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IMPACT OF HYBRID COMPOSITES BASED ON RUBBER TYRES PARTICLES AND SUGARCANE BAGASSE FIBRES

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Abstract: The paper describes the impact behaviour of hybrid composites made of sugarcane bagasse fibres and disposed rubber particles. The analysis was carried out using a full factorial design (2^5) on samples subjected to drop-tower testing. The effects of the bagasse fibre treatment, length and weight fraction were considered, as well as the rubber particles size and their amount. Higher weight fractions of coarse rubber particles led to an enhancement of the absorption. Sustained chemical treatments of the bagasse fibres provided an increase of the composites stiffness, reducing therefore the energy absorption. In contrast, higher energy absorption was obtained in composites made with untreated bagasse because of the enhanced fibre pull-out mechanism.

Keywords: hybrid composite; disposed rubber; sugarcane bagasse; full factorial design; fibre treatment; drop-tower impact testing

1. INTRODUCTION

Hybrid composites consist of two or several types of reinforcements. The general use of hybrid composites has increased because of their enhanced mechanical properties [1], thermal stability and durability [2]. The use of recycled fillers as reinforcements from renewable sources has been also considered, with the aim of producing alternative materials addressing concerns related to the low sustainability of conventionally reinforced polymer composites [3].

A variety of natural reinforcements has been used in polymeric composites, such as cellulose, wood, cotton, jute, and bagasse from sugarcane. Natural fibres in general tend to affect the mechanical performance of composites by toughening, and by decreasing the deformation of the polymer and enhancing its elastic modulus [3]. Sugarcane bagasse has been widely used as reinforcing phase in cementitious and polymer composites, and it consists of waste generated by the industrial process of sugar, fuel and other products derived from sugarcane [4]. Sugarcane bagasse is considered a low cost and low-density material, with potential interesting specific mechanical strength and stiffness values [5]. The annual production of sugarcane is approximately 1.4 billion tonnes [6], which includes 604 million tonnes produced in Brazil alone. As a rule of thumb, three (3) tonnes of bagasse are generated when ten (10) tonnes of sugarcane are processed. It is therefore estimated that 54 million tonnes of bagasse are produced worldwide [6]. The majority of the disposed bagasse (85% of the total produced) is currently used as fuel of low calorific value and powering inefficient in boilers [6]. As there is still discarded bagasse residue, it is therefore necessary to increase its use in a high value application. A potential alternative application is the use of these residues as fibres in composites, since their short cycle growth is adequate to supply the market of composite reinforcements. The main advantages of bagasse fibres are their adequate mechanical and thermal properties, low cost, and high availability in tropical countries [6]. However, the bonding between fillers and polymer matrix requires surface chemical treatments of the bagasse fibres. The most common treatments include the use of alkali with immersion in a 10% NaOH solution at 80°C for up to 4 hours, and the acetic acid immersion for 1h [3]. When chemical treatments are applied, the performance of natural fibre composites can be comparable to the one of composites with glass fibres. Chemical treatments seem to be mostly beneficial when fibres have a minimum length of 5 mm [3].

The use of reinforcement from recycled sources is also an alternative route to produce sustainable composites and to reuse discarded materials. Rubber tyre particles constitute a type of reinforcement which could provide a significant positive contribution to the life cycle of the rubber component, because tyres are extremely durable and are not biodegradable. About 1.4 billion tyres are produced every year, and 17 million tonnes of tyres are disposed annually worldwide, representing 2% of the annual solid waste generated [7]. In the US only 257 million tyres have been discarded and 80 million kept in stock in 2015, all contributing to a very sizeable carbon footprint. In the UK, 37 million of transport and domestic vehicles tyres are disposed annually, however tyre disposal is estimated to increase by 63% by 2021 [7]. In Brazil, the annual disposal of tyres is estimated at 300 tonnes, with a total recycling rate of only 10% from waste [8]. These numbers clearly indicate an urgent need to find alternative usages for tyres waste, since its main current destination is landfill. The increasing costs of landfills [9], together with the restrictions on the disposal of automotive components in Europe due to the EU directive for end-of-life vehicles [10] limit the available technical solutions to dispose tyres. Rubber tyre particulates as composites reinforcements could be a way to stimulate tyre recycling. The use of fine rubber particles with a maximum of 25wt% in polymer composites gives a high packing factor [11], and rubber particles also provide a higher damping ratio in cementitious [7] and polymer composites [12]. The adhesion between polymer matrix and rubber particles, one of the most critical aspects for fillers, was considered satisfactory in microstructural tests performed by Silva et al. [13] and Krakoodi *et al.* [5].

The combination of natural fibres and rubber particles has so far shown promise in terms of mechanical properties, low cost, lighter weight and sustainability. Some of the fibres used in conjunction to rubber particles reinforcements are hemp and bagasse fibres, the latter evaluated by this research group. The use of hemp fibres with ground tyre rubber showed a general good bonding between the two reinforcements and the polyethylene polymer matrix. The use of 50% hemp fibres also contributed to a significant increase in tensile strength and elastic modulus. Flexural properties were also increased by 260% with addition of 60% hemp. On the other hand, the use of rubber particles at 26wt% led to a reduction of the tensile strength, stiffness and density, as well as an increase of the energy absorption of the composites [5]. Oliveira *et al.* [12] have reported similar findings when treated sugarcane bagasse fibres were embedded. The use of coarse rubber aggregates and longer treated fibres led to a reduced density. In contrast, the use of fine aggregates and short treated fibres contributed to a lower porosity and water absorption. The same authors observed an increased stiffness of the composites with short fibres and fine aggregates in smaller amounts. In addition, the tensile strength improved when reduced amounts of rubber (up to 25%wt.) were used. The compressive strength followed similar trends when smaller dispersions of finer rubber particles were used [12]. Durão *et al.* [4] have also investigated the delamination of sugarcane bagasse and rubber particle composites after drilling. The use of larger amounts of longer fibres associated to coarse rubber particles led to an increased resistance to delamination and an enhanced compressive strength of the composites.

The use of hybrid composites with sustainable reinforcements in secondary structural applications has shown to be adequate after performing static mechanical tests. Many efforts have been addressed to characterise the impact performance of composite materials based on individual reinforcements, such as different types of natural fibres or particles as fillers [14-16]. However, a small amount of work has been conducted toward the out-of-plane dynamic response of hybrid composites.

The damage under impact in fibre reinforced polymers is characterized by matrix cracking, delamination and fibre pull-out [17], and these are critical aspects for applications in the aeronautical and automotive sectors [18]. This work aims at investigating the energy absorption capacity of hybrid composites made from sugarcane bagasse and rubber tyre particles under out-of-plane impact loads using a Drop-Tower test machine. The effects of the size and quantity of rubber particles, length and weight fraction of bagasse fibres, as well as the type of fibre treatment have been here investigated using a Design of Experiment approach.

2. MATERIALS AND METHODS

2.1 Composite Constituents

The hybrid composites were made with epoxy polymer matrix phase, rubber tyre particles and sugarcane bagasse fibres. The epoxy resin (Renlan M) and the catalyst (HY 956) were supplied by Huntsman (Brazil). Bagasse was supplied by a local sugarcane producer located in the state of Minas Gerais (Brazil). The bagasse was shredded and milled into smaller fibres, and then sieved into two fibre lengths (5 and 20 mm). A mercerizing process (or alkali treatment) was used to modify the chemical affinity of the fibre surface to increase the bonding between sugarcane fibres and the epoxy polymer. The treatment of the fibres was adapted from the recommendations of La Mantia and Morreale [3], which describe the ideal amount of aqueous NaOH solution (10wt%) and mercerization procedures, such as the exposure time (up to 4 hours). In the present work, several preliminary tests were conducted to achieve a suitable treatment time in which the fibre was sufficiently modified to increase adhesion without excessive degradation of the fibres. This adapted procedure was also reported by Vieira *et al.* [19]. The mercerization treatment consisted of immersing the fibres in a 10% NaOH (w/v) solution for 1 hour at room temperature. The fibres were then repeatedly washed in water until a pH of 7 was reached. The fibres were subsequently left in distilled water for 24 hours, and oven-dried at 100ºC to obtain a constant weight. The rubber particles were supplied by a local remoulding tyre company (Brazil). The particles were obtained from a tyre grinding process and, after collection, were washed and dried for 24 hours. The particles were sieved into two sizes ranges (50/80 US-Tyler and 100/200 US-Tyler).

2.2 Full Factorial Design

A Design of Experiment (DoE) was performed to evaluate the effects of the individual factors and the interactions between responses through a full factorial design. An interaction indicates that the performance of one factor is dependent on the level of another factor (s) [20, 21]. The factors evaluated in this DoE were the amount of rubber particles (25 and 50%wt.), the quantity of sugarcane bagasse fibre (3 and 5%wt.), the range of the rubber particles sizes (50/80 and 100/200 US-Tyler), the length of the bagasse fibres (5 and 20 mm) and the presence/no presence of a fibre chemical treatment. The full factorial design was 2^5 (Table 1). The DoE responses evaluated in this work consisted in the impact energy (J), load at failure (N), and the energy at failure (J). Other factors, such as the mixing time (5 min), the curing time (7 days at room temperature, approx. 22ºC), the type of matrix (epoxy polymer) and the epoxy-hardener ratio (5:1) were kept constant during the experiment. The statistical analysis was performed using the Minitab v18 software [22]. A 95% confidence interval was considered across the statistical calculations associated to the DoE.

Table 1. Full Factorial Design - 2^5

	Rubber amount (wt%)	Rubber particle range (US-Tyler)	Bagasse fibre amount (wt%)	Bagasse fibre length (mm)	Fibre Treatment
C1	25	50-80	3	5	With
C2	25	50-80	3	5	Without
C3	25	50-80	3	20	With
C4	25	50-80	3	20	Without
C5	25	50-80	5	5	With
C6	25	50-80	5	5	Without
C7	25	50-80	5	20	With
C8	25	50-80	5	20	Without
C9	25	100-200	3	5	With
C10	25	100-200	3	5	Without
C11	25	100-200	3	20	With
C12	25	100-200	3	20	Without
C13	25	100-200	5	5	with
C14	25	100-200	5	5	without
C15	25	100-200	5	20	with
C16	25	100-200	5	20	without
C17	50	50-80	3	5	with
C18	50	50-80	3	5	without
C19	50	50-80	3	20	with
C20	50	50-80	3	20	without
C21	50	50-80	5	5	with
C22	50	50-80	5	5	without
C23	50	50-80	5	20	with

C24	50	50-80	5	20	without
C25	50	100-200	3	5	with
C26	50	100-200	3	5	without
C27	50	100-200	3	20	with
C28	50	100-200	3	20	without
C29	50	100-200	5	5	with
C30	50	100-200	5	5	without
C31	50	100-200	5	20	with
C32	50	100-200	5	20	without

2.3 Manufacturing and Testing

Prismatic samples (100 x 100 x 3 mm) were produced using a mould made of silicone, and according to the ASTM D7136 standard [23] (Figure 1). The epoxy resin was mixed with the hardener in a 5:1 ratio for 5 minutes. Subsequently, the rubber particles and the sugarcane bagasse were added and hand-mixed for 5 minutes. The mixture was then poured into the mould and left to cure for 7 days at room temperature. Five (5) samples were produced per experimental condition, with two replicates. A reference sample composed of the epoxy polymer in pristine conditions was produced to compare the evaluated factors. The drop-Tower impact tests were performed on an Instron Dynatup 9250HV machine. A hemispherical headed impactor was used with an impact velocity of 1.025 m/sec, equivalent to an impact energy of 2.925 J. The samples were fixed to the structure leaving an unsupported circular area of nearly 490 mm^2

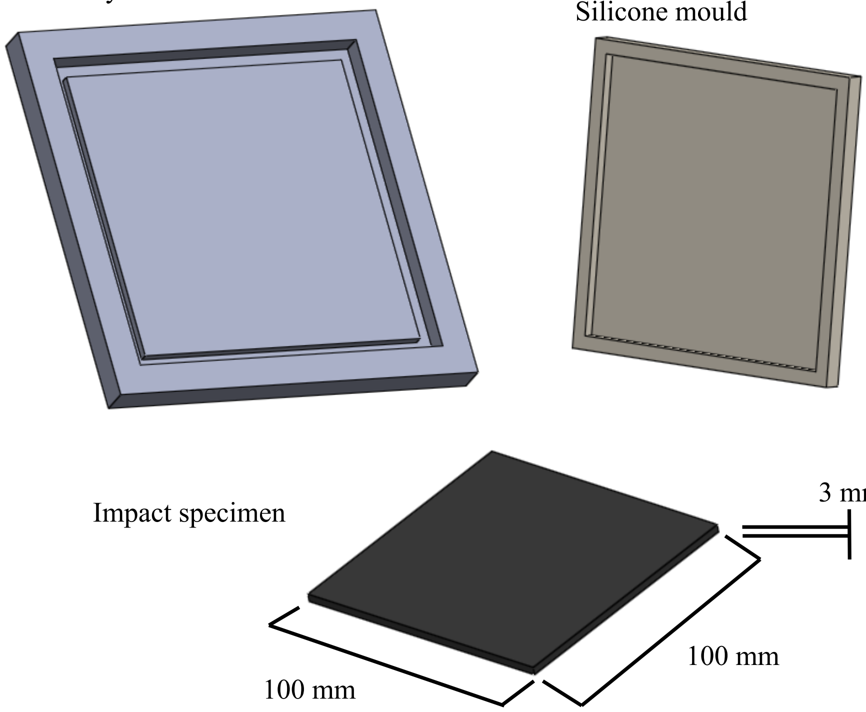


Figure 1. Silicone mould used to prepare samples for impact test.

3 RESULTS AND DISCUSSION

Table 2 shows the Analysis of Variance (ANOVA) related to the mean values of the load at failure, the energy at maximum load and the impact energy, by considering two replicates. P-values less than or equal to 0.05 indicate that the factor or interaction significantly affects the response within a 95% confidence interval. When higher-order interaction effects are significant, they are usually considered for further analysis, rather than focusing on the individual factors alone [20, 21]. The underlined P-values in Table 2 indicate the higher-order effects that will be evaluated by means of interaction plots. The values of the contributions indicate which factors or interactions are most relevant to the specific response. As shown in Table 2, the amount of rubber used was the most relevant factor that affected the impact properties. The R^2 adjusted in this work varied from 96.2% to 99.8%, which indicates a high correspondence between the and the model. The P-Value of the Anderson-Darling test is also presented in Table 2. This test verifies if the data follow a normal distribution (P-values greater than 5%), which is a requirement to validate the ANOVA findings.

Table 2. Analysis of variance of the impact properties. The P-values in bold are statistically significant.

Individual and interaction of	Impact Energy [J]	Load at failure [N]	Energy at failure [J]

factors	Contribution	P-value	Contribution	P-Value	Contribution	P-Value
Rubber amount [wt%] (RA)	22.10%	**0.000**	18.75%	**0.000**	62.32%	**0.000**
Rubber particle size [US-Tyler] (RS)	0.13%	0.155	5.59%	**0.000**	2.55%	**0.000**
Bagasse amount [wt%] (BA)	1.66%	**0.000**	2.63%	**0.000**	6.17%	**0.000**
Bagasse length [mm] (BL)	1.39%	**0.000**	0.04%	0.108	0.87%	**0.000**
Fibre treatment (FT)	1.86%	**0.000**	4.40%	**0.000**	0.00%	0.979
RA*RS	5.41%	**0.000**	6.25%	**0.000**	0.00%	0.882
RA*BA	0.00%	0.989	5.29%	**0.000**	0.07%	**0.000**
RA*BL	0.28%	**0.038**	0.22%	**0.001**	0.21%	**0.000**
RA*FT	0.01%	0.651	4.39%	**0.000**	0.12%	**0.000**
RS *BA	9.81%	**0.000**	1.33%	**0.000**	0.01%	**0.040**
RS *BL	0.43%	**0.011**	2.22%	**0.000**	1.46%	**0.000**
RS *FT	3.57%	**0.000**	3.11%	**0.000**	1.28%	**0.000**
BA *BL	2.24%	**0.000**	2.42%	**0.000**	1.03%	**0.000**
BA *FT	1.16%	**0.000**	0.11%	**0.009**	0.09%	**0.000**
BL *FT	4.35%	**0.000**	7.32%	**0.000**	1.65%	**0.000**
RA *RS *BA	1.90%	**0.000**	0.38%	**0.000**	0.60%	**0.000**
RA *RS *BL	0.54%	**0.005**	0.08%	**0.030**	0.04%	**0.000**
RA *BA *BL	0.02%	0.599	3.34%	**0.000**	0.05%	**0.000**
RA *RS *FT	5.36%	**0.000**	1.49%	**0.000**	7.80%	**0.000**
RA *BA *FT	1.84%	**0.000**	0.04%	0.106	3.43%	**0.000**
RA *BL *FT	9.54%	**0.000**	2.21%	**0.000**	0.90%	**0.000**
RS *BA *BL	2.46%	**0.000**	0.00%	1.000	0.04%	**0.000**
RS *BA *FT	2.75%	**0.000**	0.66%	**0.000**	0.00%	0.383
RS *BL *FT	0.42%	**0.013**	2.44%	**0.000**	0.03%	**0.001**
BA *BL *FT	3.42%	**0.000**	0.08%	**0.031**	0.08%	**0.000**
RA *RS *BA *BL	0.11%	0.184	1.83%	**0.000**	0.08%	**0.000**
RA *RS *BA *FT	9.00%	**0.000**	2.22%	**0.000**	1.90%	**0.000**
RA *RS *BL *FT	0.03%	0.503	8.46%	**0.000**	0.11%	**0.000**
RA *BA *BL *FT	4.94%	**0.000**	0.29%	**0.000**	5.09%	**0.000**
RS *BA *BL *FT	0.36%	**0.020**	1.02%	**0.000**	1.85%	**0.000**
RA*RS*BA*BL*FT	1.01%	***0.000***	10.93%	***0.000***	0.11%	***0.000***
Anderson-Darling	0.725		0.227		0.155	
R^2 adjust	96.23 %		99.06 %		99.85%	

3.1 Impact Energy

Figure 2 shows the interaction plot for the average impact energy involving the five factors. Figures 2.a to 2.d show that larger amounts of rubber particles contribute to enhance the impact energy absorption under all conditions, with percentages increasing between 18.5 and 25.9%. This behaviour can be attributed to the greater ratio between the energy elastically absorbed by the rubber and the overall kinetic energy when compared to the configuration with less rubber. In general, composites made of larger amount of rubber particles (50wt%) and 5wt% untreated bagasse with 20mm length showed the highest impact energies (see Fig. 2.a to 2.g). Fine rubber particles possess a higher specific surface area, and that leads to an increased interface between reinforcement and surrounding matrix. That makes the material to behave less rigidly and, consequently, to contribute absorbing more impact energy (Fig 2.e and 2.g). Fracture is usually associated with the formation of macro-cracks in the matrix, followed by fibre failure. Most of the energy absorbed during impact is related to fibre pull-out [24-25]. The sugarcane bagasse is however able to absorb more energy through the fibre pull-out effect, which indicates the progressive release of the fibre itself from the matrix during impact due to reduced fibre-matrix bonding [24-25]. A higher impact energy was obtained by using untreated bagasse fibres; this fact can be explained by the presence of a lower degree of fibre-matrix bonding. For this reason, a larger amount of longer fibres leads to an overall increase of impact energy capacity. Santos *et al.* [26] have reported that the alkali treatment of coir fibre reinforced composites is associated to the reduction of the impact resistance due to increased mechanical interlocking, reduction of the fibre pull-out and dissipation of the impact energy.

It is worth of notice that the fine rubber particles generated some different impact behaviours depending on the presence (or lack) of treatment of the bagasse fibres. Higher impact energy values were observed when a larger amount (5wt%) of untreated fibres (Figures 2.e and 2.g) were used. Coarser particles also exhibited better impact performance when longer treated fibres were added in smaller amounts (Figures 2.e to 2.g). The use of longer fibres tended to favour the impact energy absorption in all conditions tested (Figures 2.c, 2.f and 2.h), except when the composites were made using treated bagasse (Figure 2.j). In this particular case, short treated fibres can however enhance the energy absorption by approximately 6%. In general, the chemical treatment of the fibres led to reduced energy absorption due to the improved interface adhesion and the stiffening of the composite (Figures 2.d and 2.i). The opposite occurs when coarse rubber aggregates and shorter fibres were used (Figures 2.g and 2.j), in which case the treatment of the fibres tended to increase the impact energy. Bagasse fibres with 5 mm length do not appear to provide a substantial effect on the energy absorption of the composites because of their smaller contact surface [20-21].

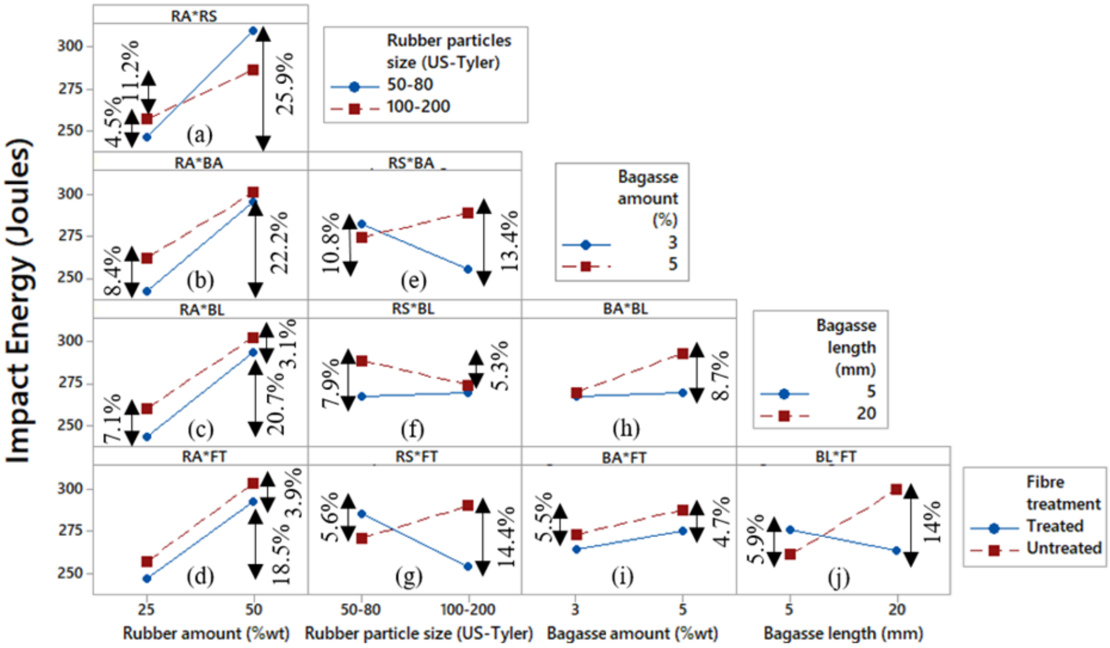


Figure 2. Interaction effect plot for the average values of impact energy.

3.2 Energy up to the maximum load

The energy up to the maximum load presented a significant 5th order interaction with a P-Value less than 0.05 (Table 2). Figure 3 shows the interaction plot related to the average energy values up to maximum load. The behaviour is similar to the one observed for the energy absorption (Figure 2), but without an evident effect provided by the length of the bagasse and chemical treatments (0.87% and 0.00%, respectively, as shown in Table 2). The main factors affecting this response are the amounts of rubber and bagasse, with 62.3% and 6.2% of contributions, respectively (Table 2). The energy absorbed up to the maximum load does not quantify the effects associated with fibre pull-out after impact. Composites made of 50wt% of fine rubber particles (100-200 US-Tyler) and 5wt% bagasse fibres achieved higher impact energies at failure (Figure 3a, 3b and 3e).

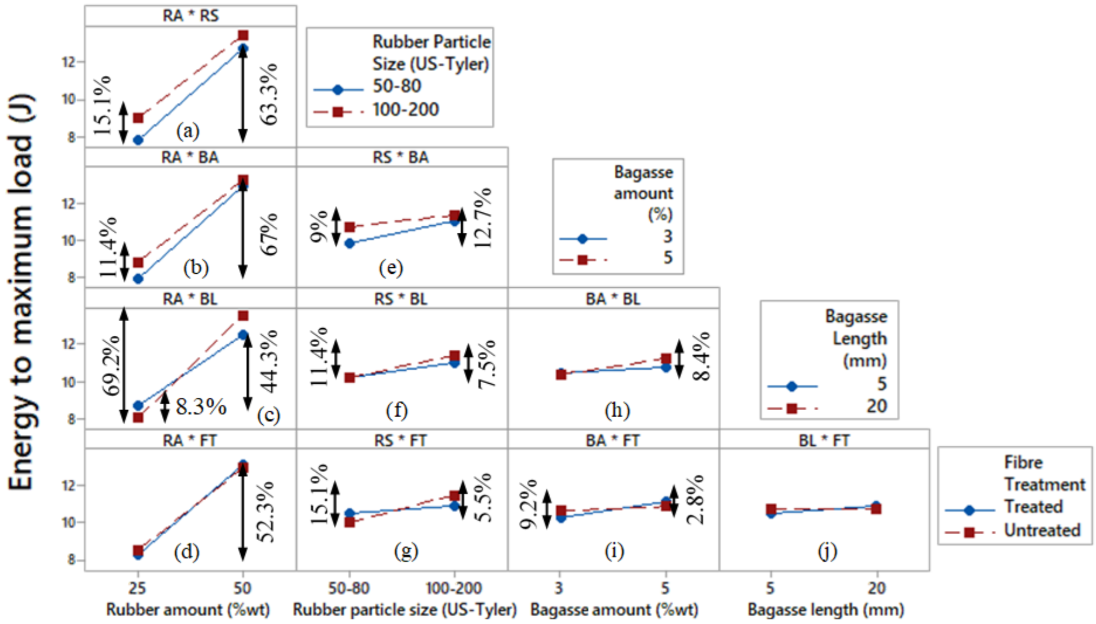


Figure 3. Interaction plots of the average energy up the maximum load (J).

3.3 Load at failure

A fifth order interaction was observed on the load at failure response and deemed significant because of its P-value of 0.031 (Table 2). Figure 4 shows the interaction plot for this response. Among the main factors, the quantity of rubber amount is the one that most affects the response, with a 18.75% contribution (Table 2). An opposite behaviour was observed for the energy up to maximum load when a larger amount of rubber was used, leading to reduced maximum load at failure with decreases between from 70.9% to 96.6% (see Figures 4.a to 4.d). The presence of factors interaction between the amounts of rubber and bagasse is observed in Figure 4.b, with higher failure loads when the factors are at their lowest levels. Finer rubber aggregates favoured not only the dissipation of higher maximum energies (Figure 3.e -g), but also higher loads at failure (Figure 4.e-g). The length of the bagasse fibres did not appear to generate a substantial effect on this response (Table 2, Figures 4.c-h). The use of a chemical treatment of the fibres increased the load at failure between 17.3% and 134.2% in all the cases considered except when longer fibres were used. In that particular instance the load at failure was reduced instead by ~18% (see Figures 4.d, 4.g, 4.i, and 4.j)

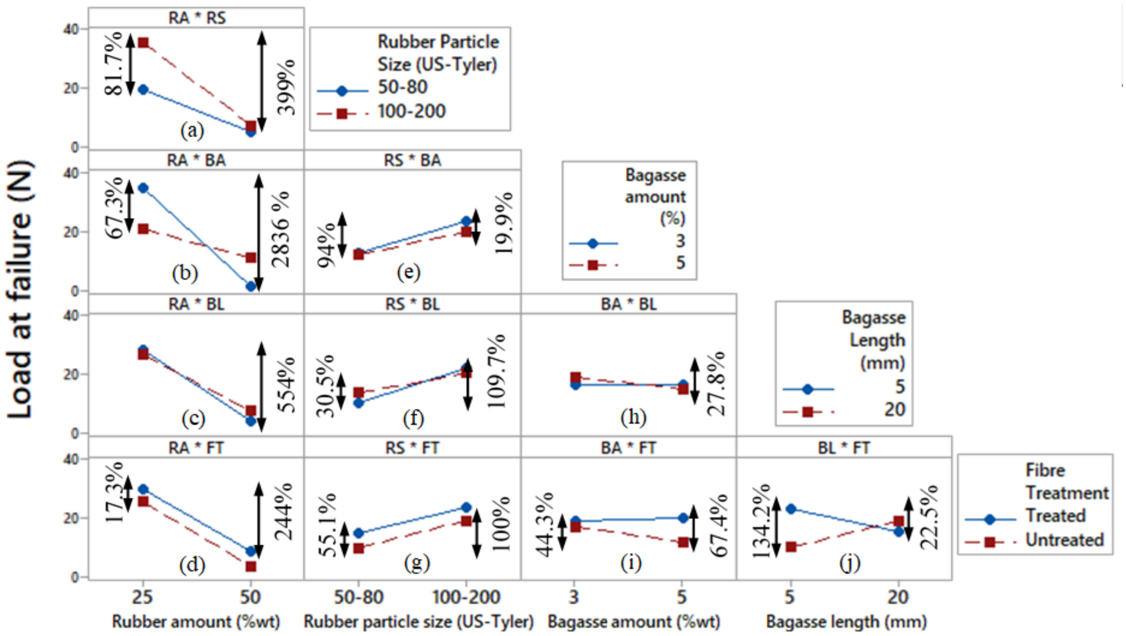
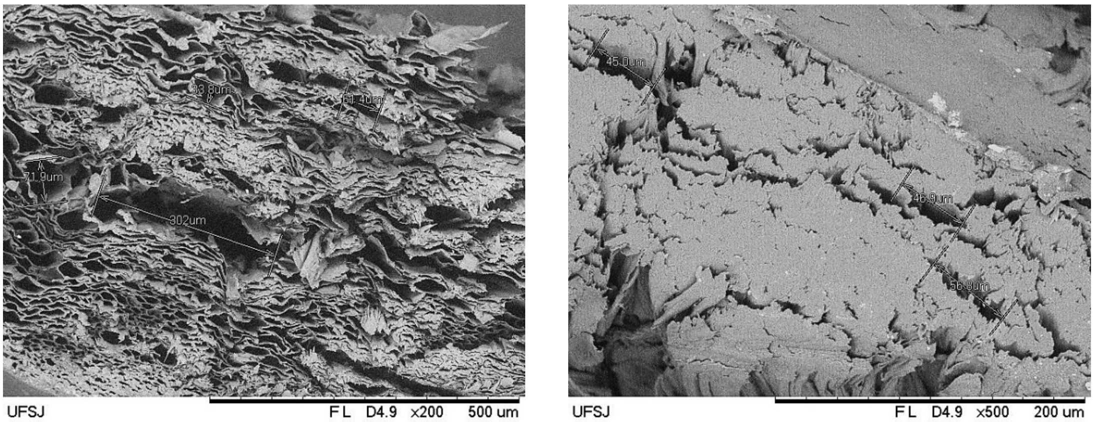


Figure 4. Interaction plots related to the average values of the load at failure (in N).

3.4 Effects of Fibre Treatment

The effect of the alkali treatment on the fibre surface morphology is depicted by Figure 5, which presents a microstructural analysis of the fibre from a table top scanning electron microscope (Hitachi TM 3000). Backscattered electron images at 15kV (BEI) of untreated bagasse fibres (Figure 5a) and treated (Figure 5b) reveal that untreated fibres exhibit a more porous surface with larger pores (from 30 to 302 µm size). Treated fibres tend to be packed closely due to the increased formation of hemicellulose removal bonds [26]. As the alkaline treatments cause the rupture of cellulose and hemicellulose-sensitive bonds, the resulting cellulose chains create new hydrogen bonds to replace the removed ones. The resulting fibre is more homogeneous due to the swelling of the fibre structure, leading to enhanced stress transfer in the interfibrillar regions [15, 26]. The pore size range of the treated fibres is 45 to 60 µm, revealing a more compact surface. Finally, the mercerisation contributes to the fibre-matrix adhesion, mainly due to the fibre surface area increase, which promotes a better load transmission between the phases, enhancing, consequently, the mechanical strength and stiffness of the composite [26]. In contrast, alkali treatment contributes to reduce its ability of absorb impact loads. However, as highlighted in the present work, fibre incorporation achieves a synergistic effect with inclusions of rubber particles, reaching satisfactory energy absorbing capacity and panel strength.



(a) (b)

Figure 5. Backscattered electron images for untreated (a) and treated (b) fibres prior to composite fabrication.

3.5 Analysis of the impact force

The time histories of the impact force for different hybrid composites is shown in Figure 5. The curves initially show a quasi-linear behaviour up to the first peak force value, and then develops into 4 different sections, or zones. The first of those parts (Zone I) is related to the moment when the impactor touches the surface of the sample. The force output in this zone increases asymptotically between points A-B. The size of the rubber particles (Figure 5.b) and the treatment of the bagasse fibres (Figure 5.d) were the factors that contributed the most to increase the impact force in the first zone. A higher capacity for kinetic energy absorption is observed in composites made with fine rubber particles (100-200 US Tyler) and untreated bagasse fibres. The second zone (Zone II) is defined by the failure created by the compression wave. The impact force at the intersection B-C tends in general to increase in a gradual manner, and particles with the smallest size increase the levels of force (Figure 5.b). The maximum impact force is recorded in the transition between Zone II to Zone III (point C in Figures 5.a to 5.e). The force suddenly reduces in Zone III due to debonding. In this case, the impact force appears to be mostly affected by the quantity of rubber particles used. Higher wt% of particles tend to provide a positive contribution to increase the energy absorption capacity. The final Zone IV is related to the presence of crack patterns away from the impact zone and caused by the ringing produced by the impact force.

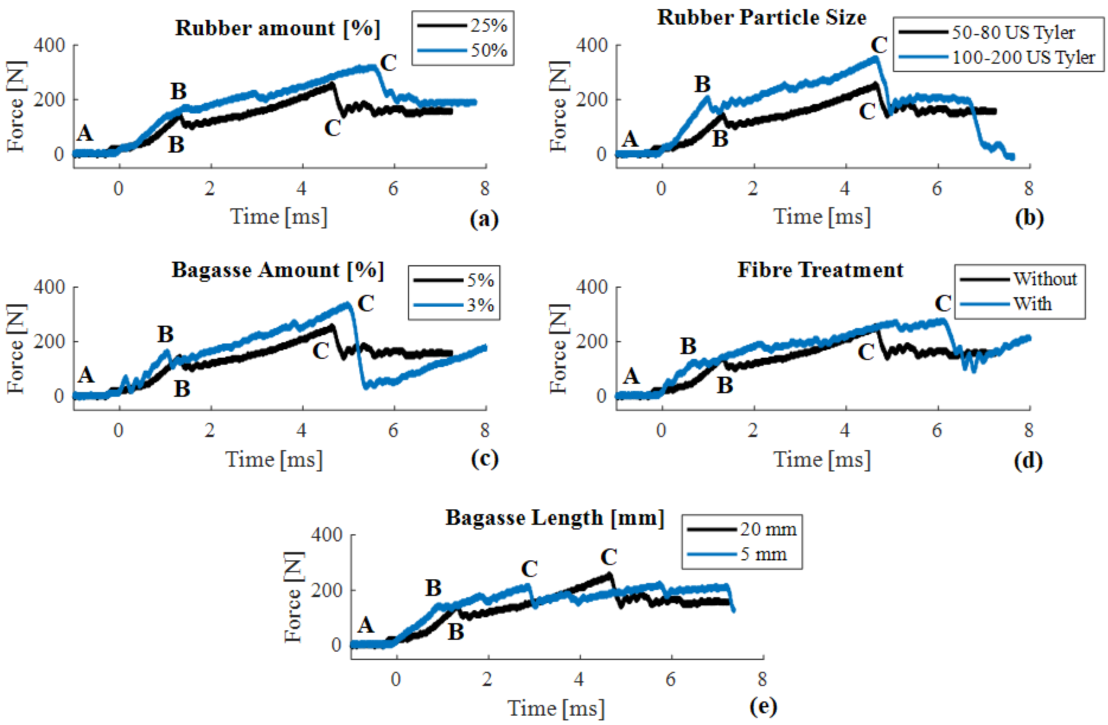
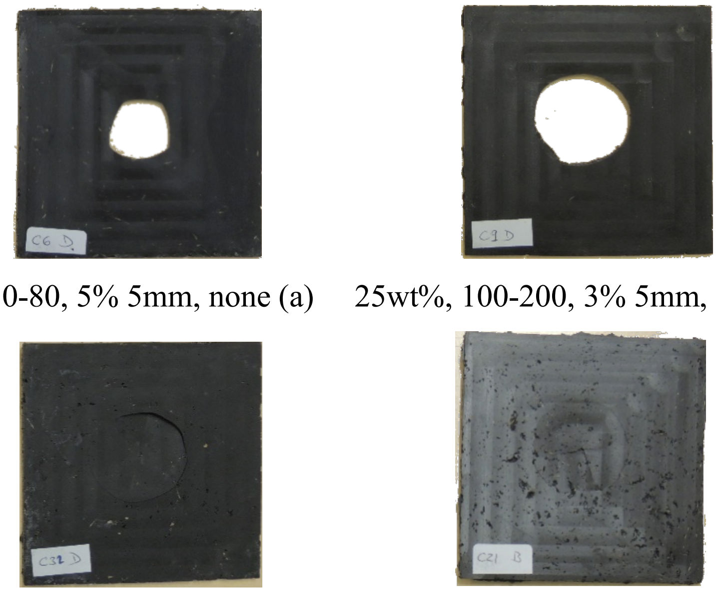


Figure 6. Force time histories during impact.

3.6 Failure Analysis

In general, the failure mechanism of the composites subjected to impact can be divided into four different stages. The first one is related to the contact and occurs as a compression wave propagating over the hybrid composite surface. The second stage is the compression failure mechanism, which may correspond to failure of the matrix and the fibres. The third stage is usually related to the debonding process between matrix and reinforcement, where the top and bottom faces begin to delaminate. Finally, the fourth stage is the erosion of the impacted intermediate zone, characterized by the presence of circular crack patterns.

Figure 7 shows the optical image of the composites C6, C9, C21 and C32 after the impact tests. No delamination process and the presence of circular cracks were identified after impact. The impact resistance and the failure mode of the hybrid composites were significantly affected by the quantity of rubber used, and this was due to their ductile characteristics. The smaller amount of rubber particles led to an evident circular failure around the impact loading position, while a higher energy absorption was achieved by 50wt% rubber particles that prevented some further deformation of the plate. Thus, the failures of C6 (Fig 7.a) and C9 (Fig. 7.b) were more rapidly propagated when compared to the C21 (Fig 7.c) and C32 (Fig 7.d) composites. In general, the fibre treatment effect resulted in extended failure propagation due to higher panel stiffness (Fig. 7b, d), which led to a fragile failure in the central area. The lower amount of fine rubber particles provided a higher propagation of the failure on the sample (Fig. 7.b), in contrast, reduced damages are obtained when added in larger amounts (Fig. 7.c).



25wt%, 50-80, 5% 5mm, none (a) 25wt%, 100-200, 3% 5mm, treated (b)

50wt%, 100-200, 5% 20mm, none (c) 50wt%, 50-80, 5% 5mm, treated (d)

Figure 7. Post-failure samples for C6 (a), C9 (b), C21 (c), and C32 (d) composites.

3.7 Comparison with other works

Table 3 presents the results of the average impact energy absorption of the most favourable condition (C32), which consists of a larger amount of fine rubber particles and larger inclusions of untreated long bagasse fibres. The composite made with fewer coarse rubber particles and larger amount of short treated fibres is also compared (C5). This comparison clearly highlights the effect of size and treatment of fibres, as well as the size and amount of rubber particles, on the impact absorbing capacity of the composite. Table 3 also exhibits some impact absorption values for natural fibre composites based on drop tower and Izod impact tests [14-16]. A particular comparison between values is not possible due to differences in matrix composition and test procedures, resulting in distinct behaviours and units. However, it is noteworthy that the hybrid composition significantly increased the overall energy absorption capacity. The main advantage of the hybrid composite is the synergistic effect between two different sustainable reinforcements, combining higher energy absorption due to rubber inclusions and higher toughness due to the pull-out effect of the longer bagasse fibres.

Table 3. Impact energy of hybrid and other ecological reinforced composites.

Setup	Composition	Impact energy
C32	50%wt 100-200 rubber + 5% wt. untreated 20 mm fibres	403.8 J
C5	25%wt 50-80 rubber + 5% wt. treated 5 mm fibres	194.7 J
Moure et al. [14]	Kevlar 129 fibre + Polyvinyl matrix	121 J (for thin plates)
Pickering, Efendy, and Le [15]	Hemp fibre + PP matrix	210 J/m (Izod test)
	Aligned Flax + PP matrix	751 J/m (Izod test)
	Jute fibre + PP matrix	195 J/m (Izod test)
Senthilkumar et al. [16]	Sisal fibre + PE matrix	110 J/m (Izod test)
	Banana fibre + PE matrix	105 J/m (Izod test)

4 CONCLUSIONS

This work has described the development and testing of a sustainable hybrid composite material made with rubber wastes and sugarcane fibres in 32 different compositions. The impact properties of these composites have been evaluated with a statistically robust DoE procedure. The main conclusions drawn from the impact tests are the following:

i. A fifth order interaction of the factors "RA*RS*BA*BL*FT" show some significant effect in the impact energy of the hybrid composites. Those composites consisted of the highest content of coarse rubber wastes (50wt%, and 50-80 US Tyler) and the lowest amount of bagasse fibres (3wt%);

ii. The composites with the highest rubber fraction (50wt%) showed an increase the energy absorption of the impact, the energy up to maximum load and a reduction of the load at failure;

iii. Alkali treatment resulted in a more compact fibre structure with reduced pore size, and improved matrix-fibre bonding due to the creation of new hydrogen bonds. The fibre treatment provided not only increased strength but also reduced energy absorption of the composites.

iv. The amount of rubber used affected significantly the failure mode, with a notable damage in the samples with the smallest rubber inclusions. The highest amount of rubber prevented the failure of the composite because of the larger energy absorption capacity. In addition, longer untreated bagasse fibres (20 mm) provided higher impact energy because of their enhanced fibre-pull out mechanism.

v. In general, the combination of rubber wastes and bagasse fibres appears to offer an appealing alternative for the development of new environmentally friendly structural materials for low-carbon impact engineering applications.

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