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Experimental Investigation of the Mechanical Properties of Woven Abaca (Musa textilis) Fiber-Reinforced Epoxy Composites

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Abstract. Abaca fiber which is also known as Musa textilis is a tropical banana species grown primarily for its fiber. It has several advantages when used as a reinforcement in polymer composites caused by its great mechanical performance, increase cellulose content, low cost, and abundant availability. It is important to note that the structure of the fibers used as reinforcing materials is a critical aspect of fabricating a strong polymer composite. Therefore, this study was conducted to determine the effects of layering as well as fiber orientation towards the mechanical characteristics of woven abaca-reinforced epoxy composites. Furthermore, this comprised the application of hand lay-up technique as well as hydraulic press molding in producing 2, 3, and 4 layers of woven abaca-reinforced epoxy composites after which the mechanical properties were analyzed based on its orientation in the warp and weft direction. The results showed that an increase in the number of layers from 2 to 4 did not affect the tensile and flexural properties at every layered stacking sequence of the fiber. Meanwhile, the material in the warp direction indicated a greater tensile as well as flexural properties in comparison to the weft direction. This means the number of layers and orientation of the woven abaca in epoxy composite possesses a significant influence towards the composites' mechanical properties.

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1 Introduction

Natural fiber-reinforced polymer composites (NFRPC) have received a lot of attention as a viable substitute for synthetic materials. This is due to the several benefits of plant fibers compared to traditional glass or carbon fibers such as the fact that they are organic, eco-friendly, inexpensive, lighter, and with excellent mechanical behavior. Therefore, scientists and engineers are becoming increasingly interested in researching and developing natural fibers as reinforcement for different industrial applications [1].

Several improvements and suggestions have been made to enhance the mechanical qualities of natural fibers in order to increase their strength and structure. For example, Jawaid & Khalil (2011) showed that polymers can be easily strengthened and their composites improved by increasing the strength of their base structures. It should be pointed out that the mechanical properties with regards to natural fiber are impacted by multiple factors, like, fiber strength modulus, fiber length, orientation, cell wall thickness, and fiber matrix surface bond strength. This implies the determination of the optimum mechanical performance with regards to woven abaca composites as well as the influencing factors requires investigating the impact of the layering sequence and fiber orientation [2].

Woven composites are complex systems in a typical weave style or pattern with additional characteristics such as interlace point, gap or interlace spacing, and unit cell of warp 0° and weft 90° fiber [3]. Woven fabrics are appealing to be used for reinforcement among all types of textiles because they offer outstanding integrity and conformability [4]. Various fabric weaves were employed in synthetic fibers, for example, carbon, glass, as well as aramid. However, the woven fiber composites produced by weaving two fiber tows together to form a layer (warp and weft) [3] are becoming increasingly popular due to their adequate mechanical qualities and ease of production. Their primary structures are in the form of a plain, satin, basket, and twill with the fabric's yarns either directly or uniformly distributed [5]. According to Alavudeen et al. (2015) and Saiman et al. (2014), plain weave is sturdy and strong but has a higher percentage of fiber crimp than other weaves, thereby, making it the most fundamental reinforced structure in textile composites [3,5]. It is important to note that the toughness of the raw materials used in the production process usually influences the stiffness of the fabric weave [6].

The alteration of the stacking sequence or the number of ply fiber orientations can also be used to fabricate NFCs with specific design needs. For example, Faizal et al. (2006) investigated the impact of ply arrangement as well as curing pressure towards the tensile properties of hand-lay-up plain-woven e-glass/polyester composites and each of the fiber plies was discovered to have a different performance. This signifies a good selection lay-up is critical to the determination of the fabrication performance and suitability of NFCs for the design parameters [7]. Rajesh et al. (2016) showed that the four-layers of plain weave fiber had the best mechanical performance in comparison to one, two, and three-layer jute fiber during the process of examining the woven natural fiber composite mechanical behavior. These results indicate the considerable influence of stacking sequence on the tensile, impact, as well as flexural properties of composites [4]. In addition, the tensile strength with regards to the four-layer hybrid composites was also discovered to be greater according to Yahaya et al. (2015) and this was observed from the better flexural capabilities of the four-layered kenaf/kevlar laminated hybrid in comparison to the three-layers. The performance and mechanical qualities of the composite were discovered to be improved by strong natural fiber and matrix interfacial bonding [8].

Bhoopathi et al. (2014) also reported that stacking sequence impacts flexural strength as indicated by the greater results produced by the three layers of glass fiber including two layers of banana fiber when compared to the two-layer fiberglass and three-layer banana fiber hand lay-up [9]. Furthermore, Rajesh et al. (2018) employed the hand lay-up technique to four layers of laminate as well as the dynamic behavior of the woven bio-fiber composite was discovered to have led to different patterns of woven sisal fiber, plain, basket, and twill as the main and short rice husk fiber as secondary reinforcing composite. The basketweave also demonstrated stronger tensile and flexural strength than plain and twill weaves based on its consistent stress distribution, less stress concentration, and the distance between two subsequent fiber strands. Moreover, there were 27.75% variances in tensile strength as well as 14.55% variances in flexural strength between the basket and plain weaves [10].

It is, therefore, important to investigate the mechanical properties with regards to natural fiber-reinforced polymer composites to predict the influence of the layering sequence and fiber orientation. It should be noted that the focus was on the tensile as well as flexural properties with regards to woven abaca fiber as an epoxy resin reinforcement.

2 Methodology

2.1 Materials

The abaca or matured leaf used as the main material in this study was prepared in plain weave at warp 0° and weft 90° while two, three, and four-layer sequences of woven abaca were purchased from Pemalang, Indonesia, cut to the appropriate measurement of 300 mm x 300 mm, and placed in an aluminum mold. Moreover, the epoxy resin 816A with of 1.2 g/cm^{3}density as well as 651A hardener selected as the polymer matrix to produce composite laminates was equipped by Impiana Z Enterprise (Malaysia) as depicted in Figure 1. In addition, a release agent was utilised to simply dispose the composite from the mold once it was cured.

(a)

(b)

Figure 1. Image of (a) plain-woven abaca, (b) epoxy resin and hardener.

2.2 Fabrication of laminated composites

A fitting 300 mm x 300 mm x 4 mm (LxWxT) mold was made by layering the fiber with the epoxy resin matrix to produce the composite plates. On the other hand, the abaca fiber composite was manufactured by manually stirring the epoxy resin as well as hardener in a 3:1 weight ratio for 5 minutes while a composite plate was produced using the hand lay-up method because of its simplicity and low reliance on machinery and several benefits over other techniques.

The woven abaca fiber-reinforced epoxy composites were arranged in 2, 3, and 4-layer of plain weaves as presented in Figure 2. Moreover, a releasing agent was utilised on the mold's interior surfaces prior the laminating process was introduced to make sure the composites do not stick to their surface and to facilitate removal. The mixture of epoxy resin and hardener was spilt into the mold following the woven fibers' placement. It is important to note that the surface was gently rolled for every single layer to guarantee every residue resin was squeezed out to achieve the wetness of the woven fabric. The procedure was continued until four layers of woven abaca fiber composite plates were formed. This was followed by the curing of the molds for approximately 24 hours at room temperature to discard the entrapped air within the laminated composites as well as permitting the resin to stiffen after which the laminated fiber woven composites were cut as per the ASTM standard. Moreover, 7 specimens were constructed for each distinct layer stacking sequence of woven abaca reinforced epoxy and tested for tensile as well as flexural properties.

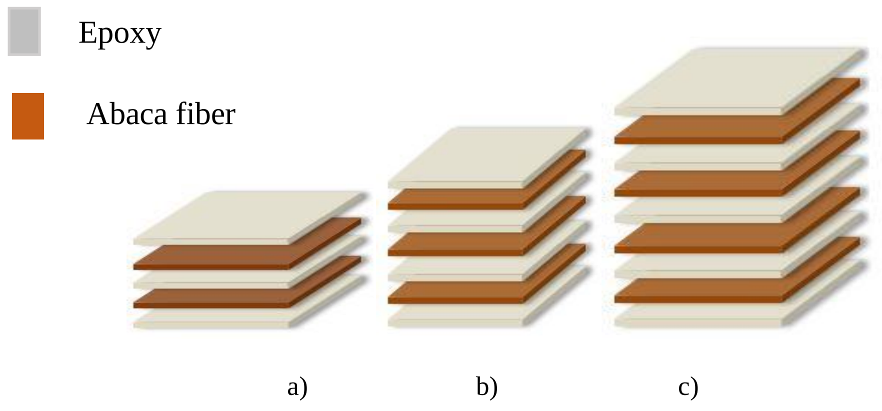

Figure 2. Schematic diagram of stacking sequence of abaca composites at (a) 2-layer, (b) 3-layer, and (c) 4-layer

2.3 Tensile test

The tensile test is among the well-known methods of determining the material mechanical properties of a material due to its ability to identify several critical characteristics like tensile strength as well as tensile modulus accepted by a material before breaking. Moreover, the test was performed employing an INSTRON 3369 universal testing machine having 2 mm/min crosshead speed and the process was in line with the ASTM D638-IV standard with regards to tensile test and related specimen dimension.

2.4 Flexural test

Flexural specimens were created as per ASTM D790 with the most prevalent bending test with regards to composite materials observed to be the 3-point bending test. Here, an INSTRON 3369 universal testing machine having 2 mm/min crosshead speed was employed for the flexural test with the focus on measuring the flexural modulus and flexural strength.

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2.5 Scanning electron microscopy (SEM)

The Zeiss Evo50 scanning electron microscope was employed to investigate the fiber surface as well as fracture morphological behavior with regards to tensile fracture specimens in abaca reinforced epoxy composites. The samples were sputter-coated with palladium thin film coating as well as positioned in an SEM holder utilising double-sided electrically conductive carbon adhesive tapes in preventing a surface charge on the specimens when revealed to the electron beam. Ultimately, the samples were analyzed using a microscope having a x300 magnification as well as an acceleration tension of 15 kV.

3 Results and Discussions

The tensile strength as well as modulus of specimens for various layer stacking sequences of 2, 3, and 4-layer with fiber orientation of warp (0°) and weft (90°) conditions are reported in Figures 3 and 4. It was revealed that the tensile properties of warp (0°) orientation composite specimens were greater than the weft (90°) orientation composite specimens. This aligns with the results of Misnon et al. (2014) regarding the tensile strength of woven hemp fiber-reinforced vinyl ester composites at various stacking sequences as well as fiber orientations of 0°, 45°, and 90° with 0° orientation reported to have the highest tensile value [11]. It is also consistent with previous studies of Tezara et al. (2022) which showed the possibility of having the highest mechanical characteristics of composites when the fiber is oriented parallel to the direction of the employed load [12]. Moreover, the tensile strength of the 3-layer measured in weft (90°) was observed to be insignificantly different to warp (0°) as indicated by an increase of 35.32% only for the warp (0°). It was also discovered that the 4 layers even have a lower value of 21.23 MPa in weft (90°) orientation compared to the 28.93 MPa in the warp (0°) and this indicates a slight decrease of 26.62% for 4-layer weft (90°) orientation.

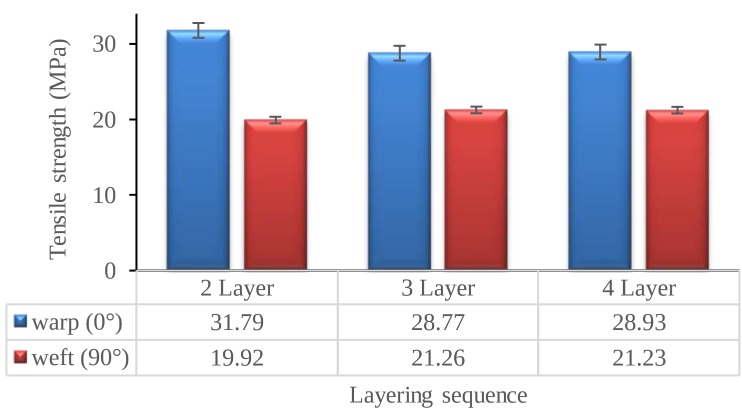
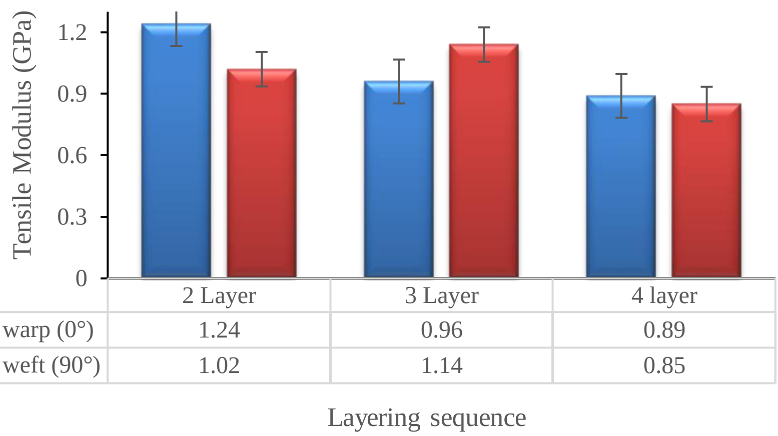


Figure 3. Summary of the tensile strength of warp (0°) and weft (90°) abaca fiber-reinforced epoxy composites.

The findings illustrated that the 2-layer warp (0°) orientation had a greater tensile strength than the 3 and 4-layer warp (0°) orientations as indicted by 31.79, 28.77 and 28.93 MPa, respectively, thereby, showing that the value was reduced by 10.50% for 3-layer and 9.89% for 4-layer. This simply shows that a decrease in the layering sequence on warp (0°) fiber orientation yield to an improvement in the tensile strength. It is, however, important to acknowledge that an increase in the number of stacking sequences beyond the critical limit is going to cause a drop in the tensile strength. Additionally, this was noticed from the findings of Ng et al. (2020) that the use of an insufficient polymer matrix to maintain reinforcement beyond the critical fiber composition in composite materials usually leads to low-stress transmission at the interface between the polymer matrix as well as the reinforcement [13]. Meanwhile, an insignificant difference was observed in the tensile strength of all three-layer sequence in a weft (90°) orientation due to the degradation of the composite with the highest value of 21.26 MPa recorded in 3-layer stacking sequence and changed to an almost similar value of 19.92 MPa for 2-layer and 21.23 for 4-layer. This indicates the tensile strength in weft (90°) orientation reduced only by 6.30% for 2-layer and 0.14% for 4 layers.



	2 Layer	3 Layer	4 layer
warp (0°)	1.24	0.96	0.89
weft (90°)	1.02	1.14	0.85

Figure 4. Summary of tensile modulus of warp (0°) and weft (90°) abaca fiber-reinforced epoxy composites.

The tensile modulus percentage was observed to be higher in the 2-layer sequences of warp (0°) orientation for abaca fiber-reinforced epoxy composite and this means the layering sequences in different orientations affect the strength properties. It was generally discovered that the tensile strength was reduced in weft (90°) and increased in warp (0°) orientation but the reduction was probably associated with the inclusion of defects like pores as well as poor interface fiber-matrix bonding throughout the laminate fabrication process. The tensile modulus of the 2-layer sequence was recorded to be 1.24 GPa in warp (0°) orientation and 1.02 GPa in weft (90°) orientation which indicates a 17.74% reduction while, in the contrast, a higher value of 1.14 GPa was found in weft (90°) orientation for the 3-layer stacking sequence compared to the 0.96 GPa for warp (0°) orientation, thereby, indicating a slight increase of 18.75% for the weft. This is associated with the good and efficient fiber arrangement that provides the composite with a robust as well as greater tensile modulus align with the results of Yahaya et al. (2015) that an enhance in tensile modulus may be caused by the perfect adhesion between matrix and fiber [8].

The findings for the flexural strength as well as modulus for 2, 3, and 4-layer woven abaca fiber-reinforced epoxy composites are plotted in Figures 5 and 6. It was discovered that the 2-layer abaca fiber composite laminate has the highest maximum flexural strength caused by the high surface roughness of the fiber as well as the matrix's excellent interfacial bonding. Moreover, the inability of the polymer matrix to hold the reinforcement due to a delay in stress transfer between the fiber as well as the polymer matrix, thus, causing to a decrease in flexural strength in addition to the optimal fiber content or the number of layer sequences

[13]. It was also observed that there was a small difference in the flexural strengths of 3-layer and 4-layer stacking arrangements as indicated by an increase of 11.03% in the 4-layer.

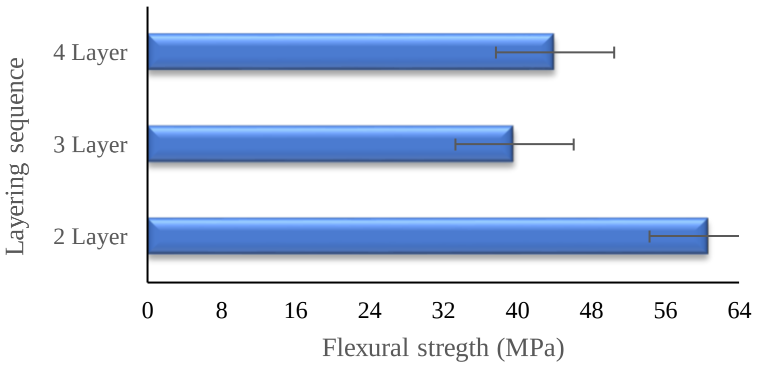


Figure 5. Flexural strength of 2, 3, and 4-layer abaca fiber stacking sequence composite.

The flexural strength with regards to the 2-layer was also found to be 15.86% greater than the 4-layer stacking sequence and this is different from the findings of Yan et al. (2012) that natural fiber usually retains stress as indicated by a considerable increase in flexural strength with the enhance in layering sequence as well as loading which improved the ductility with regards to the composite material to withstand fracture during flexure test [14]. Flexural strength is an important mechanical performance for composites and the value needs to be high for the material to be applied in structures.

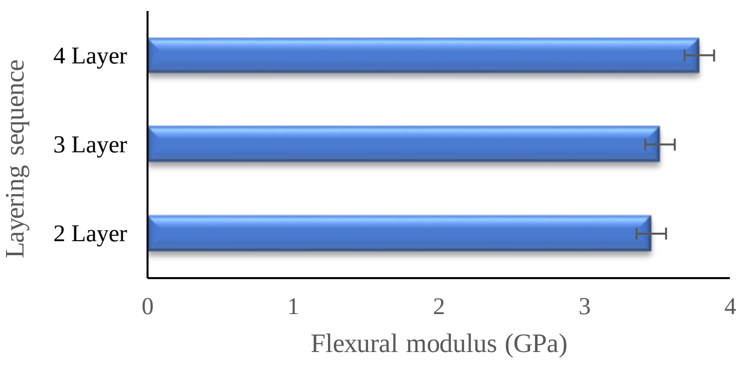


Figure 6. Flexural modulus of 2, 3 and 4-layer abaca fiber stacking sequence composite.

The results also illustrated that the greatest modulus of 3.79 GPa was obtained using a 4-layer stacking sequence. Meanwhile, the lowest was 3.46 at a 2-layer stacking sequence, thereby, indicating that the flexural modulus of the composite materials improved with an increment in the stacking sequence. This also shows a boost in the modulus from 1.73% to 7.67% as more layering sequence of woven abaca fiber was added.

The micrographs of 2-layer stacking sequence (warp 0°) woven abaca fiber-reinforced epoxy composite specimens studied through SEM are presented in Figure 7 and the fiber matrix debonding observed to have occurred during tensile loading led to the formation of significant interface voids during the fabricating, thereby, causing inadequate contact between fiber as well as matrix or poor fiber-matrix adhesions. This further impacted the stress transfer from the matrix to the fiber. This is feasible since the tensile characteristics with regards to composites are commonly affected by matrix degradation or loading and the interfacial adhesion between the reinforcing fiber as well as the polymer matrix [15]. It has also been found that a better fiber-matrix adhesion commonly yields to an effective load transfer between fiber reinforcement and matrix and, subsequently, an improvement in the mechanical behavior.

The contrast of the fracture surface under tensile loads for 2, 3, and 4 layers of woven abaca fiber is shown in Figure 7 and the matrix damage on the surface was discovered to be caused by the poor stress transfer from the fiber to the matrix. Figure 7(c) indicates that the fiber pull-out for the 3-layer was due to poor interfacial adhesion while 2-layer was observed not to have produced excessive fiber pull-out compared to the 3-layer. Furthermore, 4-layer specimens showed a lot of matrix damage due to poor fiber-matrix interface bonding throughout the laminate fabrication process and this shows that a decrease in the layers led to an increase in material rigidity. This is in comparison to the results of Rajesh et al. (2016) that the matrix damage on laminated two-layered jute fiber composites was caused by weak stress transfer from fiber to the matrix with the increased rigidity of the jute fiber composite was attributed to the rise in the number of layers observed to be strengthening the adhesion of the interface [15]. In summary, the micrographs showed that the fractured specimens subjected to tensile test experienced void, fiber breakage, fiber pull-out, interfacial bonding, weak interfacial adhesion, and matrix cracking and this led to the application of surface morphology on the fractured test specimens using optical microscopy machine to understand the failure mechanism.

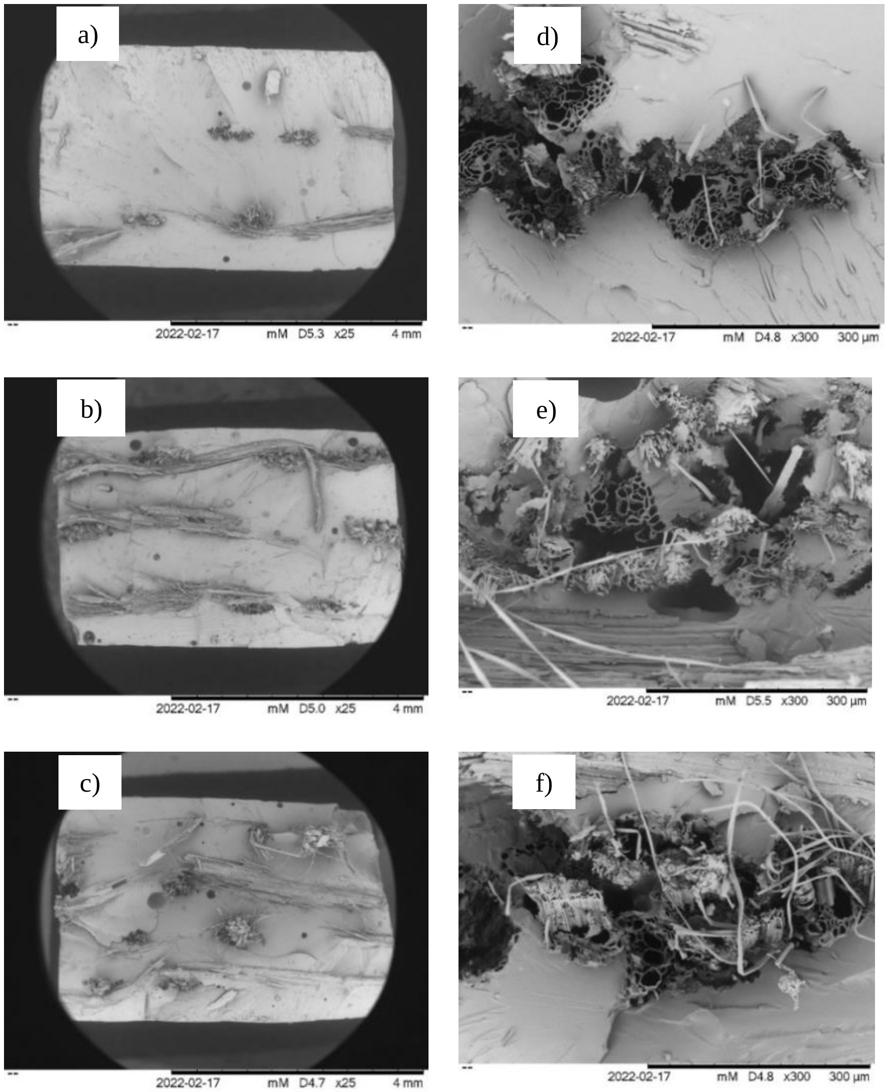


Figure 7. SEM of the tensile fracture surface of 2-layer (a and b), 3-layer (c and d) and layer (e and f) abaca/epoxy composites.

4 Conclusions

This research effectively examined the mechanical properties of woven abaca fiber composite at multiple layering sequences as well as orientations. Here, the findings revealed that the 2-layer stacking sequence enhanced the mechanical properties with regards to the material with the tensile properties of warp (0°) orientation discovered to be higher than weft (90°) orientation. Meanwhile, the decrease in the strength with regards to the material was correlated with the problems in the laminate fabrication process like the pores as well as insufficient interface fiber-matrix bonding. It was, therefore, deduced that layering stacking sequence and orientation have an essential effect on the enhancement of the mechanical properties with regards to woven abaca fiber-reinforced composites. It is recommended that future research produce fiber composite through different weave structures, for example, twill, plain, satin, as well as others because some of them have properties considered ideal for implementations necessitating modulus, high strength, as well as impact resistance.

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