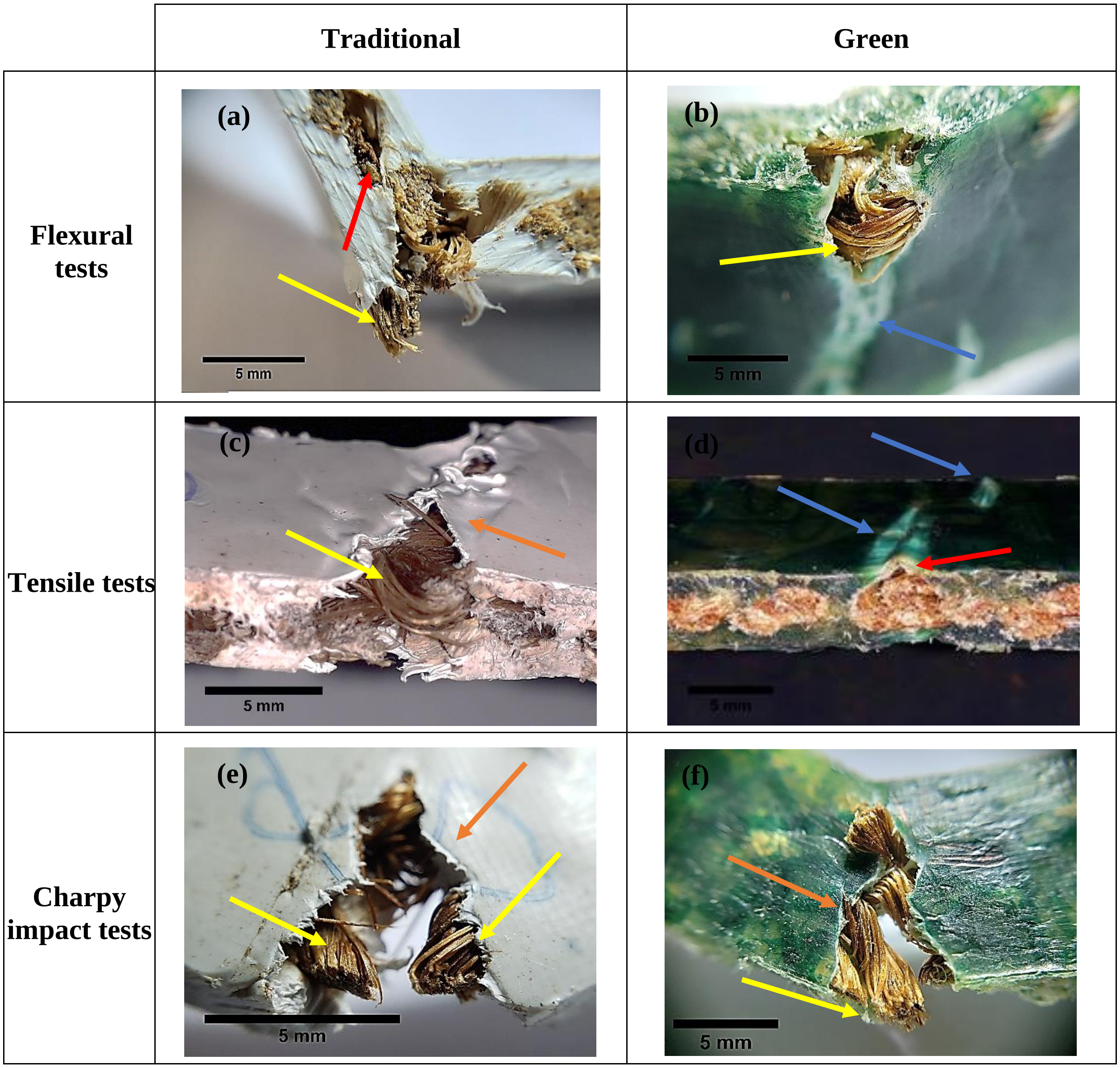

Fig. 10. Fractures analysis of the composites with woven sisal fibres at [± 45°].

4. Conclusions

This work investigated the mechanical properties of green/traditional post-consumer polyethylene composites reinforced of untreated woven sisal fibres oriented in the [0°/90°] and [±45°]. The main conclusions of this study were:

- The low-cost manufacturing process based on the hot compression moulding with controlled pressure (12.4 kPa) and temperature (185 °C) was able to manufacture the composites with homogeneity and repeatability.
- Based on ANOVA, the use and orientation of woven sisal fibres into the polyethylene matrix had a significant effect on all the mechanical properties evaluated, and values of adjusted R2 were greater than 90%, showing that the models explained a considerable variation of data.
- The green composites presented higher mean values for flexural modulus (35%) and flexural strength (13%) than traditional polyethylene without any reinforcement.
- The mean flexural modulus and flexural strength were higher for green composites with woven sisal fibres in [±45°] than composites with fibres in [0°/90°], presenting increases of 30% and 26%, respectively.
- The green composites had higher mean values for tensile strength (39%) and ultimate strain (68%) than traditional polyethylene without any reinforcement, but lower mean tensile modulus (10%) due load transmission problems between matrix and fibre.
- Tensile tests showed higher mean tensile strength for the composites with woven sisal fibres in [0°/90°] than those with fibres in orientation [±45°], presenting increase of 64% with the traditional polyethylene matrix and increase of 47% with the green polyethylene matrix.
- The energy absorbed in the Charpy impact tests of the green composites was similar to traditional polyethylene without reinforcement and composites with woven sisal fibres in orientation [0°/90°] presented higher energy absorbed than the composites with fibres in [±45°], with 126% increase with the traditional polyethylene matrix and 75% increase with the green polyethylene matrix.
- The reinforcement of woven sisal fibres into composite materials, besides improving their mechanical behaviour, it can decrease manufacturing costs because less plastic can be used, and also enables products with more environmentally friendly composite materials.

This research showed that the untreated woven sisal fibre reinforced post-consumer green polyethylene composites can be used efficiently in structural engineering applications, such as insulated panels, drywall, furniture, among others. Moreover, physical treatments on woven sisal fibres will also be considered in future investigations, to improve interfacial adhesion between phases and to avoid fibre pull-out and fibre-matrix debonding failure modes.

Acknowledgements

This study was financed in part by CAPES, “Coordenação de Aperfeiçoamento de Pessoal de Nível Superior” - Finance Code 001. The authors would also like to thank the Brazilian Research Agencies, CNPq, FAPEMIG and FAPESP, for the financial support provided.

References

[1] Xia, C., Shi, S.Q., Wu, Y., Cai, L., 2016. High pressure-assisted magnesium carbonate impregnated natural fiber-reinforced composites. Industrial Crops and Products. 86, 16-22. https://doi.org/10.1016/j.indcrop.2016.03.023.

[2] Biagiotti, J., Puglia, D., Kenny, J.M., 2004. A Review on Natural Fibre-Based Composites - Part I. Journal of Natural Fibers. 1, 37-68. https://doi.org/10.1300/J395v01n02_04.

[3] Liu, Z., Guan, D., Wei, W., Davis, S., Ciais, P., Bai, J., Peng, S., Zhang, Q., Hubacek, K., Marland, G., Andres, R., Crawford-Brown, D., Lin, J., Zhao, H., Hong, C., Boden, T.A., Feng, K., Peters, G.P., Xi, F., Liu, J., Li, Y., Zhao, Y., Zeng, N., He, K., 2015. Reduced carbon emission estimates from fossil fuel combustion and cement production in China. Nature. 524, 335-346. https://doi.org/10.1038/nature14677.

[4] Guilhen, A., Gadioli, R., Fernandes, F.C., Waldman, W.R., Paoli, M.A.D., 2017. High-density green polyethylene biocomposite reinforced with cellulose fibers and using lignin as antioxidant. Journal of Applied Polymer Science.134, 45219-45228. https://doi.org/10.1002/app.45219.

[5] Garcia-Garcia, D., Carbonell-Verdu, A., Jordá-Vilaplana, A., Balart, R., Garcia-Sanoguera, D., 2016. Development and characterization of green composites from bio-based polyethylene and peanut shell. Journal of Applied Polymer Science. 133, 1-12. https://doi.org/10.1002/app.43940.

[6] Basu, G., Roy, A.N., Satapathy, K.K., Abbas, J., Mishra, L., Chakraborty, R., 2012. Potentiality for value-added technical use of Indian sisal. Industrial Crops and Products. 36, 33–40. doi:10.1016/j.indcrop.2011.08.001.

[7] Senthilkumar, K., Saba, N., Rajini, N., Chandrasekar, M., Jawaid, M., Siengchin, S., Alotman, O.Y., 2018. Mechanical properties evaluation of sisal fibre reinforced polymer composites: A review. Construction and Building Materials. 174, 713-729. https://doi.org/10.1016/j.conbuildmat.2018.04.143.

[8] Guilhen, A., Gadioli, R., Fernandes, F.C., Waldman, W.R., Paoli, M.A.D., 2017. High-density green polyethylene biocomposite reinforced with cellulose fibers and using lignin as antioxidant. Journal of Applied Polymer Science. 134, 45219-45228. https://doi.org/10.1002/app.45219.

[9] Castro, D.O., Frollini, E., Ruvolo-Filho, A., 2015. Dufresne A. Green Polyethylene and Curauá Cellulose Nanocrystal Based Nanocomposites: Effect of Vegetable Oils as Coupling Agent and Processing Technique. Journal of Polymer Science Part B. 53, 1010-1019. https://doi.org/10.1002/polb.23729.

[10] Hughes, M., 2012. Defects in natural fibres: their origin, characteristics and implications for natural fibre-reinforced composites. Journal of Materials Science. 47, 599-609. https://doi.org/10.1007/s10853-011-6025-3.

[11] Grujicic, M., Snipes, J., Ramaswam, S., Avuthu, V., Yen, C-F., Cheeseman, B., 2016. Derivation of the material models for ultra-high molecular-weight polyethylene fiber-reinforced armor-grade composites with different architectures. Engineering Computations. 33, 926-956. https://doi.org/10.1108/EC-05-2015-0120.

[12] Kim, J.T., Netravali, A.N., 2010. Mercerization of sisal fibers: Effect of tension on mechanical properties of sisal fiber and fiber-reinforced composites. Composites Part A: Applied Science and Manufacturing. 41, 1245-1252. https://doi.org/10.1016/j.compositesa.2010.05.007.

[13] Ahmad, E.E.M., Luyt, A.S., 2012. Effects of Organic Peroxide and Polymer Chain Structure

on Mechanical and Dynamic Mechanical Properties of Sisal Fiber Reinforced Polyethylene Composites. Journal of Applied Polymer Science. 125, 2216-2222. https://doi.org/10.1002/app.36434.

[14] Fávaro, S.L., Ganzerli, T.A., Carvalho Neto, A.G.V., Silva, O.R.R.F., Radovanovic, E., 2010. Chemical, morphological and mechanic analysis of sisal fiber-reinforced recycled high-density polyethylene composites. eXPRESS Polymer Letters. 4, 465-473. http://dx.doi.org/10.3144/expresspolymlett.2010.59.

[15] Kim, J.T., Netravali, A.N., 2010. Mercerization of sisal fibers: Effect of tension on mechanical properties of sisal fiber and fiber-reinforced composites. Composites Part A: Applied Science and Manufacturing. 41, 1245-1252. https://doi.org/10.1016/j.compositesa.2010.05.007.

[16] Wang, W., Wang, Q., Tan, X., Qi, W., Yu, Q., Zhou, G., Zhuang, X., Yuan, Z., 2016. High conversion of sugarcane bagasse into monosaccharides based on sodium hydroxide pretreatment at low water consumption and wastewater generation. Bioresource Technology. 218, 1230-1236. http://dx.doi.org/10.1016/j.biortech.2016.07.074.

[17] ASTM D790, 2015. Standard Test Methods for Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulating Materials. ASTM International: West Conshohocken, PA.

[18] ASTM D3039, 2017. Standard Test Method for Tensile Properties of Polymer Matrix Composite Materials. ASTM International: West Conshohocken, PA.

[19] ISO 179-1, 2010. International Organization for Standardization. Plastics– Determination of Charpy impact properties.

[20] Rocha, G.J.M., Nascimento, V.M., Silva, V.F.N., Corso, D.L.S., Gonçalves, A.R., 2014. Contributing to the environmental sustainability of the second generation ethanol production: Delignification of sugarcane bagasse with sodium hydroxide recycling. Industrial Crops and Products. 59, 63-68. http://dx.doi.org/10.1016/j.indcrop.2014.05.002.

[21] Santos, R., Rodrigues, B., Ramires, E., Ruvolo-Filho, A., Frollini, E., 2015. Bio-based materials from the electrospinning of lignocellulosic sisal fibers and recycled PET. Industrial Crops and Products. 72, 69–76. doi:10.1016/j.indcrop.2015.01.024.

[22] Montgomery, D.C., Runger, G.C., 2013. Applied Statistics and Probability for Engineers. John Wiley & Sons.

[23] Ullah, H., Harland, A.R., Silberschmidt, V.V., 2015. Characterisation of mechanical behaviour and damage analysis of 2D woven composites under bending. Composites Part B: Engineering. 75, 156-166. https://doi.org/10.1016/j.compositesb.2015.01.036.

[24] Pothan, L.A., Mai, Y.W., Thomas, S., Li, R.K., 2008. Tensile and Flexural Behavior of Sisal Fabric/Polyester Textile Composites Prepared by Resin Transfer Molding Technique. Journal of Reinforced Plastics and Composites. 27, 1847-1866. https://doi.org/10.1177/0731684408090342.

[25] Vieira, L.M.G., Santos, J.C., Panzera, T.H., Rubio, J.C.C., Scarpa, F., 2017. Novel fibre metal laminate sandwich composite structure with sisal woven core. Industrial Crops and Products. 99, 189-195. https://doi.org/10.1016/j.indcrop.2017.02.008.

[26] Chianelli-Junior, R., Reis, J.M.L., Cardoso, J.L., Castro, P.F., 2013. Mechanical Characterization of Sisal Fiber-Reinforced Recycled HDPE Composites. Materials Research. 16, 1393-1397. http://dx.doi.org/10.1590/S1516-14392013005000128.

[27] Daniel, I.M., Luo, J-J., Schubel, P.M., Werner, B.T., 2009. Interfiber_interlaminar failure of composites under multi-axial states of stress. Composites Science and Technology. 69, 764-771. https://doi.org/10.1016/j.compscitech.2008.04.016.

[28] Leong, M., Overgaard, L.C.T., Daniel, I.M., Lund, E., Thomsen, O.T., 2012. Interlaminar/interfiber failure of unidirectional glass fiber reinforced composites used for wind turbine blades. Journal of Composite Materials. 47, 353-368. https://doi.org/10.1177/0021998312440132.

[29] Jawaid, M., Khalil, H.P.S.A., Bakar, A.A., 2011. Woven hybrid composites: Tensile and flexural properties of oil palm-woven jute fibres based epoxy composites. Materials Science and Engineering: A. 528, 5190-5195. https://doi.org/10.1016/j.msea.2011.03.047.

[30] Li, Y., Li, Q., Ma, H., 2015. The voids formation mechanisms and their effects on the mechanical properties of flax fiber reinforced epoxy composites. Composites Part A: Applied Science and Manufacturing. 72, 40-48. http://dx.doi.org/10.1016/j.compositesa.2015.01.029.

[31] Sreekumar, P.A., Leblanc, N., Saiter, J.M., 2010. Characterization of Bulk Agro-Green Composites: Sisal Fiber Reinforced Wheat Flour Thermoplastics. Polymer Composites. 31, 939-945. https://doi.org/10.1002/pc.20877.

[32] Chaudhary, S.N., Borkar, S.P., Mantha, S.S., 2010. Sunnhemp Fiber-reinforced Waste Polyethylene Bag Composites. Journal of Reinforced Plastics and Composites. 29, 2241-2252. https://doi.org/10.1177%2F0731684409345615.

[33] Weder, C., 2009. Polymers react to stress. Nat. 459, 45-46. https://doi.org/10.1038/459045a.

[34] Habibi, Y., El-Zawawy, W.K., Ibrahim, M.M., Dufresne, A., 2008. Processing and characterization of reinforced polyethylene composites made with lignocellulosic fibers from Egyptian agro-industrial residues. Composites Science and Technology. 68, 1877-1885. https://doi.org/10.1016/j.compscitech.2008.01.008.

[35] Mulinari, D.R., Voorwald, H.J.C., Cioffi, M.O.H., Silva, M.L.C.P., 2016. Cellulose fiber-reinforced high-density polyethylene composites—Mechanical and thermal properties. Journal of Composite Materials. 51, 1807-1815. https://doi.org/10.1177/0021998316665241.

[36] Zhao, X., Li, R.K.Y., Bai, S.L., 2014. Mechanical properties of sisal fiber reinforced high density polyethylene composites: Effect of fiber content, interfacial compatibilization, and manufacturing process. Composites Part A: Applied Science and Manufacturing. 65, 169-174. https://doi.org/10.1016/j.compositesa.2014.06.017.