Advance Research in Textile Engineering

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Research Article

Fabric Parameter Effect on the Mechanical Properties of Woven Hemp Fabric Reinforced Composites as an Alternative to Wood Products

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Received: September 05, 2016; **Accepted:** October 25, 2016; **Published:** October 28, 2016

Abstract

Hemp is a common natural fibre which has reliable properties and is available in the forms of staple fibres, yarns and fabrics. However, less works were done by using woven hemp fabric in composite materials, especially for an alternative to wood products. In this work, woven hemp fabrics in different fabric layering orientations have been used to reinforce vinyl ester resin by employing hand lay-up method. The properties of hemp fabric were used to investigate how these properties can affect the physical and mechanical behaviour of the fabricated composites. The results show that fabric properties and layering orientations contribute to the tensile, flexural and impact properties of the composites. Based on the comparison to wood and engineered wood products' properties, the mechanical properties of composites are found to be comparable. The comparison also shows that the woven hemp fabric reinforced vinyl ester can be an alternative for wood and engineered wood products in building industries especially in low-load bearing applications.

Keywords: Natural fibres composites; Hemp; Woven fabric; Mechanical properties; Wood products

Introduction

One of the big issues related to the environment is the uncontrolled and illegal timber logging and it has become more serious lately [1,2]. While in the building industry, it is reported by [3], United States Environmental Protection Agency (EPA) stated that 70.6 million tons of waste wood which is categorised as Municipal Solid Waste (MSW) and Construction and Demolition (C&D) debris were disposed in landfill in 2010. The waste woods is made up of softwood and hardwood which are used as building materials, furniture, pallets, container and crating, and a wide-range of consumer goods. Both issues, either the waste wood debris dumping in landfill or uncontrolled and illegal wood logging, are directly and/or indirectly giving an impact to the environment.

Thus, something needs to be done to solve or at least lessen the impact consequent upon the issues mentioned above. Bio-based composites have existed for quite sometimes and apparently the suitable nominee to be used in building industry since its current application is mainly for non-load bearing in many fields, especially in the automotive and building industries [4-8]. Bio-based materials have attracted considerable interest due to the worldwide awareness on the environmental issues such addressed as above [9-11]. The utilisation of natural fibre from plant in bio-based composites has led to the better environment and developing a more sustainable material cycle due to its lower price, global availability and complete data on its properties[7,8].

The main problem in utilising natural fibres is controlling over the fibre orientation and distribution thus the optimum mechanical properties are not efficiently utilised as reinforcement [12,13]. The availability and advancement in textile engineering as well as technology provide wide range of techniques to convert the natural fibres into yarn and then into fabric [14]. Utilisation of fibre in the form of textile fabric is more convenient considering their advantages on high strength, good fibre orientation and fibre distribution and more importantly easy to handle during composite fabrication [11,15]. Not all natural fibres can be converted into the woven fabric such as bagasse, kapok and kenaf. Only few fibres such as jute and hemp were long established in woven fabric and they possess good properties as reinforcement in composite materials [11,16].

Christian and Billington [17] asserted that utilization of hemp composites can be used as an alternative material to replace some wood and engineered wood products. This can be achieved by taking advantages of hemp fibre in the form of fabric [18] utilised woven hemp fabric in their study by comparing two different kinds of weave structure (plain and twill structures) fabric to reinforce Poly Lactic Acid (PLA) resin. They found that the composite made of twill fabric has a better result than plain weave fabric in terms of mechanical, thermal and viscoelastic properties. However, both studies did not discuss in details on the attributes of fabric parameters in their works such as fabric density, yarn size, yarn crimp in fabric and fabric strength that might affect to their composite properties. Both studies only considered the fibre volume fraction and how this fibre fraction affects the mechanical properties of the composite in their works. In detail, Christian and Billington [17] mentioned about the yarn crimp. Nevertheless, there are no specific figures on the fabric yarn crimp. This is similar with the study of Song et al. [18] study, their idea to investigate the viscoelastic and thermal behaviour of the hemp fibre composite was good but they did not explain more on the yarn crimp role.

Citation: Misnon IM, Islam MM, Epaarachchi JA, Lau K-T and Wang H. Fabric Parameter Effect on the Mechanical Properties of Woven Hemp Fabric Reinforced Composites as an Alternative to Wood Products. Adv Res Text Eng. 2016; 1(1): 1004.

The properties of fabric are mainly dependent on how the fabric is designed [11,15] physically and mechanically, and these are the fabric density, yarn size, yarn crimp in fabric and fabric strength. These fabric properties will affect the behaviour of the fabricated composites. In the case of natural woven hemp fabric, less work is done on their utilization as a reinforcement material. Apart from the issues on considering woven hemp fabric properties above, less work was done on this woven hemp fabric composite, especially on the effect of different fabric stacking sequences in relation to its fabric properties.

Therefore, in this work, woven hemp fabric was used to fabricate bio-based composites employing hand lay-up method. The composites were fabricated in different fabric layer orientations in order to investigate the stacking sequence effect on the mechanical properties. The properties of fabric were determined and measured in order to study how these fabric parameters affect the physical properties and mechanical behaviour of composite fabricated. Some comparison to wood and engineered wood products was also done to see the suitability and readiness of woven hemp fabric reinforced vinyl ester to be used in building industry.

Materials and Methods

A commercial woven hemp fabric, with the product code, FSA10 was supplied by Hemp Wholesale Australia. According to the specifications given by the supplier, the fabrics were produced by 100% yarn hemp in both warp and weft. The yarns were converted from cleaned hemp fibre into yarn through spinning processes and the twist given was 430 twists per meter before it was woven into fabric in plain weave (taffeta) structure. Other than that, the supplier did not give much data. Therefore, further investigation was needed in order to characterize and renew the data of the hemp fabrics. Vinyl ester resin product code of SPV 1356 PROM THIX and the catalyst Methyl Ethyl Ketone Peroxide (MEKP), product code of NOROX 925H were supplied by Nuplex® Composite Industry (Australia).

Characterization of woven hemp fabric

Woven hemp fabric had been characterised employing several textile materials standard methods. These standard methods are commonly used in textile industry for characterization as well as product quality determination purposes. All the tests were performed under standard atmosphere, 21 ± 1°C and 65 ±2 % relative humidity and the fabric was opened from the roll to relax for 24 hours. Woven hemp fabrics are characterised for their thickness and fabric density or fabric count while their yarn was characterised for its yarn size and crimp (for warp and weft).

'Fabric thickness' was measured according to ASTM: D1777. Twenty (20) randomly selected locations were used to obtain the average value in order to make sure the precision. The thickness values were taken in millimetre (mm).ASTM: D3775 standard method was employed to determine 'fabric density' or 'fabric count'. Woven hemp fabric was placed on a smooth surface and the number of warp and filling yarns were counted using a pick counter in a 2 cm length.

Yarn linear density was measured in accordance to ASTM: D1907. Yarn was unravelled from the fabric and then cut to 1 m length before it was weighed using a weighing balance. Ten specimens were measured and the average weight, w, in grams, was used for calculating the yarn linear density using Equation. (1).

$$\text{Yarn size}(tex), N = \frac{w \times k}{l} \quad (1)$$

Where l is the length of yarn in meter and k is the constant which equals 1000 m/g for tex.

ASTM: D3883 was used to measure yarn crimp. Parallel lines were marked in the warp direction 20 cm apart (this is the distance of the yarn in the fabric, Y_1 = 20 cm). A cut of 30 cm was made along the filling yarn, which crossed the parallel lines. Several yarns from one edge were unravelled. The next ten (10) yarns were carefully unravelled for measurement. Each yarn was pulled taut without exerting extreme force and the extended length between the two marks was measured as Y_2. The yarn crimp, C, is calculated as shown below in Equation. (2).

$$\text{Yarn crimp}(\%), C = \frac{Y_2 - Y_1}{Y_1} \times 100 \quad (2)$$

The density of the hemp fibres was determined by Multipycnometer MVP D160E. Helium gas was used as a displacement medium. The helium was added to the fibres under vacuum conditions to ensure that all interior air cavities in the submerged fibres (e.g. the fibre lumen) were filled with helium. The data reported are the average and standard deviation of 3 measurements.

The aerial density or fabric weight, W, can be measured precisely using Equation. (3) [19,20].

$$\text{Fabric weight}\left(g/m^2\right), W = \frac{N_1(1+C_1)}{P_1} + \frac{N_2(1+C_2)}{P_2} \quad (3)$$

Where N is the yarn size calculated from Equation. (1), C is the yarn crimp percentage calculated from Equation. (2) while subscripts 1 and 2 refer to warp and weft yarn respectively. P is the yarn spacing in mm which can be calculated from Equation. (4) [20].

$$\text{Yarn spacing}(mm), P_n = \frac{t}{d} \quad (4)$$

Where subscript n = 1 or 2 which refer to warp or weft yarn, t is the constant value of length for certain fabric density which is equal to 20 mm and d is the respective fabric density.

Total fabric cover factor (K) was measured using Equation. (5) and this K value is the ratio on how big the area is covered by the yarns [20].

$$\text{Total fabric cover}, K = C_1 + C_2 - C_1C_2 \quad (5)$$

Where subscripts 1 and 2 are referring to warp and weft yarn respectively and C is the fractional yarn cover which can be calculated from Equation. (6) [20].

$$\text{Fractional yarns cover}, C_n = s \times \sqrt{(N_n / f_d)} \times d_n \times 10^{-3} \quad (6)$$

Where subscript n = 1 or 2 which refer to warp or weft yarn, s is the constant which is equal to 4.44, N is the yarn size calculated from Equation. (1), f_d is the fibre density and d is the respective fibre density.

In term of mechanical properties, tensile properties of hemp fabrics were characterized using universal testing machine MTS Alliance RT/10employing ASTM: D 5034 standard method. 75 mm wide test specimens were cut in the desired direction (warp or weft)

Table 1: List of fabricated composite samples and its abbreviation.

Sample Abbreviation	Layer Orientation
HVE[0]	$[0]_{10}$
HVE[90]	$[90]_{10}$
HVE[0,90]	$[0,90]_5$
HVE[S]	$[0/45/90/-45/0]_S$

*HVE is stand for hemp vinyl ester

and then equal numbers of yarns were removed from both sides until the specimen width was reduced to 50 mm. The same procedure was followed for test strips in both warp and weft directions. Tensile tests were performed using a gauge length of 75 mm and a crosshead speed 10 mm/min. The cross-sectional area used to convert load into stress was calculated from the test specimen width and the thickness of fabric obtained from the fabric characterization [19,21,22].

Fabrication method

Resin was prepared by adding MEKP into vinyl ester with the ratio of 1:44 by weight. This prepared resin was then applied on 10 fabric layers (300 × 300 mm for each layer) by employing hand lay-up technique. Trapped air was gently squeezed out using a roller after pouring the resin on the fabric. This mixture (wet fabrics) was then laid in between of thick glass plates (400 × 400 × 100 mm in dimension) which were coated with polymer mould release agent. This assembles was compressed with a weight placed on top of this mixture to remove the excess resin and the calculated pressure given to this assembly was 4.360 kPa. This mixture was then left for the cure under room temperature for 24 hours. It was afterward post cured in an oven for four hours at 80°C. Four (4) types of composites which differ in their layer orientations were fabricated as shown in Table 1. Since the layer orientations is main focus in this work, it should be mentioned that 0° direction is based on the warp direction of the woven hemp fabric.

Physical properties of the composites

The density of the fabricated composites was determined by Multipycnometer MVP D160E in accordance with ASTM: D792. Helium gas was used as a displacement medium. The helium was added to the fibres under vacuum conditions to ensure that all interior air cavities in the submerged fibres (e.g. the fibre lumen) were filled with helium. The data reported are the average and standard deviation of three measurements.

The constituent contents of fabricated composites (weight percentage and volume fraction) were determined according to ASTM: D3171 test method II. This test method II can be employed since the distribution of fibres in the fabric form (in this case hemp) is acceptably consistent. By the densities and weights of woven hemp fabric, vinyl ester and their fabricated composites are known; the reinforcement and matrix contents were calculated. The void content of composite was calculated using Equation. (7) in accordance to ASTM: D2734 as follows;

$$V_V = 100 - \rho_c\left(\frac{w_f}{\rho_f} + \frac{w_m}{\rho_m}\right) \qquad (7)$$

Where V_v is the volume fraction of voids, ρ_c the density of composite, w_f is the weight percent of fibre (%), w_m is the weight percent of matrix (%), ρ_f is the density of fibre g/cm^3 and ρ_m is the density of matrix g/cm^3.

Testing methods

Tensile and flexural tests were performed on a universal testing machine MTS Alliance RT/10. Tensile properties were characterised in accordance with ASTM: D638. Specimens with the dimension of 250 × 25 × 5 mm^3 were cut from the fabricated samples. The tensile load was applied at a constant displacement rate of 2 mm/min. Laser extensometer was used to measure the axial strain. Ten (10) specimens were tested from each sample and tensile modulus (modulus of elasticity) was measured from the initial slope for each specimen.

Flexural test was conducted according to ASTM: D790 (three-point bending) in order to determine the flexural properties of the composites. A three-point bending fixture with cylindrical support with 5 mm radius was mounted on the table-top tester. The span length, according to the standard should be fifteen times of the specimen's thickness (in this study was measured as 80 mm). The specimen dimension used for this test was 100 × 12 × 5 mm^3. The load was applied at a constant crosshead speed of 2 mm/min. Similar to tensile test, ten (10) specimens were tested for each sample. Specimens were monitored until fibre rupture occurred and at this point, the load was taken to calculate the flexural stress. Flexural modulus was calculated as the slope in the linear range of the stress vs. strain between points at a deflection just above zero.

Impact testing was conducted in accordance with ASTM: D256 by using INSTRON Dynatup model 8200 instrument. The weight used was 2.84 kg released from 1 m height at 2.9 m/s velocity. Specimens with the dimension of 5 × 20 × 140 mm^3 were cut and the impact test was performed with at least five composite specimens [23]. The information on the materials tested including total impact energy, load-time-energy characteristics and deflection at peak load were automatically measured and recorded from the Dynatup machine

Table 2: Physical and mechanical properties of woven hemp fabric.

Physical Properties		
Thickness (mm)		0.42
Fabric Density (yarn count/ per 2cm)	Warp	25
	Weft	23
Yarn Size (Tex)	Warp	90.46
	Weft	92.97
Yarn Crimp (%)	Warp	6.0
	Weft	9.3
Total yarn weight (measured) (g/m^2)	Warp	119.81
	Weft	116.86
Total Fabric Cover, K		0.66
Density of Fibre (g/cm^3)		1.47
Mechanical Properties		
Tensile Strength (MPa)	Warp	21.98
	Weft	24.83
Tensile Strain (%)	Warp	9.3
	Weft	11.2
Tensile Modulus (GPa)	Warp	0.53
	Weft	0.49

Table 3: Constituent content results of woven hemp composites.

Sample	Density (g/cm³)	Reinforcement content (Wt. %)	Reinforcement content (vol. %)	Matrix content (wt. %)	Matrix content (vol. %)	Void Content (%)
HVE[0]	1.10	44.64	33.34	55.36	59.30	7.37
HVE[90]	1.12	44.64	33.34	55.36	59.30	7.37
HVE[0,90]	1.10	44.27	33.06	55.73	59.69	7.25
HVE[S]	1.08	43.91	32.79	56.09	60.08	7.13

[23]. Impact energy in kJ/m² was calculated by dividing the net value of absorbed energy with the cross-sectional area of a specimen.

In the preliminary study, an in-plane shear test by tension loading based on ASTM D3518 was also conducted on some selected sample composites for the purpose of comparison to wood allowable design. Specimens with dimension of 250 × 25 × 5 mm³ were cut in ±45° angle from each sample. Like tensile and flexural tests, ten (10) specimens were run in displacement-controlled mode with a displacement rate of 2 mm/min on the similar machine.

Results and Discussion

Physical properties of woven hemp composites

Table 2 shows the results of physical and mechanical properties of woven hemp fabric used in this study. This result will be used to analyse and relate with the properties of fabricated composites. The density results of fabricated composites shown in Table 3 do not show any significant difference between samples with the average value of 1.1 g/cm³. The fibre volume fractions for all samples possessed similar fibre volume fraction and their void contents were ranging from 7.13 to 7.36 %. The increase on the fibre volume fraction also increases the void content in composite [24] fabricated a composite using non-woven hemp fabric to reinforced unsaturated polyester employing hand lay-up method. With the different layers of fabric, the void content increases which ranges from 12.56 to 18.64%. These void content figures are more than double of the present composites. Non-woven fabric is made by entangling the fibre by means of needle punch; hydro-entangling, plastic fuse etc. The transformation of fibres into fabric in one stage could lead to the uneven fibre distribution especially when using natural fibre. The direction of fibres in non-woven fabric is scattered and it is very common for the non-woven to have a lot of holes effects from the entangling mechanism. This could create kind of cavity on the fabric and thus creates void in the composite. Unlike non-woven, hemp fibre has gone through several processes before it becomes fabric. These processes ensure the uniformity of fibres distribution thus give consistency in density in fabric. In the case of small different between void contents among woven hemp composites, it is believed that hand lay-up technique might contributes in creation of voids. However, since the volume fraction of fabric for all composite as well as density of composites are similar, thus the similar voids were expected for woven hemp composite samples and this would affected the mechanical properties directly.

The consistent density for all samples is attributed to the woven fabric properties and its properties are determined before fabric is woven [11,15]. The woven hemp fabric used in this study was designed to be balanced so that it should have similar weight on warp and weft yarns which reflects to its fibre distribution in both directions. The fibre distribution can be determined based on; (1) fabric density, (2) yarn size and, (3) yarn crimp percentage. Fabric count or density is always been discussed to justify the fibre distribution in woven hemp fabric composites [17,18,25,26]. However, even though a fabric has similar number of fabric count, the fibre distribution in warp and weft direction is not necessarily equal because it depends on the warp and weft yarns size and the crimp percentage. Therefore, by taking into consideration three (3) woven fabric properties mentioned above, the weight of yarn in warp and weft directions can be measured thus enables fibre distribution to be determined.

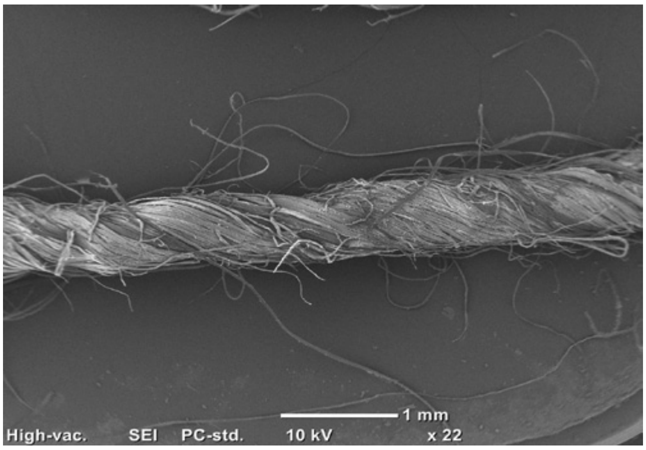

Figure 1: Scanning electron image of hemp yarn in woven hemp fabric.

Based on the Table 2, although the total warp number is higher (25 yarns/2 cm) than weft yarn (23 yarns/2 cm), the size and crimp percentage of weft yarn are higher than warp. The result of measured warp weight was slightly higher than weft. The slight difference between the warp and weft yarn in woven hemp fabric is due to the irregularities (Figure 1) that is well known existed in natural textile. It is clearly shown in Figure 1 that the rough surface and uneven fibres causing the yarn irregularities. Therefore, the differences among the weights can be said insignificant and can been proven statistically [19].

The consistent fibre distribution in warp and weft direction leads to the consistent fibre volume fraction in all the fabricated composites (Table 3). Whether the fibres are man-made or natural, only in fabric form can the consistent fibre distribution be achieved, thus produces consistent fibre fraction [11,15,18,27]. This is because the fibre in woven fabric has been arranged twice before it becomes a woven fabric. Usually, it depends on the fabric design and the manufacturing machines, the amount of fibre per area will be ensured for consistency [11,15,28]. That is why, for a woven fabric and similar number of layers used in composite fabrication, the fibre volume

Table 4: Tensile properties results of fabricated woven hemp composites.

Composite Types	Tensile Strength (MPa)	Tensile Strain (%)	Tensile Modulus (GPa)
HVE[0]	68.89(±5.51)	2.05(±0.12)	6.91(±0.60)
HVE[90]	64.05(±2.00)	2.42(±0.20)	6.22(±0.50)
HVE[0,90]	67.41(±1.08)	2.10(±0.07)	6.44(±0.26)
HVE [S]	64.48(±0.97)	2.27(±0.14)	6.31(±0.61)

*Figures in bracket indicate standard deviation.

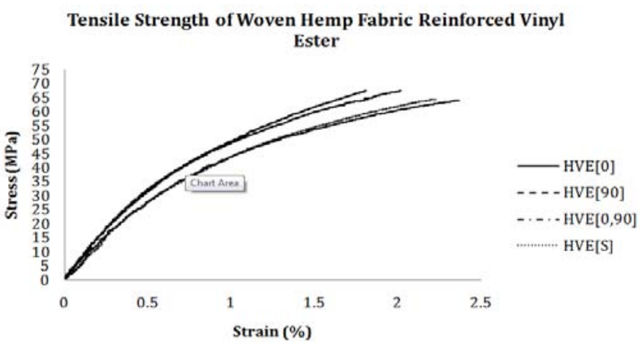

Figure 2: Tensile stress-strain response for woven hemp composites.

fraction is normally consistent throughout the plate [17] used woven hemp fabric to reinforce cellulose acetate and poly (hydroxybutyrate) matrices and the fibre volume fraction of their composite is similar and consistent.

It is not easy to control distribution of fibre per area in the plate when using short fibres and this result to inconsistency in density and fibre volume fraction. The density and volume fraction of hemp short fibre composite made by [29] was vary most probably due to inconsistent fibre distribution since the fibre was randomly laid. The density and fibre volume fraction of hemp yarn composite made by [30] is more consistent and this might be because of the arrangement of fibre in yarn form and filament winding technique they employed for their composite. Therefore, employing woven fabric could produce composite material with consistent density and fibre volume fraction.

Fabric density, yarn size and yarn crimp percentage determine the mechanical properties of fabric [19]. These properties affect the tensile strength; modulus and strain of fabric (refer Table 2). Another property that relates to fabric mechanical properties is woven structure [18]. However, since the structure of hemp fabric utilised in this study was similar (plain/taffeta weave), the comparison of mechanical properties of woven hemp fabric is free from the woven structure influence. The mechanical properties of woven hemp fabric are closely related to the mechanical performance of the fabricated composite and this topic will be discussed in further detail in the next section.

Tensile properties

Table 4 summarizes the average tensile properties for all fabricated composite samples. For each sample, it was observed that the stress-strain behaviour of all specimens cut from a plate were consistent. The typical tensile stress-strain response for each sample is shown in Figure 2. As it will be discussed further, typical behaviour shows the linear trend in the earlier stage (strain < 0.5%) then become the non-linear as the acting tensile force getting higher and this is attributed

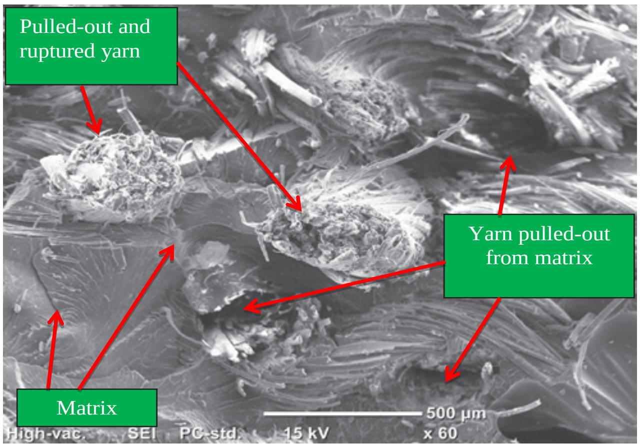

Figure 3: Scanning electron image of woven hemp composite failure surface.

to nonlinear behaviour of the vinyl ester [17]. Found that their woven hemp composite behaviours were bi-linear for warp and tri-linear for weft directions and these were attributed to the non-linear polymer matrices and higher weft yarn crimp respectively. The tensile strains of their composites were found relatively high, which ranges from 4 to 10% and this was because poly (hydroxybutyrate) and cellulose acetate resin they used were thermoplastics. Unlike thermoplastic, vinyl ester is the thermoset type resin which is well known to be more rigid and brittle. Therefore, the tensile strain of composite fabricated in this work is likely less than 3%.

All the specimens became faded and lightened in colour (from light brown to whitish brown) within the gauge length when subjected to tension. This colour fading is more likely due to the crazing of the matrix yet no cracking was visually observed. No significant cracking was observed between all the samples. The failure normally happened starting from the resin fails and then followed by reinforcement failure [18,31]. Therefore, the crazing that happened during the tensile loading showed a failure initiation on the vinyl ester resin before the woven hemp fabric. Since the tensile strength and modulus of fabric in warp direction are recorded slightly higher than its weft direction, the stress concentrations and high localized straining in the matrix are likely existed at the weft yarn fibre surface within the cross-section of the transverse fibres (refer to Table 2). Thus, the matrix was more likely to fail (crack) here leading to ultimate composite failure at the cracked cross-section.

The failure of all the specimens was perpendicular to the longitudinal sample direction. Figure 3 shows the scanning electron microscope image taken from the fracture surface of the woven hemp fabric reinforced vinyl ester composite. From the figure, it shows that there are short ruptured protruding yarns as well as the yarns pulled-out from the surface. This figure confirms the failure mode that, while the fibres within the yarn ruptured, the yarn is pulled-out from the matrix near the failure surface.

The composite tested in the warp direction, HVE[0] possessed the highest strength and stiffness among all of other samples. This was expected because even the tensile strength of the fabric in warp direction were slightly lower than weft direction, the concentration of fibre was higher for warp and this can be translated with the

Table 5: Flexural properties results of fabricated woven hemp composites.

Composite Types	Flexural Strength (MPa)	Flexural Strain (%)	Flexural Modulus (GPa)
HVE[0]	109.35(±1.96)	3.00(±0.10)	6.31(±0.06)
HVE[90]	102.45(±1.98)	3.23(±0.10)	5.51(±0.12)
HVE[0,90]	104.26(±4.21)	2.91(±0.21)	5.91(±0.11)
HVE [S]	96.72(±2.30)	2.91(±0.15)	5.29(±0.08)

*Figures in bracket indicate standard deviation.

higher total weight of warp in Table 2. Additionally, the lower tensile strain was due to lower crimp percentage of warp direction than weft direction, leading to higher stiffness for sample HVE[0]. As for the sample HVE[90], its tensile properties were recorded the lowest in comparison with other samples. As expected from the fabric properties, this was due to slight lower concentration of fibre on the weft direction as compared to the warp direction.

Tensile properties of sample HVE[0,90] possessed higher results than the sample HVE[90] due to the changing half of the total fabrics (in warp direction) which layered in 90° orientations. The higher tensile modulus than the sample HVE[90] is attributed to the layering in 0° orientations in the fabricated composite which effectively reduced the crimping in the weft direction. Sample HVE[S] possessed the lower tensile properties than samples HVE[0,90]. With 4 layers layered in the 45° direction and two layers layered in 90° direction out of the total of 10 layers woven hemp fabric, the sample was subjected to the tensile force in 0° direction. The tensile strain is reduced to 2.27% in comparison with sample HVE[90] and thus increased the tensile modulus. The tensile properties of the composite fabricated in this work are comparable with the composite made by [17] and [18]. This is a good work which emphasised on the reinforcement of woven hemp fabric.

Some other works utilised different types of fibre and reinforcement to reinforce vinyl ester resin. Tensile strength and tensile strain of banana fibre (untreated, treated with 5% NaOH and hybrid of banana and coconut shell fibre) reinforced with vinyl ester made by [32] were ranging from 11.41 to 19.61MPa and 4 to 7% respectively [33] work with woven sisal fabric reinforced with vinyl ester and the tensile strength and strain were recorded 36MPa and 1.9% respectively. Non-woven kenaf fibre reinforced vinyl ester made by [34] are differed in fibre volume fractions loading which are 15, 22.5 and 30%. These composite tensile strength and tensile modulus were recorded ranging from 44 to 55 MPa and 4.5 to 5.6 GPa respectively. Those composites tensile properties were found lower in comparison to composites fabricated in this work might be due to the utilisation of different fibre (banana, sisaland kenaf), different fibre reinforcement types (fibre, woven fabric and non-woven) as well as different fibre volume fractions [11].

Nevertheless, none of the tensile strengths measured out of their composites as well as composites fabricated in this work exceed the strengths of the typical unreinforced vinyl ester resins as mentioned by [34]. Typical tensile strength, modulus and strain of vinyl ester is 86MPa, 3.2GPa and 5-6% respectively [34]. He emphasised that the reduction in strength is due to the inclusion of defects such as voids and poor interfaced during manufacturing of the reinforced laminates. As voids in a composite sample is concerned, the void content in this works were measured ranging from 7.13 to 7.36 % (refer to section 5.1 and Table 3). It is believed that this is the main reason why woven hemp fabric composite of this work did not exceed typical vinyl ester tensile strength. Although there is negative point in tensile strength, the positive side can be sighted from the tensile modulus. The incorporation of woven hemp fabric can enhances tensile modulus or stiffness of vinyl ester from 3.2GPa to at least 6.22GPa and this is almost 50% increment. As a result from the tensile modulus increment, there was reduction in the tensile strain which ranges from 2.05 to 2.42%, less than half of the typical vinyl ester resin strain.

Flexural properties

The flexural properties determined from the load-displacement results are summarised in Table 5. The typical stress-strain response for each sample of the woven hemp fabric reinforced vinyl ester tested in flexural test is shown in Figure 4. The difference between the samples' response is attributed to the different fabric layering orientations since the matrix used for all samples is similar. Similar with the tensile response, the linear part of the typical behaviour were less than 0.6% and then they become the non-linear as the flexural loading increase which is attributed to non-linear behaviour of the vinyl ester. All specimens failed in a single crack located at mid-span where the loading was applied.

The higher flexural strength of sample HVE[0] than all other samples is due to the higher concentration fibre (total weight of warp yarn) in warp direction and its higher modulus is due to the lower warp yarn crimp percentage than weft yarn. Thus, the lower flexural strength and modulus of sample HVE[90] than the sample HVE[0] were due to the lower total weight of yarn and the higher crimp percentage of the weft direction of woven hemp fabric (refer Table 2). It must be remembered that the flexural strain here actually represent the deflection of the specimen when subjected to the flexure load not the differences of elongation of sample as in tensile strain.

In the case of sample HVE[0,90], the flexural strength and modulus were recorded higher than the sample HVE[90]. This is because the concentration of fibre in weft was increased with the fibre from warp direction. Changing half of the total fabrics layer in 90° orientation makes this sample became stiffer due to the restriction in strain affected by lower yarn of warp direction. Flexural properties of sample HVE[S] were found to be the lowest in comparison with all other samples. The reason of this most probably due to the total of 4 layers of 45° fabric orientation layered in HVE[S] sample, which had

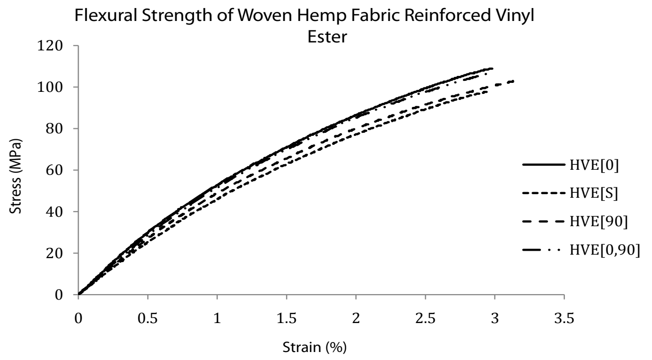

Figure 4: Flexural stress-strain response of woven hemp composites.

Table 6: Impact property results of fabricated woven hemp composites.

Composite Types	Energy to failure-1 (J)	Total time-1 (ms)	Total energy-1 (J)	Impact Strength (kJ/m²)
HVE[0]	1.73(±0.11)	1.68(±0.06)	1.73(±0.11)	17.97(±1.18)
HVE[90]	1.48(±0.10)	1.75(±0.14)	1.55(±0.12)	16.23(±1.2)
HVE[0,90]	1.40(±0.13)	1.66(±0.11)	1.45(±0.11)	14.97(±1.16)
HVE[S]	1.26(±0.22)	1.31(±0.09)	1.24(±0.10)	12.67(±1.04)

*Figures in bracket indicate standard deviation

lessened the fibre concentration in the 0° and 90°. Since the sample was cut and tested in 0° orientation of the samples, the existence of 45° fabric orientation had been resulting the flexural force distribution throughout specimens was a little ineffective. The flexural force is acting along the width and perpendicular to the length of samples by loading nose. Therefore, the higher concentration of fibre loading on the width and length directions of the sample (alike other samples) could enhance the resistant of acting flexural force more effectively. That is the reason of the lowest flexural properties of the sample HVE[S]. Flexural properties of the composites made by [35] was lower in 0° orientation in comparison with their 90° orientation samples. Most of their results were contradicted from the fabricated composites in this study. The only reason is, with the similar size of yarn in their fabric, the fabric density in warp direction (0°) was lower than in the weft direction. However, without taking into consideration their orientation wise, their composite flexural properties are relatively comparable with the material fabricated in this study.

Flexural properties of banana fibre/vinyl ester composite made by [32] were recorded in the range from 33.84 to 48.21 MPa for flexural strength and from 1.7 to 2.8% for flexural strain. Reinforcing vinyl ester with non-woven kenaf fabric could enhance flexural properties better than banana fibre. Flexural strength and modulus of non-woven kenaf/vinyl ester fabricated by [34] were recorded ranging from 70 to 85MPa and from 2.8 to 3.8 GPa respectively. This is almost 50% enhancement by non-woven kenaf fabric as compared to banana fibre. The addition of jute fabric could enhance the composite even better than kenaf and banana. [36] fabricated bi-directional jute fabric/vinyl ester and the flexural strength and modulus were recorded ranging from 83 to 103 MPa and from 5.5 to 6.6GPa respectively. Even though the flexural properties of composites fabricated in this work were recorded higher than other types of fibre, similar reason with tensile properties, the variation of results are influenced by type of fibre (banana, kenaf and jute), different fibre reinforcement types (fibre, woven fabric and non-woven) as well as different fibre volume fractions.

Impact properties

The overall impact toughness of all manufactured samples in this study is attributed to the higher volume fraction of vinyl ester matrix in composite. Since the volume fractions of woven hemp fabric in all the fabricated composites are similar (refer Table 3), the impact properties are not to be influenced by this factor but to fabric layering orientation instead [18,35]. Typical impact responses in Figure 5 show the similar trend for all samples fabricated in this study and the differences between them were only the intensity of the peaks which indicate the level of energy absorptions.

Based on the Table 6, clearly sample HVE[0] possesses the highest impact strength (17.97 kJ/m^2). Unlike flexural properties, impact

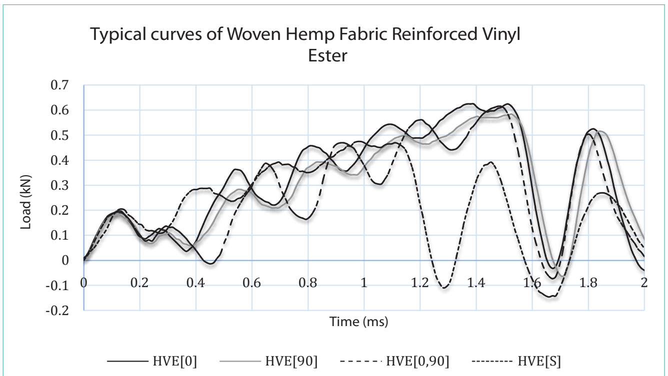

Figure 5: Typical impact response of woven hemp fabric reinforced vinyl ester.

strength of the sample HVE[0,90] was found lower than the sample HVE[90]. This shows that the combination of 0° and 90° orientations could not tolerate the immediate load which was applied upon them. Similar occurrence happened to sample HVE[S] which was found to have an impact strength result lower than HVE[0,90]. Apparently, the existence of woven fabrics in 45° layer orientation does not help to enhance the impact strength of the samples.

The crimp percentage of warp (0° direction) of woven hemp fabric was recorded lower than weft (90° direction) in fabrics thus, the energy dissipation should be better for weft since it could be elongated more than the warp yarns [37,38]. This means that impact resistance of HVE[90] is expected to be better than the sample HVE[0]. Nevertheless, the impact properties results for both samples did not happen as expected and even contradicted. This is because the impact energy has been mostly dissipated by the vinyl ester matrix since its volume fraction is higher than the woven hemp fabric.

SEM images of the fracture surface of impact specimen in Figure 6(a) confirm its fracture mode. Pulled out yarns and the consistent holes are observable in the impact specimen and the surfaces of the pulled out fibres are quite clean (Figure 6(b)). The protruded yarns and holes indicates poor adhesion between the fibre (in this case, yarn) and matrix [39]. This can be seen in Figure 6(b) where there are the gaps between the fibre (surface of yarn) and vinyl ester which could occur due to deboning during impact testing or the incompatibility between fibre and resin. Woven hemp fabric used in this study possesses total fabric cover of 0.663 (refer Table 2). This means that 66.3 % of woven hemp fabric sheets are covered by yarns and basically a good penetration of resin to the whole fabric system is expected [19]. Figure 7 shows the structure of woven hemp fabric used in this work and it can be observed that the yarns are not fully filled the gap due to the irregularities of yarns which is normal for natural yarn. Hence, with these gap spaces in fabric structure, the woven hemp fabric in this study can be considered fully wet with vinyl

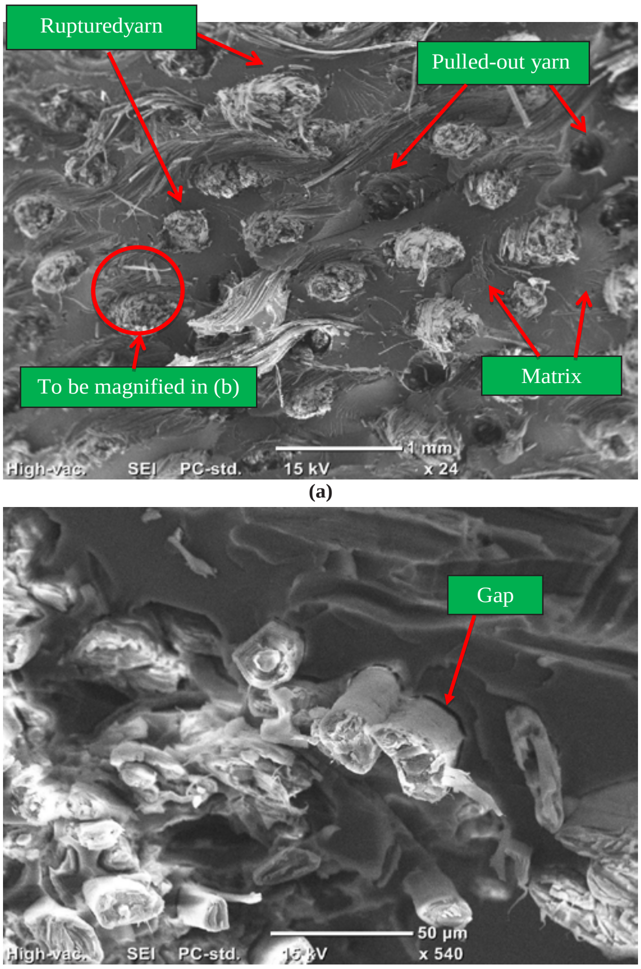

Figure 6: Scanning electron image of an impact failure surface; (a) overview of the fracture surface of specimen, (b) magnified images from the indicated surface from image (a).

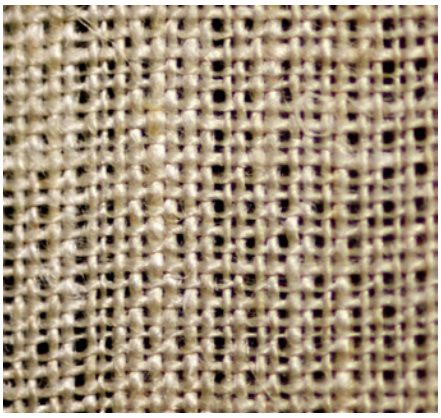

Figure 7: The structure of woven hemp fabric.

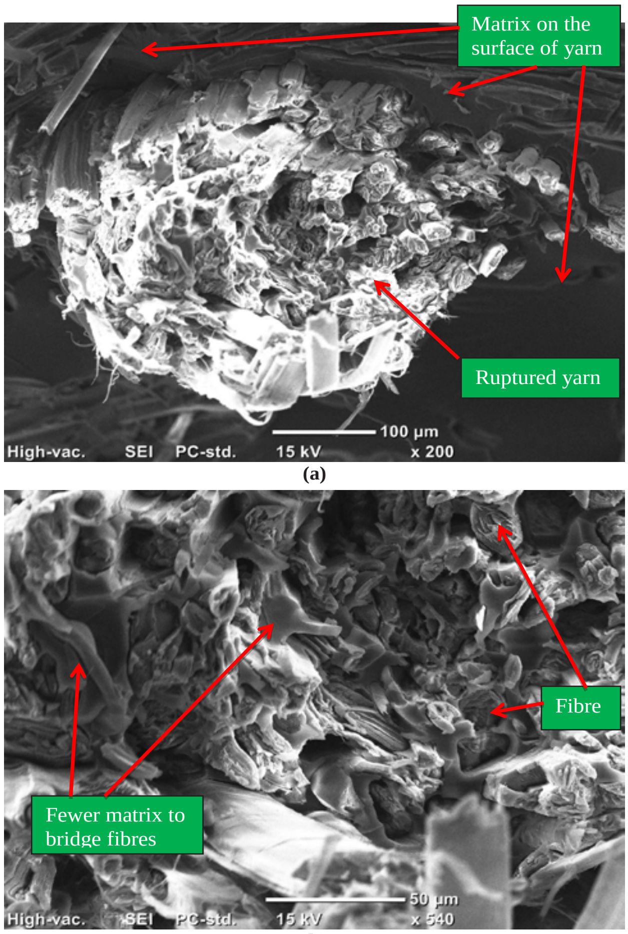

Figure 8: Scanning electron image of an impact specimen; (a) ruptured yarn is fully enclosed by vinyl ester, and (b) magnified image from image (a) indicates the penetration by vinyl ester resin into the yarn.

ester resin at least on the surface of yarns. This can be observed in Figure 8(a) where the ruptured yarn is fully surrounded by vinyl ester and this proves that the fabric has been fully wet by vinyl ester during its fabrication. Under tensile and flexural load, the degradation of the specimen occurred in two phases, which starts with the cracking of resin and then followed by the fibre rupture. When the resin is cracked, the force is transferred to the fabric and from here, the crimp from the yarn is straightened thus affected the specimen performance either on its strength or stiffness. This can happen because the test is executed under a low speed (2-5 mm/min) and steadily increasing load [18,31]. However, under impact load, the fabricated specimen failed catastrophically and the failure happened in an instance. Since the resin penetrated the fabric well, the resin restricted the movement of yarns and the impact of energy from hammer was not well absorbed by the fabrics. Therefore, the influence of crimp percentage to dissipate immediate impact force (high velocity) can be said insignificant.

Back to the impact property results of all samples in this study, apparently, the impact strength is influenced by the concentration of fibres. The highest impact energy possessed by sample HVE[0] and this is due to the highest concentration of fibre in 0° orientation which perpendicular to the impact direction acted on the specimens. The higher concentration of fibre in 0° (warp) than 90° (weft) can be translated by their slight differences in weight as recorded in Table 2. Regardless the adhesion of fibre and matrix, it is true that with the yarns' total cover factor of 0.663, the resin can easily wet all the fibres.

Table 7: Mechanical properties of woven hemp fabric composites, wood and engineered wood products.

Material	Tensile Strength (MPa)	Tensile Modulus (GPa)	Shear Strength (MPa)	Flexural Strength (MPa)	Flexural Modulus (GPa)	Density (kg/m³)
Woven hemp fabric reinforced vinyl ester	69	7.0	*27.4-28.2	109	6.3	1000-1100
Douglas-Fir (Coast) [41]	-	-	7.8	85	13.4	480
Western Hemplock[41]	-	-	8.6	78	11.3	450
Ponderosa Pine [41]	-	-	7.8	65	8.9	400
Plywood (B-B Class 1) [17,40]	27	10.3	1	27	10.3[a]	400-810
Oriented Strand Board [42]			1.2	21.2	5.25	490-810
Glulam [41,43]	-	-	-	26-72	10.6	320-720

*Shear strength of sample HVE [0] and HVE [0,90] from preliminary testing.
[a]Modulus for ply parallel to grain.

Table 8: Allowable design properties of several woods used in construction [17].

	Material	Flexural modulus of rupture (MPa)	Flexural modulus of elasticity (MPa)	Shear strength (MPa)
Clear green properties	Douglas-Fir (Coast)	53	10,800	6.2
	Western Hemplock	46	9000	5.9
	Ponderosa Pine	35	6900	4.8
Strength ratio/quality factor		4%-98%	80%-100%	-
Adjustment factor		2.1	0.94	2.1
Properties adjusted for defects	Douglas-Fir (Coast)	2.1-51.9	8640-10,800	6.3
	Western Hemplock	1.9-41.2	7200-9000	5.9
	Ponderosa Pine	1.5-34.2	5520-6900	4.8
Allowable properties	Douglas-Fir (Coast)	1.0-24.7	9190-11,490	3.0
	Western Hemplock	0.9-21.5	7660-9575	2.8
	Ponderosa Pine	0.7-16.3	5870-7340	2.3
Biocomposite properties	Hemp/CA	95	6560	12.3
	Hemp/PHB	65	5050	9.9

Nonetheless, with higher density of fibres (in this case 0° orientation for HVE[0]) and the pressure given during the fabrication processing, the resin is only wet on the surface of yarn and less penetrated into the whole fibres in the yarns. As a result, there is a corresponding decreased of matrix on the fibre and bridging between the fibres. The less penetrated matrix to bridging the fibres in yarn is shown in Figure 8(b).

This makes the samples less rigid internally, creates some kind of cushioning effect while the hammer hit the specimen thus the impact forces was absorbed not only by the matrix but also the fibres [10]. Therefore, sample HVE[0] could withstand the impact energy higher than all other samples [35] in their work implied that there is no obvious effect of lay-up angle on the impact properties of woven perform reinforced composite laminate. However, although the difference between the samples was quite insignificant in this work, the trend was obviously related to the fabric layer orientation and this matter is worth to discuss in order to justify the slight differences in their impact properties. Impact strength of banana fibre (untreated, treated with 5% NaOH and hybrid banana and coconut shell powder) reinforced vinyl ester made by [32] were recorded ranging from 2.56 to 3.63 kJ/m². This is too low in comparison with woven hemp composite and might be due to the low fibre volume fraction (30%) or the mechanical properties of banana itself.

Comparison to properties of wood and engineered wood products

Natural based composite materials have properties mostly similar to wood and engineered wood products [17]. A comparison is briefly presented here, focusing on properties of several wood commonly used in construction, namely Douglas Fir (coastal), Western Hemlock and Ponderosa Pine, and also to the engineered wood products plywood, Oriented Strand Board (OSB) and glue laminated timber (glulam). Table 7 shows comparison between woven hemp fabric reinforced vinyl ester mechanical properties tested here to wood used in construction. The values shown by woods and engineered wood products in this table were the values of samples tested/loaded parallel to grain.

When comparing with woods, woven hemp fabric composite has shear strength at least three times higher than woods. Flexural strength of woven hemp fabric composite is comparable and even higher than the woods loaded parallel to the grain. In terms of flexural modulus, woven hemp fabric composite is roughly half than that of wood parallel to grain. Nevertheless, [40] reported that the flexural modulus of wood perpendicular to the grain is about 11 to 35 times less than parallel to grain. Therefore, while the woven hemp fabric composite has a more balanced bidirectional strength and stiffness as expected, the example of woods given in Table 7 suffered with lower flexural strength and modulus in perpendicular to grain direction.

For design purposes, the wood properties must be adjusted to consider for their defects, variation in density, moisture content and grain slope typical in structure lumber. This adjustment is needed because wood mechanical properties exhibit large coefficient of variations thus make the design values established near minimum strength and stiffness for the population of lumber. Table 8 shows the allowable mechanical properties used for design with the woods considered here in comparison with bio composites made by [17] as per ASTM: D245. They expected that their bio composites possesses higher mechanical properties than the allowable wood design except the bio composites' modulus of elasticity. Similar expectation can be used for the case of woven hemp fabric reinforced vinyl ester fabricated in this study since its mechanical properties were recorded higher (refer Table 7) than the bio composites in Table 8.

The woven hemp fabric composite fabricated in this study has the mechanical properties comparable to or even higher than the properties measured for the engineered wood products except for the flexural modulus of glulam. The flexural modulus of plywood stated in Table 7 is for a ply parallel to grain. However, in practice, the plies is always in a combination of parallel and perpendicular to grain thus make the modulus 35 times smaller than parallel to grain. Therefore, the modulus of woven hemp fabric composites can be considered higher than that of plywood. With the comparison shown in Table 8, the composite fabricated in this study can directly replace engineered wood products and woods considering some other advantages it possesses such as easy to tailor its properties and able to mould into structural shapes (including hollow sections).

The only significant problem with the woven hemp fabric composite is its greater densities (1000-1100 kg/m^3) as compared to the woods and engineered wood products (320-810 kg/m^3). In order to replace woods products, a composite should be engineered to be lighter weight. Nevertheless, at least the densities of the fabricated composite in this study are lower than the bio composites fabricated by others [17,29,44].

Conclusion

- The results of this work have positively shown that the parameters of fabric can affect the mechanical properties of a composite material. The conducted characterisation in this work shows a number of findings, which relates the physical properties and mechanical behaviours of the fabricated composites attributed to the fabric properties and layering orientationDensity and fibre volume fraction (1.1 g/cm^3 and 33% respectively) was consistent for all samples due to the good fibre distribution in the fabric which can be determined by the weight of the warp and weft yarns.

- A composite which has all fabric layered in warp direction will have higher tensile properties and the reduction of layer fabric in warp direction will lead to reduce tensile strength due to slightly higher fabric strength in warp rather than weft direction. The flexural strength and modulus for composites also show similar trends with tensile properties.

- Impact energy is mostly dissipated by vinyl ester since its volume fraction (60%) is higher than woven hemp fabric in the composites. Impact strength of fabricated composites is influenced by the loose fibres rather than yarn crimps. The slight difference in weight consequently made the warp to have higher loose fibre than weft direction thus energy can be dissipated more effectively in 0° than 90° directions.

- Based on the comparison to some of the woods, shear strength and flexural strength of the composite is higher than those woods and its balanced properties made the composite even better, much more consistent and stable. When comparing to the engineered wood products, the composite flexural modulus can be considered higher than that of plywood and this confirms that it can directly replace the engineered wood product.

- The main problem for this composite is just its density is relatively higher than those woods and engineered wood products. However, the composites densities in this work are lower than hemp composite from other works.

Altogether, the study shows the importance of fabric properties with respect to the physical and mechanical properties of hemp fabric composites. Hence, fabric properties are worth to be analysed not only to determine fibre distribution and to comprehend the mechanical properties of composite but also important for the consistency of this material production. The hemp fabric composites also demonstrate good performance which is potentially suitable to replace some type of woods and engineered wood products.

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Adv Res Text Eng - Volume 1 Issue 1 - 2016
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Citation: Misnon IM, Islam MM, Epaarachchi JA, Lau K-T and Wang H. Fabric Parameter Effect on the Mechanical Properties of Woven Hemp Fabric Reinforced Composites as an Alternative to Wood Products. Adv Res Text Eng. 2016; 1(1): 1004.