DOI: 10.2507/33rd.daaam.proceedings.xxx

Comparative Analysis of Polymeric Composite Reinforced with Glass Fibre, Mat and Viscose Rayon

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This Publication has to be referred as: Ezenwankwo, J[ohnson] U[gochukwu]; Josef, Ž[ak] & Iva, P[etríková] (2022). Comparative Analysis of Polymeric Composite Reinforced with Glass Fibre, Mat and Viscose Rayon, Proceedings of the 33rd DAAAM International Symposium, pp.xxxx-xxxx, B. Katalinic (Ed.), Published by DAAAM International, ISBN 978-3-902734-xx-x, ISSN 1726-9679, Vienna, Austria.
DOI: 10.2507/33rd.daaam.proceedings.xxx

Abstract

Natural fibre-reinforced polymer composites (NFRPC) have taken centre stage in materials and engineering. They present many advantages over their synthetic counterparts, including environmental concerns, ease of disposal and reuse, and a high strength-to-weight ratio. Aerospace engineering and other critical engineering sectors are actively turning to NFRPCs for various reasons. Reinforcement in polymeric composites plays a vital role in forming the framework support system upon which the matrix is based; this, in turn, affects the vital mechanical properties of the composite formed and its impact-bearing characteristics. This paper evaluates selected mechanical properties of glass fibre and rayon yarn. The laminates were made so that the thickness was approximately equal. Five tensile tests each were performed following ASTM 3039/D3039 - 08 standard, and the average of each set is plotted and compared accordingly. The material is weighed, and the fibre and matrix volume fractions are calculated. The standard failure location, area and mode are described with the ASTM standard. A simplified micromechanical analysis is employed to demonstrate the homogenization of the laminate's representative volume element (RVE) to obtain the relevant engineering constants.

Keywords: Matrix; rayon; yarn; laminates

1. Introduction

From time immemorial, science and technology have greatly attributed processes' success and functionality to materials. Material selection plays a big role in systems' operation and useful life. For instance, a simple automobile engine can have materials made of aluminium, copper, iron, plastic, rubber and a mixture of two or more in the form of alloys. The same goes for composites reinforced with various natural/synthetic fibres singly or as a mixture (hybrid). There is now a global clarion call to switch from harmful synthetic fibres to bio-degradable. There are numerous evidential advances in composite materials as their application begins to foray into other areas of engineering. Recently, a study was carried out investigating fabric's usability and suitability and the electromagnetic compatibility of a chosen composite element. The study further delved into determining the fibre content to be effective for the particle shielding test [1]. Another study used fused deposition modelling process in additive manufacturing samples infused with carbon fibre. The study investigated the mechanical properties of two polyesters reinforced with carbon fibre by making comparisons of type and print angle of orientation according to specified standards [2]. Fibre-reinforced polymer composites present a huge advantage in engineering practice and natural fibres because of their many desirable properties compared to their synthetic counterparts. In the past two decades, the ease of making quality composites into various shapes has also increased its desirability and market chase. Low density and cost-effectiveness are reasons natural fibres are popular, especially in automobile industries [3]. Other advantages possessed by natural fibres include relative non-abrasiveness, high specific strength and modulus, ease of processing, and high flexibility. Generally, the manufacturing of polymer matrix composites (PMC) and natural fibre-reinforced polymer composites (NFRPC) can be fundamentally classified into three broad groups: short-fibre suspension methods, squeeze flow methods and porous media methods [4]. Most of the known manufacturing procedures for PMCs and NFRPCs fall into at least one of these categories. These desirable properties make up for the drawbacks presented by natural fibres reinforced polymer composites which include relatively low impact strength and hydrophilic tendencies (due to the hydroxyl ion cellulose and hemicellulose components), which encourages high water absorption [5]. Material scientists and engineers have developed many design-based approaches and models formulated to address these challenges [6][7][8][9][10][11]. One special technique is fibre hybridization, where fibres of varying geometric properties are used singly or woven together to enhance the mechanical properties of composites. Kumar *et al.* [12] performed a comparative analysis of kenaf/glass fibre hybrid composite. The study used woven kenaf/glass fibre and epoxy resin as the matrix while investigating such properties as tensile strength, Young's modulus, and the stress-strain curve of samples with different percentage contents of fly ash. The choice of fabrication method is vital during the manufacturing of composites. In their book, Safarabadi *et al.* [13] presented the effect of fibre waviness on the compressive strength of a laminate. Yahaya *et al.* [14] studied the effect of layering sequence and chemical treatment on the mechanical properties of woven kenaf-aramid hybrid laminated composites. The results showed marked improvement in the tensile properties of hybrid composites in 3 layers compared to 4. Also, hybrid composites containing kevlar at the outer layers displayed overall better mechanical properties than the others. In their research, Tagarielli *et al.* [15] addressed the issue of an efficient and reliable method to measure the through-thickness of a material owing to the sheer difficulty in manufacturing thick laminates with relatively high thickness. The study also proclaimed that the onset of failure, which occurs in through-thickness cases in composite laminates, largely depends on direct and shear inter-laminar stresses. Paul S. *et al.* [16] loaded banana composites in tension and monitored the effect of chemical alteration by treatment of the composites. The study showed the role of chemical treatment and how it improves the thermo-physical properties of the material tested. Vijayan *et al.* [17] experimented with the effect of hybridization by infusing aloe vera fibre with roselle and glass in various formations. The study also demonstrated the flexural (bending) test on the 3-point method up to a breaking criterion. The flexural strength and modulus were tabulated for the different sample configurations. Meenakshi *et al.* [18] investigated, via experiments and FEM, the mechanical response of glass, aloe vera, and kenaf in various configurations produced by the vacuum-assisted resin transfer moulding method. The study aims to study the mechanical behaviour of four different natural fibres when used as a reinforcement material in NFRPC/PMC. Its novelty lies in the material composite produced. Viscose rayon, in particular, is unique beacuse viscose rayon is not commonly used, as shown in many similar works on both natural and synthetic fibre. Hence, the problem addressed, or the specific novelty of the paper, lies in the fabrication of laminates and the comparative investigation of the mechanical properties of the different laminates produced according to stacking sequence. A simplified micromechanical analysis of the composite is performed in *Ansys r22 Material Model* Module using the hexagonal geometry type with a fibre diameter of 2µm. A comparison is drawn between the properties of E-Glass (Fibre Glass) with the resin used as they relate to the engineering constants, and relevant plots are obtained.

2. Materials and Method

The method chosen is dependent on the type of material involved in the manufacturing of the composite. The selection of suitable resin also plays an important role. Some of the manufacturing processes include the simple method called hand layup, compression moulding, injection moulding, pultrusion etc. The mechanical properties of composites largely depend on reinforcement, matrix, and the binding dynamics between them. Material preparation techniques and process is described in detail in section 2.1 below.

2.1 Composite Laminate Preparation

Preparing the sample involved obtaining the reinforcement fabric, cutting it into the specified dimension of 250mm x 250mm, mixing the epoxy and hardener mixture at a specified ratio, and following the hand layup procedure for making the laminate before thermal compression and curing. This section describes the hand layup method for preparing the laminate at the KMP-TUL lab. The glass fibre and mat were obtained from Havel Composites Company, and the viscose rayon (2440 dtex) yarn in simple weave architecture was prepared at the KMP lab. The epoxy-hardener mixing ratio was 2:1. The gauge length of the textile composite sample was 78.8 mm, as marked from the Instron 9000 series testing machine gauge kit. Prevailing environmental conditions were 24ºC, 37.5% RH and the mean value of the tests were considered. As described before, the three different reinforcement configurations prepared are given as follows: $[0_{2gf}]s$, $[0,45_{gf}]s$, $[0_{gf}, Mat]s$, $[Mat_2]s$ and $[0_{2ry}]s$.

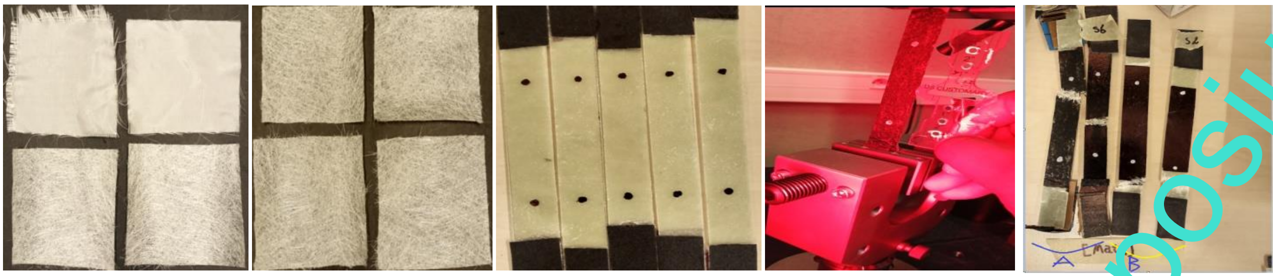


Fig. 1. (a) [0_{gf}, Mat]s and (b) [Mat_2]s configurations (c) Mat Composite Test Samples (d) Strain Gauge Marker (e) Proper Tab Configuration and Effects

The fibre materials are cut 250mmx250mm. The nylon material serves as the enclosure for the lay-up system and is laid open-leaf. The bleeder material is placed on one side of the leaf, and the separator material, which helps in easy detachment of the laminate after curing, is placed over the bleeder material. A reasonable quantity of matrix is applied, and the first fibre is laid on it; the process is repeated until all fibres are laid. Then the second side of the leaf is used to close the arrangement. The hot compression chamber consists of a top and lower platen with separate temperate controls. The platens are pre-heated to 75°C for both platens. The material is finally rammed and pressed manually with a hand roller to crush local bubbles to reduce the occurrence of voids. The lay-up is placed inside the compression chamber, and the pressure is set to 20kN, as shown in Figures 7 and 8. A glass enclave forms the sliding door that keeps the temperature inside in equilibrium through the curing process. The process continued for 1.5 hours, after which the sample was allowed to cool inside the chamber by adjusting the setpoint temperature to 24°C (room temperature) for about 12 hours.

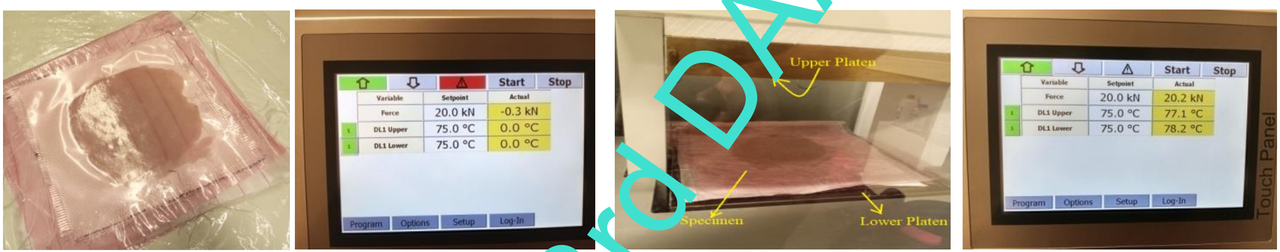


Fig. 2. (a) Fibre Material Hand Layup (b) Compression Controls Setpoint (c) Material Inserted for Compression (d) Compression Controls Actual Values

Fibre	**Stacking Sequence**	**Orientation**	**Sample Thickness (mm)**
Glass	G-G-G-G	[0]	1.02
Glass	G-G-G-G	$[0,45]_S$	1.02
Mat	M-M-M-M	-	1.01
Viscose-Rayon	R-R-R-R	[0]	1.45
Galss-Mat	G-M-M-G	$[0_{gl}, -]$	1.01

Table 1: Stacking Sequence, Orientation and Sample Thickness of Composite Laminate

3. Governing Equations

In the book by Autar Kaw K. [19], the concept of composite mechanics analysis, theory, experimental procedures and failure mechanics is expounded.
The surface area of the composite is given as follows:

$$S_f = a \cdot b \cdot n \quad (1)$$

where a and b are the geometric dimensions of the specimen and n is the number of plies (layers) mass of fabric,

$m_f = S_f \cdot \gamma$ (2)

In relation to laminate density,

$\rho = \rho_f V_f + \rho_m V_m$ and $V_m + V_f = 1$ (3)

Where ρ is the density of the composite.

Hence, $V_f = \dfrac{\rho - \rho_m}{\rho_f - \rho_m}$ (4)

The longitudinal ultimate tensile strength is given as

$(\sigma_1^T)_{ult} = (\sigma_f)_{ult} V_f + (\varepsilon_f)_{ult} E_m (1 - V_f)$; (5)

The transverse ultimate tensile strength is given as

$(\sigma_2^T)_{ult} = E_2 (\varepsilon_2^T)_{ult}$ (6)

The longitudinal ultimate compressive strength is calculated using two formulas, of which the lesser value is adopted.

The relations are given below

$(\sigma_1^C)_{ult} = \dfrac{E_1 (\varepsilon_2^T)_{ult}}{v_{12}}$ or (7)

Using the shear stress failure mode;

$(\sigma_1^C)_{ult} = 2[(\tau_f)_{ult} V_f + (\tau_m)_{ult} V_m]$ (8)

The transverse compressive strength is given as

$(\sigma_2^C)_{ult} = E_2 (\varepsilon_2^C)_{ult}$ (9)

The ultimate shear stress is given as

$(\tau_{12}) = G_{12} (\gamma_{12})_{m-ult}$ (10)

4. Results and Discussion

The result and discussion session present the test outcome from the Instrom 9000 series machine. The samples are loaded with the appropriate tab material applied according to ASTM 3039/D3039-08 standard [20]. The crosshead speed is determined based on displacement as 1mm/min. The various laminates produced were tested for five samples each and up to failure of the specimen. The tab configurations before loading are shown in Fig. 1e above. The tabs play a crucial role as specified in the ASTM standard. The tabs help to avoid localized stress concentration around the edge/ zone where the crosshead grips the material, thereby limiting the occurrence of failure around this zone, which in practice, would be wrong. An in-depth study into the effect of tabs on specimens can be found in the work of Belingardi et al. and Tabrizi et al. [21, 22], where the authors investigated the effect of various tab configurations during tensile tests.

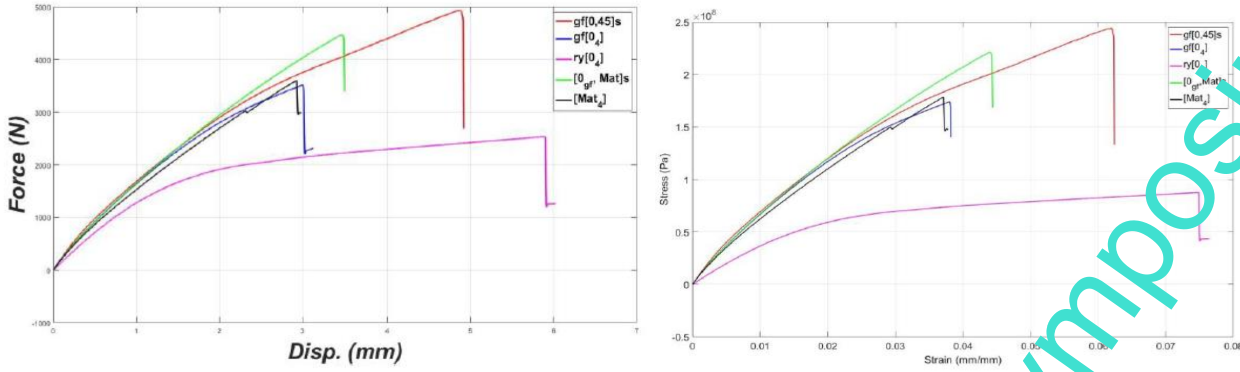


Fig. 3. (a) Average Force-Displacement Plot of Different Samples (b) Stress-Strain Average Plot of Different Samples

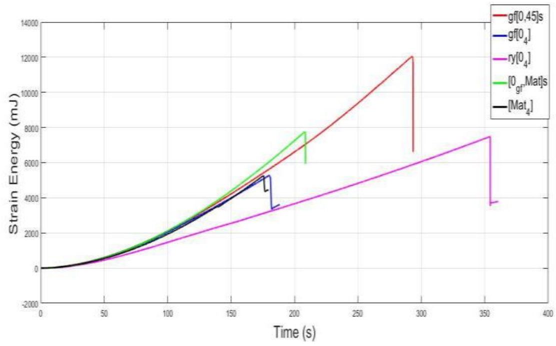
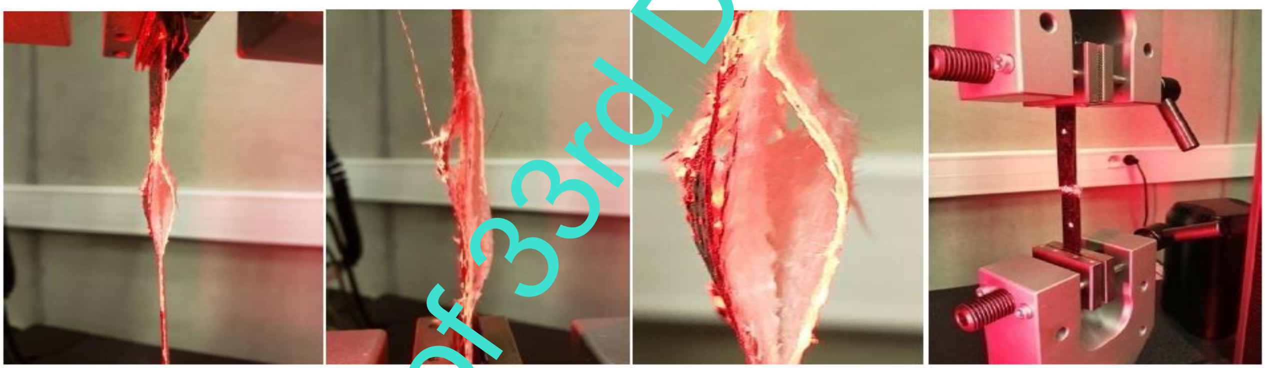


Fig. 3. (c) Strain Energy Vs Time



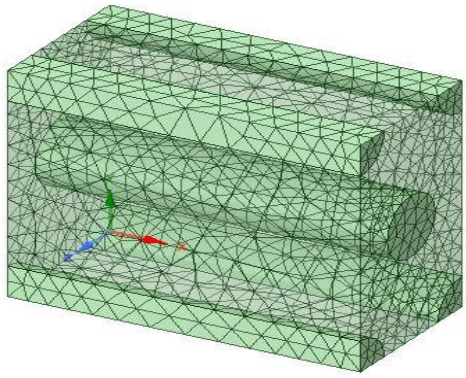
(a) (b) (c) (d)

Fig. 4. (a,b,c) Mid-zone edge delamination [Mat_4] (d) Mid-zone long splitting.

Figure 3 shows the various plots of displacement and force, stress-strain and strain energy as it relates to time, whereas Figure 4 captures the various failure profile discussed in ASTM 3039/D3039M - 08 standard.

4.1. FEM Micromechanical Homogenization of a Laminate

Homogenization is a critical step towards constructing and designing composite structures [23]. The fundamental idea is to establish the macroscopic behaviour of composites knowing that they are heterogeneous at the microscopic level to generate engineering constants E_{11} (axial direction), E_{22} (transverse direction), G_{12} (in-plane shear modulus), G_{23} (out of plane shear modulus), and v_{12} (in-plane Poisson's ration). Voigt, 1889 and Reuss, 1929 devised the earliest method, called the rule of mixture (ROM), for deducing the values of the engineering constants of a laminate. The more recent Halpin_Tsai model succeeded but is still limited in predicting the value of G_{23}, as is ROM. However, since the inception of finite element method (FEM)/finite element analysis (FEA) has been extensively used by researchers and scientists to determine the elastic properties of composite materials [24][25][26].



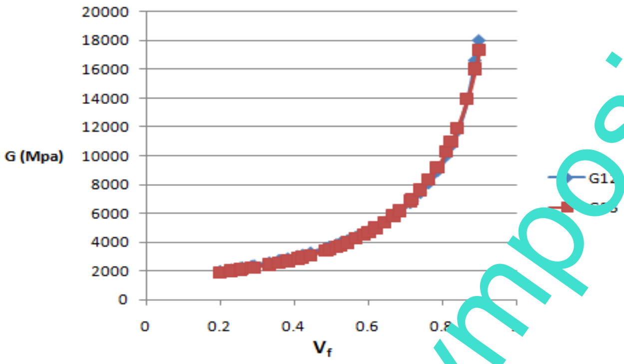
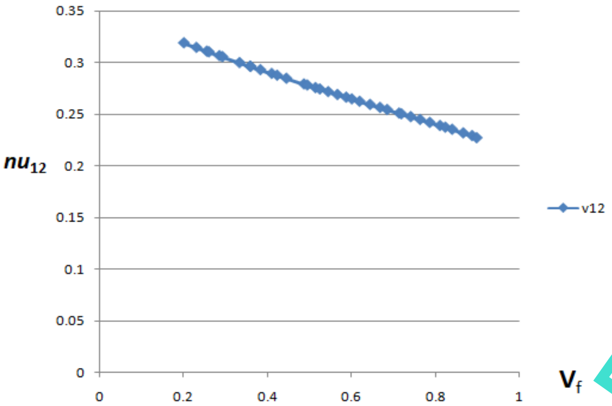


Fig. 6. (a) 3D RVE of a laminate (hexagonal type) (b) Plots of *G(long. and transv.)* and V_f



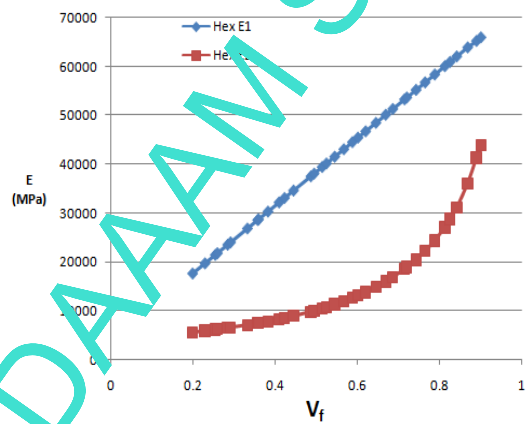


Fig. 7. (a) Plots of ν_{12} and V_f (b) Plots of *E (long. and transv.)* and V_f

Although further work already in progress will compare more results by looking at two other model types different from Figure 6a. It will compare the results from other resin types, including polyamide and polyester resins. This method presents a suitable means of calculating the material properties by homogenization.

5. Conclusion

As shown in Figure 4, the failure profile is described considering three criteria: *failure type*, which could be angled, edge delamination, grip/tab, lateral, multi-mode, or explosive. The second criterion is *failure area*, denoting that failure could occur inside the grip/tab, at the grip/tab, within the gauge zone, multiple areas, etc. The last criterion is failure location, which specifies the failure domain on the composite and includes bottom, top, left, right, middle, and various locations combined. Further work will be in the simulation of the failure of laminates using Comsol-multiphysics macromechanical analysis of laminates and the development of failure envelopes in terms of failure indices and safety factors. The layering configuration affects the mechanical behaviour and response of the laminate. The laminate with rayon yarn showed comparably higher strain than the other laminates making it a good fit for applications requiring strain applications. A cloud-based tool called CDMHub is also proposed to be used for modelling the laminates. Other areas of further research will be the hybridization of fabrics used for reinforcement, as mentioned in Section 1. Two different types of yarn are woven to form one fabric; this has been shown by research to improve the mechanical characteristics of fabric taken from the individual yarns which make up the hybridized fabric. Finite element tools have proven to be productive enough to determine the properties of unidirectional composite materials in homogenization. Other areas of further research and continuation are on macromechanical analysis of laminates in Comsol and Ansys ACP Pre.

5. Acknowledgements

This publication was written at the Technical University of Liberec as part of the project “Research of advanced materials, and application of machine learning in the area of control and modelling of mechanical systems” no. SGS-2022-5003 with the support of the Specific University Research Grant, as provided by the Ministry of Education, Youth and Sports of the Czech Republic in 2022.

6. References

[1] Skocik, Petr & Korbel, Jiri (2017) Assessment of shielding effectiveness and percolation threshold of composite materials, Proceedings of the 28th DAAAM International Symposium, pp.0054- 0062, B. Katalinic (Ed.), Published by DAAAM International, ISBN 978-3-902734-11-2, ISSN 1726-9679, Vienna, Austria DOI: 10.2507/28th.daaam.proceedings.007

[2] Hodzic, D. & Pandzic, A. (2019). Influence of carbon fibres on mechanical properties of materials in FDM technology, Proceedings of the 30th DAAAM International Symposium, pp.0334-0342, B. Katalinic (Ed.), Published by DAAAM International, ISBN 978-3-902734-22-8, ISSN 1726-9679, Vienna, Austria. DOI: 10.2507/30th.daaam.proceedings.044

[3] Ramesh, M.; Sri Ananda, A. T.; Aswin, U. S.; Eashwar, H. & Deepa, C. (2014) Processing and mechanical property evaluation of banana fibre reinforced polymer composites; 12th Global Congress on Manufacturing and Management; Procedia Engineering, pp. 97:563 – 572.

[4] Astrom, B. T. (2001) Introduction to manufacturing of polymer-matrix composites. ASM, International, Materials Park, OH, pp. 421 – 422.

[5] Gupta, M. K. & Srivastava, K. R. (2015) Mechanical properties of hybrid fibres-reinforced polymer composite: a review. Jour. of Pol. & Plas. Techn. and Eng., vol. 55, No.6, pp. 626 – 642. DOI:10.1080/03602559.2015.1098694.

[6] Todor, P. M.; Bulei, C. & Kiss, I. (2018) Composite materials manufacturing using textile inserts with natural origins fibres. IOP Conference Series: Mat. Sci. & Eng., 399 012088. DOI:10.1088/1757-899X/399/1/012088.

[7] Zaman, H. U.; Khan, A.; Khan, A. R.; Huq, T.; Khan, A. M.; Shah, Md.; Rahman, Al-Mamun Md & Poddar P. (2010) Preparation and characterization of jute fabrics reinforced urethane based thermoset composites: effect of UV radiation. Jour. of Fiber and Polymers, vol. 11, No 2, pp. 258--265. DOI 10.1007/s12221-010-0258-7.

[8] Idriss, A. K. M.; Khan, M. A. & Ali, A. M. (1997) Study on jute material with urethane acrylate by UV curing. Radiation Physics Chemistry. vol. 49, No. 3, pp. 383 – 388.

[9] Zhu, J.; Zhu, H.; Njiguna, J. & Abhyankar, H. (2013) Recent development of flax fibres and their reinforced composites based on different polymeric matrices. Materials Conference, vol. 6, pp. 5171 -5198.

[10] Bahrami, M.; Abenojar, J. & Martinez, M. A. (2020) Recent progress in hybrid bio-composites: mechanical properties, water absorption, and flame retardancy. www.mdpi.com/journal/materials. Material, vol. 13, pp. 5154, DOI:10.3390/ma13225145.

[11] Nguyen, H., Zatar, W. & Mutsuyoshi, H. (2017) Hybrid polymer composites for structural applications. Woodhead Publishing, Elsevier. DOI:10.1016/B978-0-08-100785-3.00002-4; Corpus ID: 136205525.

[12] Kumar, P. A. & Mohamed, N. M. (2017) A comparative analysis on tensile strength of dry and moisture absorbed hybrid kenaf/glass polymer composites. sagepub.co.uk/journals 0(00) 1 – 24, DOI:10.1177/1528083717720203.

[13] Safarabadi, M. & Shokrieh, M. M. (2014) Understanding residual stresses in polymer matrix composites. Science Direct. DOI:10.1533/9780857098597.2.197.

[14] Yahaya, R.; Sapuan, S. M.; Jawaid, M.; Leman, Z & Zainudin, E. S. (2015) Effect of layering sequence and chemical treatment on the mechanical properties of woven kenaf-aramid hybrid laminated composites. Jour. of Materials and Design vol. 67. pp. 173 – 179. http://dx.doi.org/10.1016/j.matdes.2014.11.024.

[15] Tagarielli, V. L.; Minisgallo, G.; McMillan, A. J. & Petrinic, N. (2010) The response of a multi-directional composite laminate to through-thickness loading, Jour. of Comp. Sci. and Tech. vol. 70, pp. 1950 – 1957. doi: 10.1016/j.compscitech.2010.07.013.

[16] Paul, S. A.; Boudenne, A.; Ibos, L., Candau, Y., Joseph, K. & Thomas, S. (2008) Effect of fibre loading and chemical treatments on thermophysical properties of banana/polypropylene commingled composite materials; Composites Part A: Applied Science and Manufacturing; vol. 39(9), pp. 1582-1588.

[17] Vijayan, R. & Krishnamoorthy, A. (2018) Experimental analysis of hybrid (roselle, aloe vera and glass) natural fibre-reinforced composite material. International Journal of Mechanical and Production Engineering Research and Development, vol. 8, Issue 4, pp. 303-314.

[18] Meenakshi, M. C. & Krishnamoorthy, A. (2019) Experimental and finite element analysis on the mechanical performance of hybrid fibre-reinforced epoxy composites. International Journal of Mechanical and Production Engineering Research and Development, vol. 9, Issue 4, pp. 1195 - 1202.

[19] Autar K. K. (2006) Mechanics of composite Materials; ISBN:10:0-8493-1343-0, 13: 978-0-8493-1343-1; Taylor and Francis; TA418.9.C6K39-2005.

[20] ASTM 3039/D3039-08. Standard test method for tensile properties of polymer matrix composite materials. ASTM Int'l: PA 19428 – 2959.

[21] Belingardi, G.; Paolino, D. S. & Koricho, E. G. (2011) Investigation of the influence of tab types on tensile strength of E-glass/epoxy fibre reinforced composite materials. Comp A: vol. 10, pp. 3279-3284. https://doi.org/10.1016/j.proeng.2011.04.541.

[22] Tabrizi, E. I. & Yildiz, M. (2019) Determining tab materials for tensile test of CFRP laminates with a combined usage of digital image correlation and acoustic emission techniques. Comp A: vol. 127:105623. https://doi.org/10.1016/j.cpompositesa.2019.105623.

[23] Yan, C. (2019) On homogenization and de-homogenization of composite materials. PhD Thesis, Drexel University, PA, USA.

[24] Alexander, A. & Tzeng, J. (1997) Three-dimensional effective properties of composite materials for finite element applications. Journal of Composite Materials. Vol. 31(5), pp. 446—485.

[25] Michel, J.; Moulinec, H & Suquet, P. (2009) Effective properties of composite materials with periodic microstructure: a computational approach. Computer Methods in Applied Mechanics and Engineering, vol. 172(1—4), pp.109—143.

[26] Sun, H.; Di, S.; Zhang, N.; & Wu, C. (2001) Micromechanics of composites materials using multivariable finite element method and homogenization theory. International Journal of Solids and Structures, vol. 38(17), pp.3007 – 3020.