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Impact Behavior of Woven Coir-Epoxy Composite Prepared by Compression Molding and Vacuum Bagging Methods

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ABSTRACT

This work investigated the impact penetration behaviour of woven coir-epoxy composite fabricated by two alternative methods, compression moulding and vacuum bagging. The impact response such as maximum load, displacement at maximum load, energy absorbed at maximum load, total energy absorbed and ductility index were observed. An image analysis method was developed to determine the area and perimeter of the damaged composites. Composite failure was examined using scanning electron microscopy (SEM). The responses in both methods were compared. Analysis of variance (ANOVA) was employed to determine the significant factors that predominantly influence the impact behaviour of the composites. It was found that the composite fabrication method significantly affects the maximum load, energy absorbed at maximum load and total energy absorbed. The results demonstrated that compression moulding helps to improve those responses. Composites fabricated with compression moulding methods also showed enhanced fibre-matrix interfacial bonding. It is concluded from the experiment that woven coir-epoxy composites fabricated by the compression moulding method are preferable to achieve improved impact performance.

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INTRODUCTION

Impact has been defined as the relatively sudden application of impulsive force to a limited volume of materials or part of a structure (Reid and Zhou, 2000). It is concerned with the reaction forces that develop during dynamic response and the collision of a structure. The impact properties of natural fibre composite have shown great potential. Research exploring natural fibre-based composite was embarked upon owing to the unpleasant effect of artificial fibre-based composite on the environment, its cost, etc. (Nunna *et al*., 2012). Coir fibre as composite reinforcement has been investigated in depth by researchers primarily to explore its prospective and value-added properties (Verma *et al*., 2013; Azrin Hani *et al*., 2012; Monteiro *et al*., 2008). Coir is a resilient, strong and highly durable fibre as a result of its high content of lignin and low cellulose content (Reis, 2006). The impact properties of coir composite were found to outperform kenaf composite (Azrin Hani *et al*., 2012). The expansion of particular research work to determine the best reinforcement structures of coir composite has revealed that woven structure exhibits the greatest impact performance (Azrin Hani *et al*., 2013). Therefore, a woven reinforcement structure was selected for this research. Harish *et al*. (2009), demonstrated that coir has great potential to be used as a reinforcing material for making low load-bearing thermoplastic composites. In comparison with other natural fibres, Wambua *et al*. (2003), agreed that coir fibre composites have better impact strength than jute and kenaf, although it produces lower mechanical properties. Moreover, composites exceeding 50 wt% fibres loading were found to be rigid and agglomerated (Monteiro *et al*., 2008). This was also observed by Arrakhiz *et al*. (2012), who reported that 30 wt% of fibre content shows the optimum set of mechanical properties.

The impact design of composite structures is still at the demonstration phase, as claimed by the researcher (Belingardi and Vadori, 2002). Approaches including controlling fibre/matrix interfacial bonding, matrix modification, lamination design, through thickness reinforcements, hybridization and many more have been conducted to improve the impact resistance (Jang *et al*., 1989). The properties of composite materials can also be tailored by the proper selection of production methods (Ho *et al*., 2012). The composite manufacturing

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process can be done in various ways. Each of the fabrication processes has characteristics that define the type of products to be produced. The most common methods for fibre-reinforced composite are open mould hand lay-up, compression moulding, the vacuum pressure method, resin transfer moulding and pultrusion. It was found that an adaptation of the vacuum manufacturing process resulted in higher fibre content but did not essentially lead to greater mechanical strength. Researcher agreed that fibre content was not the only factor, but also took into consideration the matrix composition as well as the fibre-matrix bonding behaviour (Behr *et al*., 2000). Most of the research on coir composite covers compression moulding and the hand lay-up manufacturing process. Compression moulding offers advantages such as producing materials with more uniform density, lower manufacturing cost, low levels of waste, uniform shrinkage due to uniform flow, and dimensional stability (Medina *et al*., 2009). Fewer attempts have been made to use the vacuum bagging method, while no studies have reported comparison of more than one composite manufacturing method utilizing those coir fibres in a fabric laminate preform. Vacuum bagging is a clamping method that uses atmospheric pressure to hold the adhesive or resin-coated components of a lamination in place until the adhesive cures. Vacuum bagging delivers firm and evenly distributed pressure to the entire surface of the material being laminated, resulting in thinner, more consistent glue lines and fewer voids. The process also results in higher fibre-to-resin ratios. Both methods (compression moulding and vacuum bagging) apply pressure on the sample, where the pressure compacts the laminate, providing good consolidation and interlaminar bonds. It is well known that optimization of the adhesion of the fibre to the matrix is crucial as it has effects on the efficacy of the stress transfer from the matrix to the fibre, resulting in the attainment of good mechanical properties.

The purpose of this investigation was to achieve an understanding of the role of the composite manufacturing process in the impact behaviour of imbalanced (3 warp/inch, 31 weft/inch) woven coir composite. In this study, composites were prepared by two different manufacturing methods: compression moulding (CM) and vacuum bagging (VB). Impact properties such as the maximum load, deflection at the maximum load point, energy absorbed at the maximum load point, total energy absorbed and ductility index were determined from the load-deflection graph of the impacted samples. The composite's morphology images and damage assessment under impact penetration were further analysed.

MATERIALS AND METHODS

Materials:

Coir yarns were used as received from BTex Engineering Ltd., India. The density of coir as reported in previous literature was 1.15 g/cm^3 (Akil *et al*., 2011). Coir yarns were twisted as 2-ply spun in the S direction and the linear density was recorded as 923 Tex. The matrix used was epoxy DER 332 of density 1.16 g/ml. Jeffamine D-230 hardener of density 0.948 g/ml was used as curing agent. Both the resin and hardener were supplied by Penchem Technologies Sdn. Bhd. Malaysia.

Fabrications and consolidation:

An imbalanced woven fabric structure as composite reinforcement was produced using a self-designed handloom. The woven structure is depicted in Fig. 1. Woven composites were prepared by means of compression moulding (CM) and vacuum bagging (VB). The schematic drawings of both methods are shown in Fig. 2. Woven fabric preform by the CM method was laid inside the mould before the resin was poured. The mould was closed and placed in a pressing device overnight. A heating element on the pressing device was turned to 80^{o}C for 6 h later for post-curing. As for VB, the suction pressure was set to reach 600 mmHg for about 30 minutes. The samples were then left overnight for curing and post-curing for another 6 h at 80^{o}C in the oven. For both methods, single layer fabric preform was used and fibre-matrix ratios were fixed at 3:7 by weight percent.

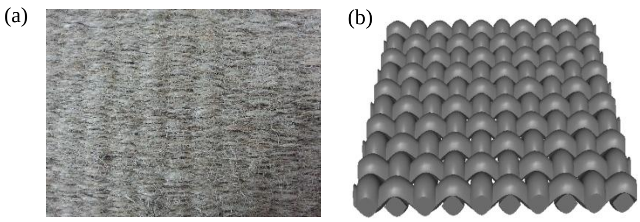

Fig.1: Woven structure: (a) actual; (b) modelling.

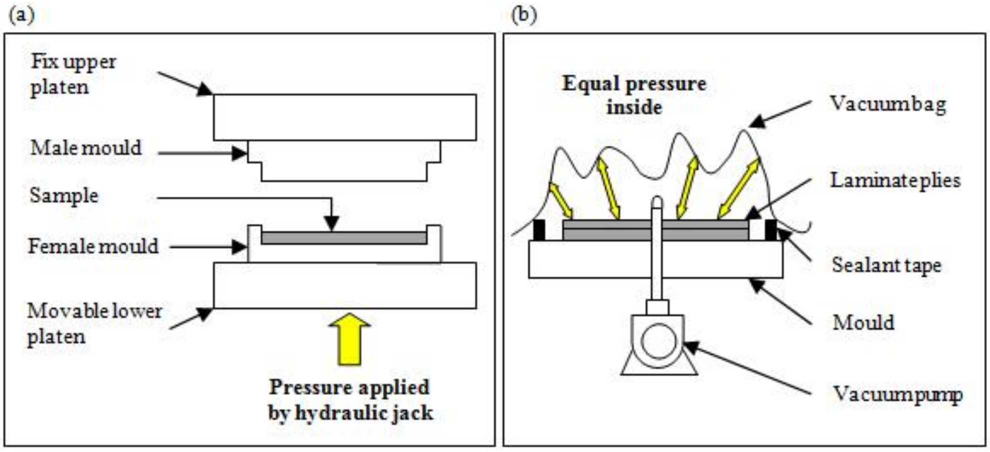

Fig. 2: Composite fabrication methods: (a) compression moulding; (b) vacuum bagging.

Woven fabric characterization:

The fabric characterization analysis involved fabric thickness, fabric weight, fabric density, fabric wavelength and inter-yarn fabric porosity. Fabric thickness (*t*) was measured using digital callipers. Fabric weight, on the other hand was determined by weighing fabric specimens of a predetermined size on a balance scale. The fabric weight in grams/metre^2 was calculated from the area measured. The density of a fabric is weighed relative to thickness, expressed in grams/centimetre^3. In contrast, warp and weft density were reported separately and expressed in warp or weft per inch. The crimp percent, k, as defined by ISO 7211-3 was calculated using Equation (1). L is the distance between two ends of the projection of a yarn onto the fabric plane and P is the actual length of the yarn. Yarn crimp refers to the degree of yarn undulation and is a property of the weave (Lim *et al*., 2012).

$$k = \left[\left(P - L\right)/ L\right] \times 100\% \qquad (1)$$

Figure 3 illustrates the schematic of the plain weave structure. The weft crimp wavelength, λ, was measured in order to see the crimp effects of the structure. Finally, inter-yarn fabric porosity (ε) was calculated using Equation (2). Porosity in fabric is defined as the ratio of the projected geometrical area of the opening across the material to the total area of the material (Cay *et al*., 2007).

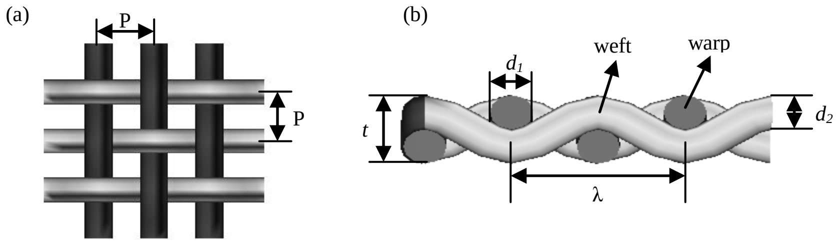

Fig. 3: Model of plain weave fabric: (a) top view; (b) cross section view.

$$\varepsilon = \frac{\text{open pore area}}{\text{total area}} = \frac{P_1 - P_2}{(P_1 + d_1)(P_2 + d_2)} \qquad (2)$$

Impact test:

Shimadzu Hydroshot Impact Test Machine was used to perform a 9 m/s impact puncture test. It was performed in accordance with ASTM D3763. Fig. 4 presents the actual and schematic view of the impact test machine. Composite samples were cut into 100 mm x 100 mm squares. A thickness of approximately 3 mm was maintained for all the samples. At least three replicates were carried out for each sample and the average value and standard deviation were later reported. The tests were conducted at ambient temperature. Specimens were positioned horizontally in the testing cassette of the machine. An impactor with a nose tip of about 1.27 cm was dropped by a hydraulic system actuator and the striker was equipped with a load transducer whose output was fed to a data acquisition board installed in a computer. The load-deflection curve was obtained from the software. The load-deflection relation is the most fundamental way to describe the behaviour of composites during impact. This relation can give insight into how a composite is damaged. Most importantly, it shows how the composite absorbs the impact energy throughout the impact process. The absorbed energy was calculated by integrating the area enveloped by the load-deflection curve. The load and deflection at maximum load point were symbolized by P_{max} and δ_{max}. The energy at the maximum load point can also be identified as initiation energy (E_i), and E_t represents the total energy absorbed by the specimen in complete penetration. The energy dissipated after the yield point is defined as E_p (propagation energy). Moreover, the ductility index, $DI = E_p/E_i$ reflects the ductility of the material. A higher ductility index would mean that most of the total energy is expanded in crack propagation. The larger the DI value, the more ductile the composite material.

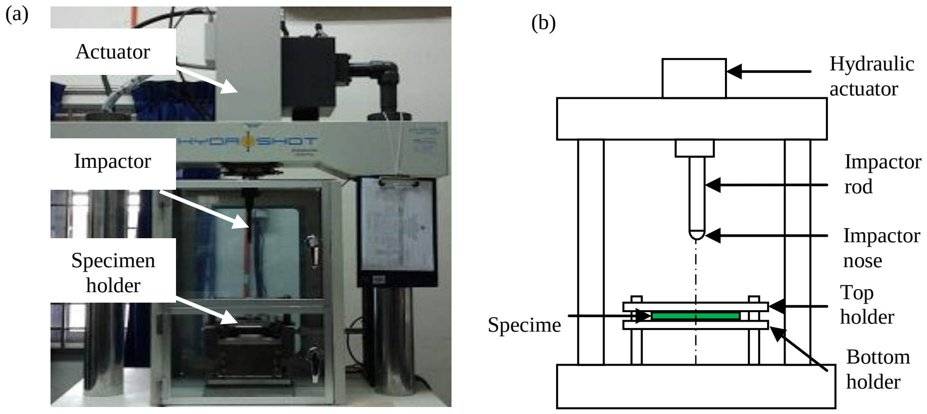

Fig. 4: Impact test: (a) actual machine; (b) schematic.

Damage region evaluation was conducted by the image analysis method. The damaged area on the front and rear of the specimens as well as the damage perimeter were evaluated. The detailed procedure is well explained in Nunes *et al*. (2004). A flatbed scanner was used to scan the damaged samples and the images were processed in Matlab software with image processing tools. Samples were scanned at 600 dpi (dots per inch). Programming commands were developed in the software in order to detect the damaged edges, remove unwanted particles and calculate the respective areas and perimeters. The morphological study of fractured composite surfaces was observed using a scanning electron microscope (SEM) performed with Hitachi Tabletop Microscope TM-1000 at 650X magnification. A gold coating of a few nanometres in thickness coated the impact-fractured surfaces. The samples were viewed perpendicular to the fracture area.

Statistical analysis:

One-way analysis of variance (ANOVA) was used to compare the impact performance between the two composite structures fabricated by means of the different composite manufacturing methods. A P-value of less than 0.05 was considered significant.

RESULTS AND DISCUSSIONS

Characteristics of woven coir fabric:

Table 1 shows the physical characteristic of the woven coir fabric produced. The result shows that the crimp percent of the woven fabric structure is low (< 20 crimp %). This is an advantage as higher crimp results in the deterioration of mechanical properties (Lim *et al*., 2012). Moreover, inter-yarn fabric porosity has an effect on the penetrability through the thickness matrix. Reasonable woven porosity allows good penetration of the matrix liquor through the woven fabric structure (Cay *et al*., 2007).

Table 1: Characteristics of woven coir fabric.

Characteristic	Value
Thickness, t (mm)	2.4
Weight (g/m^2)	5600
Density (g/cm^3)	2.3
Warp density (warp/inch)	3
Weft density (weft/inch)	31
Crimp percent, k (%)	2
Weft crimp wavelength, λ (mm)	20
Inter-yarn fabric porosity, ε	0.35

Characteristic of impact events:

The load-deflection curves of the composite samples produced using the different manufacturing methods are given in Fig. 5. Since they had very similar characteristics, only one representative curve of each test is displayed in the figure. An open curve in the load-deflection represents the occurrence of total perforation on the specimens. The curves are labelled to portray their condition. The slope of the ascending section of each curve is termed the impact bending stiffness. It represents the stiffness of composites under impact and bending induced at the beginning of the impact process. A slight drop in the ascending section can be explained as crack initiation. As the load increases, matrix cracking occurs, and as it increases further, the size and extent of the matrix crack and fibre breakage may progress. Individual maximum loads are eventually reached before perforation takes place. A descending curve follows because of the frictional force between the impactor and the composite plate. The area under the slope up to the peak load is the initiation energy, whereas the area bounded by the open force-deflection curve and the deflection axis is the total energy absorbed by the perforated specimens. The absorbed energy increases as the bounded area increases. As can be seen from the curve, the slope for the CM composite is higher than that for the VB composite. This shows that the CM composite has a higher modulus than the VB composite counterpart. It can be said that the VB composite is more brittle in structure, while the CM composite exhibits higher composite toughness. Furthermore, the progress of multiple cracking or micro-fragmentation on the VB composite, as noticed in Fig. 5, clearly demonstrates the brittleness of the composite (David *et al*., 2009).

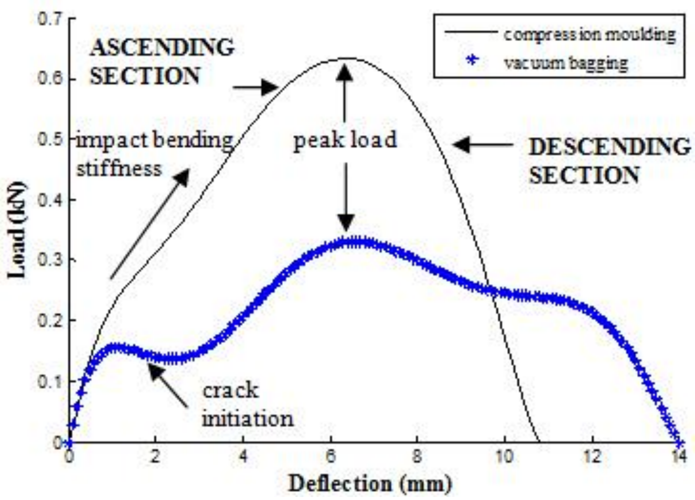

Fig. 5: Load-deflection curve of composite samples produced by compression moulding and vacuum bagging.

Impact performance of composites:

Statistical analysis was carried out using one-way ANOVA and a summary of R^2 and P-values obtained is presented in Table 2. The difference in the manufacturing method proved to have a significant effect on P_{max}, E_{max} and E_{tot} with a P-value of less than 0.05 at 95% confidence level (highlighted with bold font). However, the effect of the manufacturing method on deflection (δ_{max}) is not significant as the P-value shows more than 0.05 at 95% confidence level. Distributions of residuals demonstrate a low degree of variability (R-square) for P_{max}, E_{max} and E_{tot}, therefore data obtained from the experiment can be accepted as normal and stable.

Table 2: ANOVA (R-square and P-value) of the composite impact response.

Response	R-square	P-value
P_{max}	0.97	0.000
δ_{max}	0.08	0.596
E_{max}	0.86	0.007
E_{tot}	0.81	0.015
DI	0.14	0.466

As can be seen in Fig. 6a, P_{max} for composites fabricated by the compression moulding method is much better than the vacuum bagging method. The P_{max} is found to have increased by about 97% compared to P_{max} of the vacuum bagging composite. On the other hand, the effect on δ_{max} is found not to be significant, as proved by the ANOVA result in Table 2. The results in Fig. 6b show that the value for E_i and E_t has improved for composites fabricated by the compression moulding method. A difference of about 71% can be distinguished for E_i, whereas a 52% improvement is obtained for E_t. In contrast, DI is seen to have no significant effect in either fabrication method (P-value > 0.05). The toughness of the materials determines the amount of energy that can be absorbed (David *et al*., 2009). The toughness of the CM composite proved able to resist a higher impact load and absorb more impact energy.

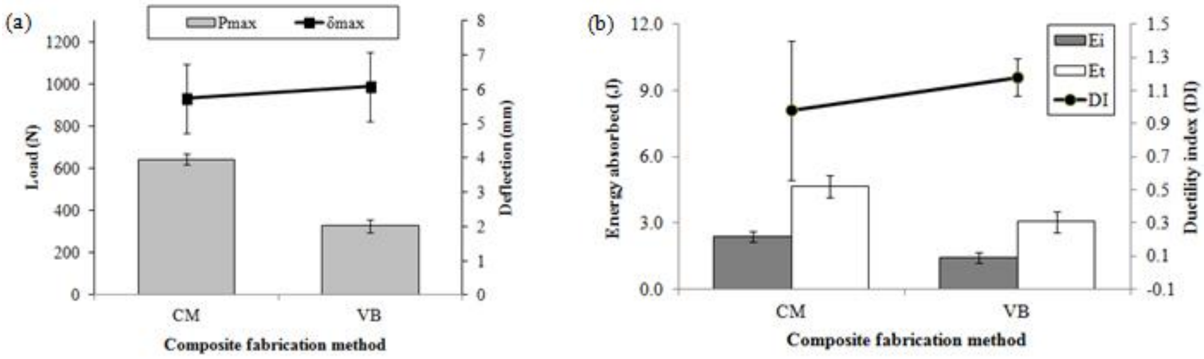

Fig. 6: Impact response of both fabrication method: (a) maximum load and deflection at maximum load; (b) energy absorbed at maximum, total energy absorbed and ductility index.

Damage analysis and fracture morphology:

Table 3 represents the fracture area and perimeter of the composite samples measured by an image processing technique. ANOVA results confirm that there is no significant difference in the fracture area and perimeter for the two fabrication methods, as the P-values are greater than 0.05.

Table 3: Fracture area and perimeter of composites.

Fabrication method	Fracture area (mm^2)		Fracture perimeter (mm)	
	Front surface	Rear surface	Front surface	Rear surface
Compression moulding	6.21 ± 1.73	6.55 ± 1.78	1.60 ± 0.20	1.61 ± 0.58
Vacuum bagging	4.37 ± 1.25	4.76 ± 1.19	2.19 ± 0.48	4.36 ± 2.04

Fig. 7 represents the scanned image of the fractured composite structures. It can be seen that the damage extends to a wider area in weft direction. This is expected to be due to the imbalanced number of yarns in the warp and weft directions. More yarns in the weft direction help to prevent the crack from propagating to a larger area in the warp direction. Lim *et al*. (2012), explains that damage can be minimized by optimizing the weave density. The direction with higher density contributes to better impact resistance, as indicated by the smaller damage length. Low density favours crack growth during impact loading, and so results in a bigger damage length. The composite manufactured by the VB process is found to result in markedly higher fibre content. It is agreed that different methods of sample preparation can cause a difference in fibre concentrations. As in the VB process, the vacuum pressure concentrated the laminate and reduced the matrix content. However, fibre content does not necessarily lead to higher impact performance, as the matrix composition and the bond between fibres and matrix also govern the composite properties (Behr *et al*., 2000). A better way to observe and explain the fibre-matrix adhesion and failure mechanism is through SEM observation.

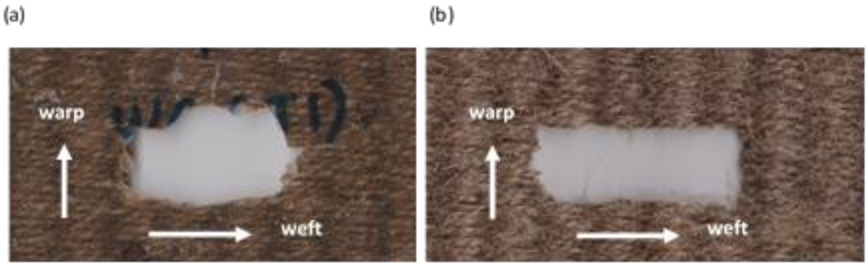

Fig. 7: Scanned image of fractured composite structure: (a) CM; (b) VB.

SEM images of the top surfaces and fracture area are displayed in Fig. 8. It is clearly observed from Fig. 8a that the CM composite samples exhibit better fibre-matrix adhesion, as the matrix is seen covering the fibres. The fibre surface is cleaner in Fig. 8b, indicating worse adhesion between the coir fibre and epoxy resin. Findings from the image explain why composites with higher fibre content are not mechanically better, as impregnation of the fibres with matrix polymer plays an important factor. It is agreed that by improving the adhesion characteristic, the surface tension and surface roughness increase, resulting in the improvement in mechanical properties (Wan *et al*., 2000; Faruk *et al*., 2012). Compaction of the fabric laminate plies in the composite triggered the consolidation phase of the fabrication process. Besides improving the adhesion characteristics, compaction causes a reduction of the voids between the individual plies, resulting in superior mechanical behaviour.

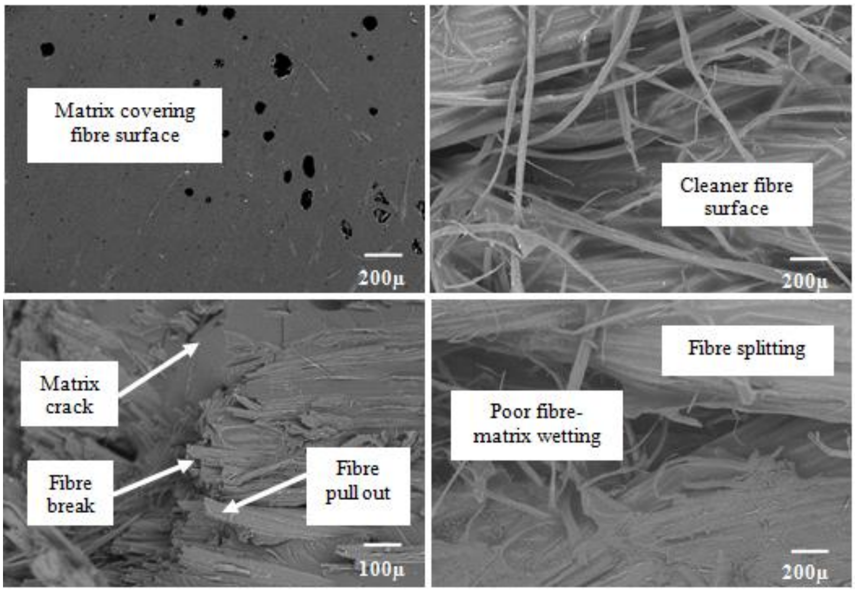

Fig. 8: SEM images of: (a) top surface of CM; (b) top surface of VB; (c) fracture area of CM; (d) fracture area of VB.

The predominant failure mode of the CM composite is found to be due to fibre breakage, matrix cracking and fibre pull-out, as illustrated in Fig. 8c. Both the matrix and the reinforcement act to resist impact, dissipate the impact energy and delay perforation fractures as they have good bonding performance. The impact energy was also dissipated via the fractures and debonding of the reinforcement. Hence, bigger fractures contribute to better energy absorption. The method of resisting impact and dissipating energy shows the contrary in the VB composite samples. Substantial fibre splitting (fibrillation) is observed in Fig. 8d, which indicates poor wetting between the fibres and the matrix. The existence of higher fibre content is seen in the VB composites. The fibrillation is also apparent due to severe contact pressure between the fibre plies. This phenomenon can reduce the strength of the composite sample. With high fibre content, when impact is applied to the composite, the impact energy is taken mainly by the fibre. A decrease in energy transfer from the fibre to the matrix will occur due to fibre agglomeration and an increase in fibre-to-fibre contact (Idicula *et al*., 2005).

Conclusions:

On the basis of the results obtained, the following conclusions can be drawn:

a) ANOVA analysis results proved that the fabrication method influences the maximum impact load, energy absorbed at the maximum impact load and the total energy absorbed.

b) Woven coir-epoxy composite fabricated by the compression moulding method was revealed to have higher maximum impact loads and better energy absorption.

c) Composites fabricated by the compression moulding method demonstrated better fibre-matrix adhesion, whereas composites fabricated by vacuum bagging showed higher fibre content in the composites and caused poor wetting.

d) The differences in the damaged area and perimeter on woven coir-epoxy composites under impact were found not to be significant between composites prepared by means of compression moulding and vacuum bagging.

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