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Influence of Laminated Textile Structures on Mechanical Performance of NF-Epoxy Composites

A. R. Azrin Hani, R. Ahmad, and M. Mariatti

Abstract**—**Textile structures are engineered and fabricated to meet worldwide structural applications. Nevertheless, research varying textile structure on natural fibre as composite reinforcement was found to be very limited. Most of the research is focusing on short fibre and random discontinuous orientation of the reinforcement structure. Realizing that natural fibre (NF) composite had been widely developed to be used as synthetic fibre composite replacement, this research attempted to examine the influence of woven and cross-ply laminated structure towards its mechanical performances. Laminated natural fibre composites were developed using hand lay-up and vacuum bagging technique. Impact and flexural strength were investigated as a function of fibre type (coir and kenaf) and reinforcement structure (imbalanced plain woven, 0°/90° cross-ply and +45°/-45° cross-ply). Multi-level full factorial design of experiment (DOE) and analysis of variance (ANOVA) was employed to impart data as to how fibre type and reinforcement structure parameters affect the mechanical properties of the composites. This systematic experimentation has led to determination of significant factors that predominant influences the impact and flexural properties of the textile composites. It was proven that both fibre type and reinforcement structure demonstrated significant difference results. Overall results indicated that coir composite and woven structure exhibited better impact and flexural strength. Yet, cross-ply composite structure demonstrated better fracture resistance.

Keywords**—**Cross-ply composite, Flexural strength, Impact strength, Textile natural fibre composite, Woven composite.

I. INTRODUCTION

TAKING into consideration the challenges of reducing petroleum-based products and wanting to find renewable solutions, more researchers are looking at the advances in natural fibres. Natural fibre composite material was found as an attractive alternative to replace synthetic composites with cost equivalence and improved properties. Previous literature reviews the advantages offered by natural fibres such as convenient renewability, natural abundance, biodegradability, environmentally friendliness, low self-weight, high strength, free formability, substantial resistance to corrosion and fatigue, good specific strength, high toughness, good thermal insulation, less abrasion and minimal dermal and respiratory irritation [1]-[3]. The United Nations General Assembly had announced 2009 as the International Year of Natural Fibres where the main objective was to raise awareness and stimulate demand for natural fibres. It has been seen that natural fibres promote to a healthy, responsible, sustainable, high-tech and fashionable choice [4].

Numerous researches had been conducted to investigate the natural fibre’s potential. They found natural fibres such as sisal, coir, jute, ramie, pineapple leaf, bamboo, and kenaf have the potential to be used as a replacement for glass or other traditional reinforcement materials in composites. Research done by Harish et al. [3] demonstrated that coir has high potential to be used as reinforcing materials for making low load bearing thermoplastic composites. Zampaloni et al. [5] reported that kenaf-maleated polypropylene composites manufactured in his study have a higher modulus/cost and higher specific modulus than sisal, coir and even glass fibre. Wambua et al. [6] on the other hand, had made a study on different types of natural fibers (sisal, kenaf, hemp, jute, and coir) reinforced polypropylene composites by compression moulding method. The results displayed a comparable tensile strength and modulus between kenaf, hemp, and sisal. Nevertheless, the impact properties of hemp were better than kenaf. With the increment in fibre weight fraction, the tensile modulus, impact strength and the ultimate tensile stress of kenaf reinforced polypropylene composites were found to increase. Coir fibre composites were found to have better impact strength than of jute and kenaf although it produces lower mechanical properties. According to Wambua et al. [7], flax composites demonstrated better energy absorption than hemp and jute composites. Generally the specific properties of the natural fibre composites were found to compare favorably with those of glass. More research findings on the properties of natural fibres could be retrieved from previous works [8]-[11]. Summerscales et al. [12], [13] had carried out an extensive review on bast fibres from its plant origin till the properties of its composites. Collections of research work done specifically on kenaf fibre composites had been compiled rigorously in a review paper by Akil et al. [14]. They concluded that it is highly reasonable for the application of kenaf fibre reinforced composite as an alternative composite material, particularly in building and construction with both lightweight and low cost as its primary strength.

Textile composites have demonstrated exceptional mechanical properties for the production of high specific-strength products [15]. It was utilized extensively in commercial applications including products for energy

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absorption, automotive, aerospace, and defence research as well as agricultural products. Textile composite structure can be explained as the combination of a resin system with a textile fibre, yarn or fabric system as reinforcement. Fabric system can be clustered as woven, knitted, braided and non-woven fabric. Among all the fabric type, woven and cross-ply non-woven laminated structure were found to be used extensively in composites. Woven is a continuous reinforcement which leads to supreme characteristic such as higher intra- and interlaminar strength and damage resistance. Cross-ply non-woven in contrast comprises of fibres or yarns arranged in a certain degree of orientation. This kind of structure also offers better uniformity. A number of studies varying fabric structures and angle ply laminates were conducted in determining the damage resistance and tolerance of composites [16]–[18]. Research done by Kushwaha and Kumar [19] agreed that the properties was enhanced in the woven glass mat reinforced hybrid composites compared to the strand mat. Dorey et al. [16] pointed out that unidirectional (UD) composite structure was better than woven structure in terms of static mechanical properties. Moreover, Karahan [17] reported that UD nonwoven was 16% lighter in weight and more flexible compared to woven for the same number of ply. It was also found that UD contributed to better impact energy absorption and improved ballistic energy propagation compare to woven structure. Kim and Sham [18] from their research findings explained that a lower maximum load with smaller damage area, higher ductility index and higher residual compression after impact was exhibited by woven fabric laminates over cross-ply laminates. Othman and Hassan [20] added that better ballistic performance in terms of higher energy dissipation and minimum layer of projectile arrest upon impact was found on cross-ply laminated aramids over woven aramids.

Documented research concerning the effects of textile reinforcement structure only focuses on synthetic types of materials. There are no data collected on natural fibre composites although research on natural fibre is getting so much attention. Realizing the potential of varying fabric reinforcement structure, this paper aims to investigate the effects of different reinforcement structure particularly imbalanced woven, 0/90 degree cross-ply and +45/-45 degree cross-ply in two different types of natural fibre which are coconut coir and kenaf. The impact strength and flexural strength of woven and cross-ply coir and kenaf composite were evaluated.

II. EXPERIMENTAL PROCEDURE

A. Experimental Design

Factorial design was seen as one of the most effective ways for experiments which involve study of the effects of two or more factors [21]. This method is one of the powerful designs of experiments (DOE) which provides an efficient and systematic approach. Factorial design will includes all possible experimental runs. Therefore, misleading conclusions could be avoided. Factors or parameters of study need to be identified at the first place, followed by the selection of levels at which each factor will be examined [22]. Reviews on previous related works revealed a number of factors that would influence the mechanical properties of fibre based textile reinforced composites. This research works have focused on two factors which are yarn type and fabric structure. Levels for each factor were decided based on manufacturing capability and competence. Two levels were chosen for yarn type whereas three levels were picked for fabric structure. Therefore, factorial with mixed levels or multi-level experimental design was employed. In this research, Minitab R.14 software was used. Randomization was activated in order to reduce the possibility of nuisance factors affecting the experiment.

B. Materials

Coir and kenaf yarns were used as received from BTex Engineering Ltd., India and Juteko Co. Ltd., Bangladesh respectively. The density of coir and kenaf fibre as reported in previous literature were 1.15g/cm^3 and 1.4g/cm^3 [14]. Coir yarns were twisted as 2-ply spun in S direction whereas kenaf yarns were twisted as single ply spun in Z direction. Yarn fineness value was recorded as 616 Tex for coir and 764 Tex for kenaf yarn. The matrix used was epoxy DEN 431 of density 1.21g/ml cured with 32% Jeffamine D-230 hardener of density 0.948g/ml supplied by Penchem Technologies Sdn. Bhd.

C. Fabrication of Composites

Imbalanced plain woven and cross-ply (0°/90° and 45°/-45°) structure were prepared in this research. Woven were produced using self-designed handloom. The fabricated woven coir samples indicated 3 numbers of yarns per inch in vertical (y) direction, whereas in horizontal (x) direction showed 35 yarns per inch on average. Technically, warp and weft set of the woven coir structure was 3epi (ends per inch) and 35ppi (picks per inch). In contrast, the made-up woven kenaf was having warp and weft set of 3epi and 27ppi. On the other hand, cross-ply structure was constructed by manual winding on a wooden jig frame. On average, the fabric density for 0/90 degrees cross-ply was recorded as around 17 to 20 yarns per inch, whereas for 45/-45 degrees, it shows 14 to 16 yarns per inch for both yarn types on each direction. Schematic of the fabric structures were generated using open source textile modelling software, TexGen as depicted in Fig. 1. Manufacturing of structural composite samples involved hand lay-up and vacuum bagging technique. The laminated comprised of single ply for woven structure whereas 2-ply unidirectional was used for 0/90 and 45/-45 degrees cross-ply structure. Samples were left for overnight cured and post-cured for another 6h in the oven at 80°C.

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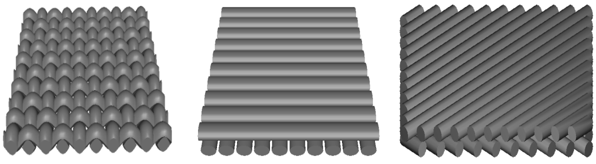
(a) (b) (c)

Fig. 1 Dry fabric structures (a) plain woven, (b) cross-ply 0°/90° (c) cross-ply 45°/-45°

D. Testing and Characterizations of Composite

Shimadzu Hydroshot Impact Test Machine was used to perform high speed impact puncture test. It was performed in accordance with ASTM D3763. The geometry of the specimens was 100mm x 100mm x 3mm. At least three replicate tests for each different composite type were carried out and the average values later reported. The striker punch speed of 10m/s at ambient temperature was set up and testing specimens were positioned horizontally in the testing cassette of the machine. The machine data processing software generated impact energy value in Joule [J] at maximum load applied. The results were then being converted to impact strength value in joule per meter square [J/m^2] by using (1)

$$\sigma_{impact} = \frac{E_{\max}}{\pi d^2 / 4} \tag{1}$$

where σ_{impact} is impact strength, $E_{\max}$ is the energy value at maximum force, and *d* is the striker diameter at a value of 12.7mm.

The flexural property is especially important because flexural loading induces a complex stress combination in the beam, consisting of tensile, compressive, and shear stresses [23]. Flexural analysis was carried out at room temperature as specified in ASTM D 790-86 using Instron 3367 Universal Testing Machine. The speed of the crosshead was 2mm/min and the span length was 50mm. The specimens were having dimensions of 120mm length, 12mm width, and 3mm of thickness. Five replicates were made for each composite type. Flexure load-extension and stress-strain curve were automatically generated by the machine's software and flexural strength was calculated using (2)

$$\sigma_f = \frac{3PL}{2bd^2} \tag{2}$$

where, *P* = peak load at a given point on the load-deflection curve (N), *L* =support span (mm), *b* =width of samples (mm), *d* = thickness of the samples (mm).

The morphological study on fractured composite surfaces was observed using field emission scanning electron microscope (SEM) performed with Hitachi Tabletop Microscope TM-1000. Samples were cut into 10mm x 10mm and no coating was applied to the samples.

III. RESULTS AND DISCUSSIONS

This experiment would be referred to as 2^1 x 3^1 multilevel full factorial design. These variables (factors) are shown in Table I with their corresponding test levels. All possible variable combinations, samples identification and composite samples density of these combinations are illustrated in Table II.

TABLE I
FACTORS AND FACTOR'S LEVELS OF 2^1 X 3^1 MULTILEVEL FACTORIAL

Factor	Low level	Medium level	High level
Yarn type	Coir	-	Kenaf
Fabric structure	Woven	Cross-ply 0°/90°	Cross-ply 45°/-45°

TABLE II
IDENTIFICATION AND DENSITY OF COMPOSITE SAMPLES

Composite type	Identification	Composite density (g/cm^3)
Woven coir	WC	0.89
Woven kenaf	WK	0.84
Cross-ply coir 0°/90°	CPC 90	0.69
Cross-ply coir 45°/-45°	CPC 45	0.82
Cross-ply kenaf 0°/90°	CPK 90	0.71
Cross-ply kenaf 45°/-45°	CPK 45	0.75

A. Impact Properties

Normal probability plot of the residuals for impact strength demonstrated a lower degree of variability in the experimental data distributions for impact test samples. It shows a high R^2 value of 0.950, therefore data obtained from the experiment can be concluded as a very stable data (Fig. 2). Points that do not fit the line well usually signal active effects. Active effects are larger and further from the fitted line. Inactive effects tend to be smaller and centred around zero, the mean of all effects. Analysis of variance (Table III) reported that all mean values for each group is significantly different (P-value<0.05). A big value of F with a small P-value (less than 0.05) means that the null hypothesis is discredited. Null hypothesis here is that the group means are equal. It is proven that each variable gives significant effects towards impact strength performance of the composites.

Interaction plot for impact strength results of coir and kenaf with different fabric structure was built up as shown in Fig. 3. It shows that coir composites tremendously outperform kenaf composites for woven structure. Nevertheless, kenaf composites for 0/90 degrees cross-ply showed better impact strength performance compare to coir composites of similar structure.

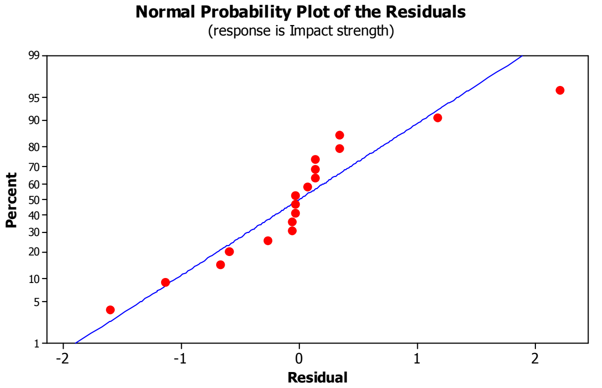

Fig. 2 Normal plot of residuals for impact strength achieved by all samples

TABLE III
ANOVA FOR IMPACT STRENGTH OF ALL SAMPLES

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Type of yarn	1	5.894	5.894	5.894	6.31	0.027
Fabric structure	2	155.568	155.568	77.784	83.24	0.000
Type of yarn*Fabric structure	2	53.121	53.121	26.561	28.42	0.000
Error	12	11.213	11.213	0.934		
Total	17	225.796				

Where DF: degree of freedom, SS: sum of squares, MS: mean square, F: F-test and P: P-value.

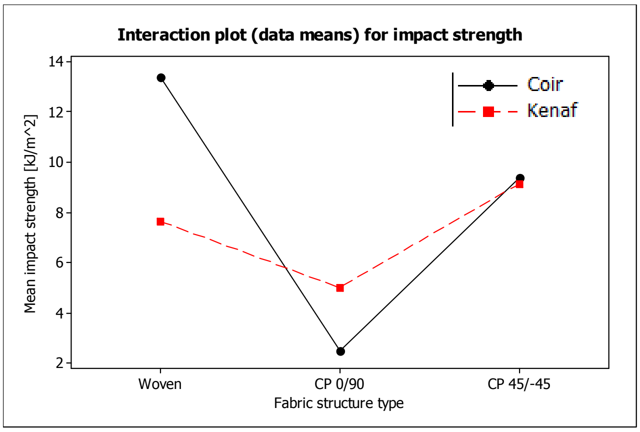

Fig. 3 Interaction plot for impact strength of different fabric structure for coir and kenaf

Moreover, CP 45/-45 degrees structure exhibits almost the same impact strength for both composite types. Specifically referring to coir composites, woven structure exhibit the best impact strength followed by CP 45/-45 and CP 0/90 degrees. On the other hand, kenaf composites for CP 45/-45 structure revealed to be the best structure followed by woven kenaf composites, whereas CP 0/90 showed the least impact strength value.

Previous investigations on composites with various ply orientation done by Dorey et al. [16] found that 45°/-45° ply orientation of carbon/Kevlar 49 hybrid composites offered a superior impact resistance and improved residual strengths. A 45°/-45° ply orientation was suggested to increase the flexibility of the composite, thereby improving its ability to absorb energy elastically. Moreover, this ply orientation serves to protect the load-bearing 0° against damage induced by the impinging projectile [16]. Moreover, in another research conducted by Stevanovic et al. as reported in Cantwell and Morton [24] using instrumented Charpy tests on a series of multidirectional T300 carbon fibre composites, they showed that 45°/-45° composites were capable of absorbing considerably more energy than other ply orientation laminate. Mcdaniels et al. [25] had explained in detail about the crimp effects suffered by woven fabrics. Tensile loading of woven fabrics induces transverse loads at fibre overlap sections as crimped fibres attempt to straighten. This reduces the translation of fibre strength to fabric strength and decreases long-term fatigue and creep rupture performance. However, these kinds of crimp effects depend on the strength and elasticity of fibre/yarn. Although woven fabrics offer better structural integrity, ballistic grade fibre for non-interlaced fabric structure had proven to give better energy absorption under ballistic impact [26].

Results for both yarn types in this research show dissimilarity of impact strength performance for woven structure. As mentioned in previous findings, the materials used were among the ballistic grade fibres that have high elasticity and tensile strength and modulus compare to coir and kenaf natural fibre. Therefore, fibre failure mode was expected to be different. A better way to explain the composites failure mechanism was through SEM observation in section III.*C*. On the other hand, lower fabric density (warp and weft set) of fabricated woven kenaf composite due to its higher yarn Tex value might be the reason why its performance shows contrast with coir composite. This condition might decrease its structural integrity whilst decreasing its tensile modulus and strength [27].

B. Flexural Properties

Fig. 4 illustrates the normal probability plot of the residuals for flexural strength. R^2 value shows 0.937 which indicated low degree of variability of data obtained. Hence, the data distributions were stable. Based on analysis of variance (Table IV) for flexural strength, null hypothesis can be discredited. It means that mean values for each group is significantly different with P-value of less than 0.05. The interactions between each variable; yarn types, fabric structure as well as interaction between yarn type–fabric structures give a significant effect towards the flexural strength performance.

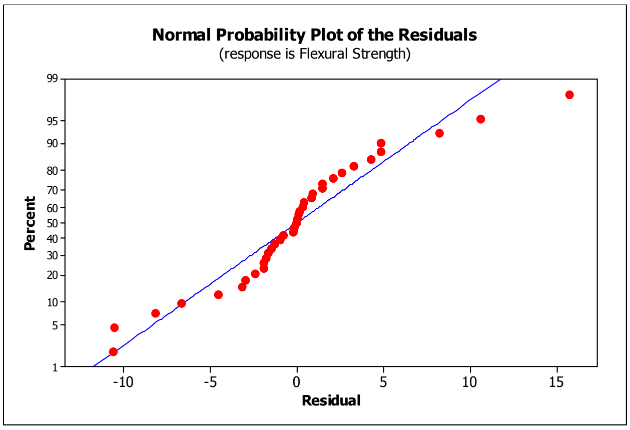

Fig. 4 Normal plot of residuals for flexural strength achieved by all samples

TABLE IV
ANOVA FOR FLEXURAL STRENGTH OF ALL SAMPLES

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Type of yarn	1	313.7	320.1	320.1	10.10	0.004
Fabric structure	3	12607.4	12581.7	4193.9	132.32	0.000
Type of yarn*Fabric structure	3	719.6	719.6	239.9	7.57	0.001
Error	29	919.1	919.1	31.7		
Total	36	14559.8				

Where DF: degree of freedom, SS: sum of squares, MS: mean square, F: F-test and P: P-value.

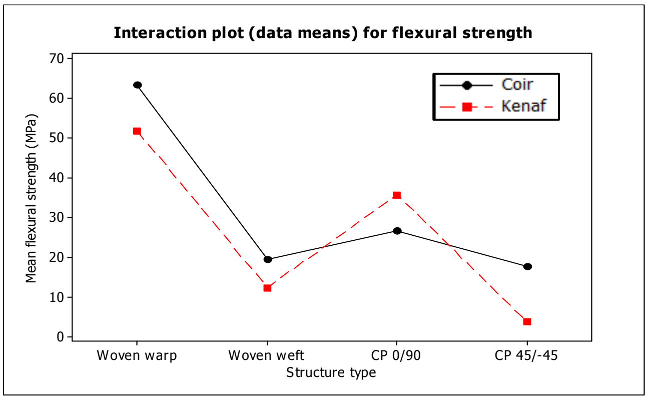

Fig. 5 Interaction plot for flexural strength of different fabric structure for coir and kenaf

Meanwhile, interaction plot of flexural strength results of coir and kenaf with different fabric structure was displayed in Fig. 5. The results exhibited coir composites to have higher effects on flexural strength performance compare to kenaf composites for almost all structures except for CP 0°/90°. In terms of fabric structure, both yarn types demonstrated same trend of flexural strength whereby woven warp demonstrated the highest, followed by CP 0°/90°, woven weft and finally CP 45°/-45°.

During flexural test, composites faced compressive and tensile fracture. Compressive mode was on the surface layer while the tensile mode on the bottom layer. The change of fracture mode can have an effect on the flexural strength and modulus of composites. The flexural strength also depends on the composites material rigidity and the maximum stress at the compressive layer [23]. Variation of flexural strength generated from the results was associated with its changes in damage mechanism [28]. Coir composite was found to encompass higher maximum stress but being more brittle compared to kenaf composite. Woven coir composite was expected to exhibit better flexural strength due to its higher fabric density. It contained higher aligned fibres which produced higher resistance to compressive stress at the compressive layer. For woven specimens tested, the main failure process occurs in compression whereas fibres submitted to tensile stress did not break. Nevertheless, for both cross-ply structures for each yarn, the primary failure induced on the tensile layer due to delamination. Delamination failure may cause severe reduction in in-plane strength and stiffness, leading to catastrophic failure of the whole structure [18].

The orientation of yarns in fabric also resulted in the difference of flexural strength value. In a single layer warp woven composites, there are more yarns that can support the compressive and tensile stress induced during the flexural test, whereas in weft woven composite sample, the flexural load was applied in between weft yarns where only a single warp yarns support the load in the transverse direction to the load cell. On the other hand, 0/90 degrees composites displayed better flexural strength resistance compare to woven weft and 45/-45 degree composite structure due to the bigger number of long yarns that could bear the load in the transverse direction of the load cell applied. 45/-45 degrees composites could not withstand higher bending stress as it samples consists of short yarns. Short yarns in composite limit their tensile stress dispersion. Therefore, as the tensile stress try to propagate upwards, inter-ply delamination failure occurred thus reduces its flexural strength [18], [29].

C. Composite Failure Analysis

Impact fracture modes for coir and kenaf composites for all structures were investigated. The crack size was measured and depicted in Fig. 6. Damage on woven coir and kenaf composite were found to be uneven. In both samples, damage extends to a wider area in weft direction. It is expected due to an imbalance number of yarns in both warp and weft directions. Direction with higher density contributed to better impact resistance, hence indicated by smaller damage length. Low density favoured crack growth during impact loading, therefore resulted in a bigger damage length. Damage of woven coir sample was observed as a combination of matrix crack and fibre breakage (Fig. 7) whereas fibre breakage was the most substantial failure observed on woven kenaf sample besides matrix crack (Fig. 8). Woven coir sample has a clean crack hole and the perforation failure mode was hardly observed as compared to woven kenaf sample with half broken clusters remained. Woven coir composite sample was found to be more brittle than the woven kenaf sample. Fibre-matrix bonding of coir composite was considerably good as matrix debris was seen covering the fibres. However, poor interfacial bonding of fibre-matrix was detected on kenaf composite as fibres were not adequately covered by matrix. This is expected to be the main reason of poor impact and flexural strength of kenaf composite as compared to coir composite.

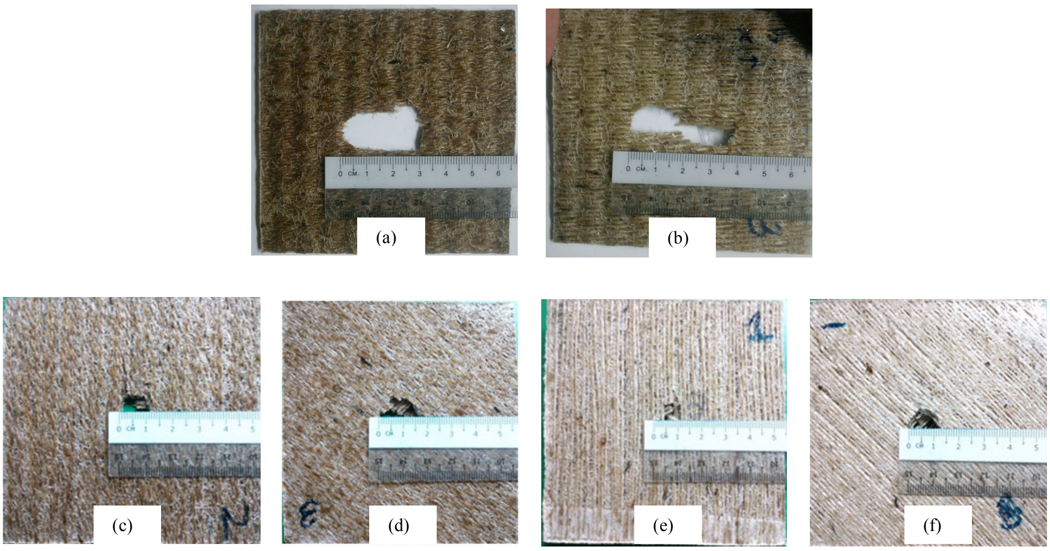

Fig. 6 Composite fracture image after impact test; (a) WC, (b) WK, (c) CPC 90, (d) CPC 45, (e) CPK 90 and (f) CPK 45

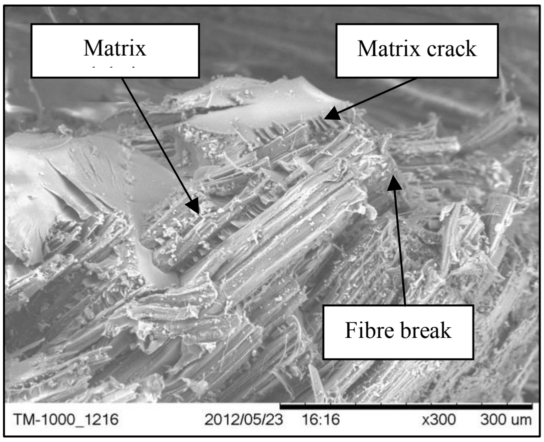

Fig. 7 SEM image of woven coir composite fractured sample

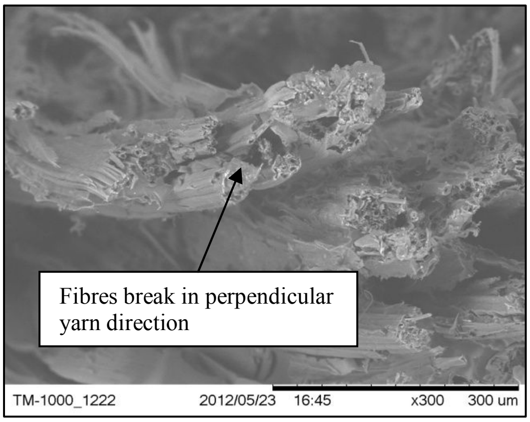

Fig. 8 SEM image of woven kenaf composite fractured sample

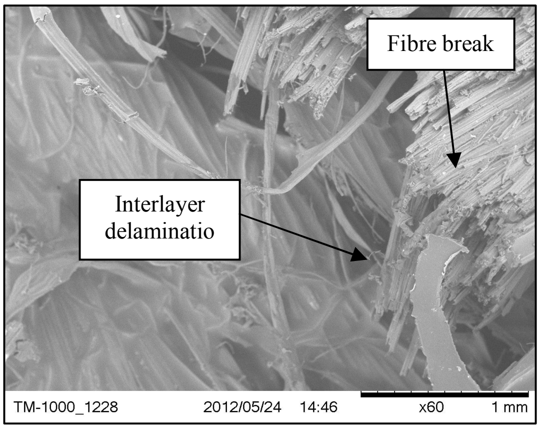

Fig. 9 SEM image of cross-ply composite fractured sample

As for cross-ply composite structure, it revealed a better fracture size compare to woven composite structure (Fig. 6). Woven was expected to have higher fracture size due to the intermingled yarns in the warp and weft direction. This intersection of fibres creates energy roadblocks resulted in reducing the rate at which energy can be dissipated [26]. However, poor interfacial bonding of cross-ply structure (Fig. 9) makes it very weak and fragile structure which decreases its ability to resist impact and flexural strength as reported in the previous section. Kenaf cross-ply (Fig. 6 (e) and (f)) shows a slightly better fracture resistance than coir cross-ply (Fig. 6 (c) and (d)) since the area of crack propagation is smaller. In comparing between the ply orientations, CP 0/90° shows the best fracture resistance although the impact strength is higher for orientation +45°/-45°. This could be due to the number of yarns that hit by the impactor probe is higher in orientation +45°/-45° than in 0/90° orientation. As a result, the stress is dispersed in a greater area which initiates the crack propagation and thus a bigger fracture area occurred. All the cross-ply laminated composite structure however suffered delamination. Yarns on top and bottom surface were badly split especially on the impacted area. Poor fibre-matrix bonding triggered this issue. This is also another reason contributed to low impact and flexural resistance.

IV. CONCLUSIONS

Based on the results obtained, the following conclusions can be drawn:

1) ANOVA analysis results had proven that yarn types and fabric structures gives significant effects towards the performance of impact and flexural properties.
2) Coir composites were mostly demonstrated better impact and flexural strength compared to kenaf composite.
3) Woven structure exhibited greater impact and flexural strength performance compare to cross-ply 0°/90° and cross-ply 45°/-45°.
4) Impact and flexural strength of kenaf cross-ply 0°/90° were found to outperform coir cross-ply 0°/90° composite.
5) Bigger fracture size was observed on woven composite structure, whereas cross-ply composite structure revealed to have better fracture resistance.
6) Poor fibre-matrix bonding was found on kenaf composite structure. Therefore, appropriate fibre treatment prior further processing or change of composite manufacturing method was recommended to improve its performance.

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