

ANALYSIS OF HYBRID COMPOSITES OF 3-D WOVEN CARBON FIBRE AND PARTICULATES REINFORCED ULTRA-HIGH DENSITY POLYETHYLENE FOR HUMAN HARD BODY ARMOUR APPLICATION

Agbo, S.^{1*}, Sumaila, M.¹ and Umaru, S.^{1,2}

¹Department of Mechanical Engineering, Ahmadu Bello University Zaria

²Department of Mechanical Engineering, Air Force Institute of Technology, Air Force Base Kaduna

*Corresponding email: steveagbo1@gmail.com

ABSTRACT

The insecurity which has taken over the nation gave rise for the research and development of Human Hard Body Armour protection. The device serves as an important tool in the hands of military and para-military for protection against projectile. This research aimed at designing and producing hard body armour hybrid composite materials. A hybrid composite from the 6cm of (3-D) woven mat Carbon Fibre and particulates: 0.075 μ m Metal Chips (Mild Steel), 0.075 μ m of Aluminium Silicate (Glass), 0.040 μ m Alumina (Ceramic) were the reinforcements while the smelted ultra-high-density Polyethylene was the matrix for the production of the hard human armour. The percentage by weight of Polyethylene (matrix) was varied from 44wt% to 76wt% for optimization. The sample specimen of composites were produced for Mechanical property tests; Tensile Strength of (10x15x100)mm³, Impact Strength of (10x10x100)mm³, Flexural Strength of (30x30x100)mm³, and Hardness Strength of (30x30)mm². The experimental results showed that the highest Tensile Strength of 113MPa, Impact Strength of 2.855J, Flexural Strength of 122.517MPa and Hardness Strength of 67Hv were obtained. The variation of the storage modulus 350MPa (E') of the percentage by weight of resin in composite was determined. The loss modulus (E'') as a function of temperature for the composite was analysed and the variation of the damping factor 0.27 (Tan δ) as a function of temperature of the composite was considered. The Dynamic Mechanical Analysis (DMA) showed that the Human Hard Body Armour could withstand impact energy at the temperature of 115°C. It is hereby recommended that more research work should be carried out using local materials readily available with high mechanical properties to minimize cost.

Keywords: Dynamic mechanical analyses, Armour, Storage Modulus (E'), Loss Modulus (E''), Damping Factor (Tan δ)

1 INTRODUCTION

Hybrid composites are manufactured with more than one type of reinforcement fibre in the same matrix. To further enhance the properties of synthetic fibre composites, reinforcements such as carbon and aramid fibres are hybridized with natural composites. Recently, reinforcements in hybrid form have been introduced for use in composites to exploit the advantages of hybrid structures, such as their superior mechanical and dimensional stability [1]. The performance of hybrid composites are determined by many factors, such as the matrix, fibre–matrix interfacial bonding, length and shape of individual fibres, and volume fraction of the natural or synthetic fibres.

Previous researchers have studied the effect of varying the fibre content on the mechanical properties of hybrid composites consisting of natural and carbon fibres. Temperature is a key environmental factor and it has a significant influence on the mechanical properties of materials. Elevated temperatures can impair the mechanical performance of composite materials during tests and will cause damage, such as matrix cracking, inter-laminar cracks, intra-ply damage, subsurface delamination, and fibre breakage compared with synthetic fibres, natural fibres tend to degrade at lower temperatures. [2] stated that this is a major issue for both the manufacture and application of composites. The thermal degradation of certain natural fibre-reinforced composites has been investigated. However, the effect of elevated temperature on the mechanical properties of metal chips, aluminum silicate, alumina, carbon and polyethylene reinforced hybrid composites has not yet been investigated. The use of metal chips, aluminum silicate, alumina, *carbon and* polyethylene reinforced hybrid composites offers many advantages, such as acceptable specific strengths and moduli, reduced tool wear, and superior biodegradability. [3] evaluated the performance of glass/sisal hybrid composites focusing on mechanical (flexural and impact) and dynamic mechanical analyses (DMA). Hybrid composites with different fibre loadings and different volume ratios between glass and sisal were studied. The effect of the fibre length has also been investigated. The densities of the composites were compared with the theoretical values, showing agreement with the rule of mixtures. The results obtained in the flexural and impact analysis revealed that, the properties were always higher for higher overall reinforcement content. By DMTA, an increase in the storage and loss modulus was found as well as a shift to higher values for higher glass loading and overall fibre volume. It was noted that, there was an increase in the efficiency of the filler and calculated activation energy for the relaxation process in the glass transition region. The fiber length did not significantly change the results observed in all analysis carried out in this work. The calculated adhesion factor increased for higher glass loadings, meaning the equation may not be applied for the system studied and there are other factors, besides adhesion influencing energy dissipation of the composites. [4] investigated the dynamic mechanical and thermal properties of hybrid jute/sisal fibre reinforced epoxy composites. The hybrid composites were prepared by hand lay-up technique having total fibre loading of 30% by weight with different weight ratios of jute and sisal fibres. Dynamic mechanical properties such as storage modulus (E'), loss modulus (E'') and damping factor ($\tan \delta$) were investigated in the temperature range of 30 to 200°C. The thermal stability of the prepared composites was studied using thermo gravimetric analysis. Other thermal properties such as glass transition temperature (T_g), crystallization temperature (T_c) and decomposition temperature (T_d) were also obtained by differential scanning calorimetry. The results indicated a positive effect of hybridization in terms of increase in dynamic mechanical and thermal properties. Storage modulus, loss modulus and T_g were found to be higher for hybrid composite having a higher percentage of jute fibres. [5] carried out an investigation on thermal behavior and dynamic mechanical analysis of pennisetum purpureum/glass-reinforced hybrid composites. Hybrid composite laminates were fabricated using untreated 5% or 10% using a vacuum infusion process. The volume fractions of p.purpurem, glass fibre, and epoxy resin were 24%, 61% and 70% respectively. Thermogravimetric analysis (TGA) demonstrated that the amount of residue of the hybrid composite decreased as the concentration of the alkali used to treat the p.purpurem fibres were 64, 64, 67 and 63°C respectively as determined by dynamic mechanical analysis (DMA). [6] carried out a dynamic mechanical analysis to determine the influence of moisture on the mechanical properties of interwoven hemp/polyethylene terephthalate (PET) hybrid composites. Composite laminates were fabricated using vacuum infusion process; from epoxy resin reinforced with interwoven hemp and PET fibres woven hemp, woven PET, and interwoven hemp/PET hybrid composites were produced. The hybrid hemp/PET composites yielded the highest final residue percentage due to the PET fibres which improved the thermal stability. From the glass transition temperatures of the woven hemp, woven PET and interwoven hemp/PET hybrid composites were 68, 67, and 69°C respectively. [7] carried out the dynamic and static mechanical properties of randomly oriented intimately mixed short banana/sisal hybrid fibre reinforced polyester composites. Dynamic properties such as the storage modulus (E'), damping behavior ($\tan \delta$) and static mechanical properties such as tensile, flexural and impact properties were investigated as a function of total fibre volume fraction and the relative volume fraction of the two fibres. The storage modulus was found to increase with fibre volume fraction above glass transition temperature (T_g) of the matrix and maximum value was obtained at a volume fraction (V_f) of 0.40. The $\tan \delta$ peak height was minimum

and peak width was maximum at $0.40V_f$. Tensile modulus and flexural strength were found to be highest at 0.40 volume fraction, which indicates effective stress transfer between the fibre and matrix. A positive shift in T_g of polyester matrix at $0.40V_f$ also indicates better fibre/matrix interaction. In this research, a hybrid composite from the 6cm of (3-D) woven mat Carbon Fibre and particulates: $0.075\mu\text{m}$ Metal Chips (Mild Steel), $0.075\mu\text{m}$ of Aluminium Silicate (Glass), $0.040\mu\text{m}$ Alumina (Ceramic) were the reinforcements while the smelted ultra-high-density Polyethylene was the matrix. The percentage by weight of Polyethylene (matrix) was varied from 44wt% to 76wt% for optimization. The variation of the storage modulus 350MPa (E') of the percentage by weight of resin in composite was determined. The loss modulus (E'') as a function of temperature for the composite was analysed and the variation of the damping factor 0.27 ($\text{Tan } \delta$) as a function of temperature of the composite was considered. The Dynamic Mechanical Analysis (DMA) showed that the Human Hard Body Armour could withstand impact energy at the temperature of 115°C .

2 METHODOLOGY

Materials used include Carbon Fibre which was obtained from Nigerian Air Force, Air Force Base Kaduna. It is the dense carbon fibre with three dimensional woven fibre for high mechanical properties performance. Metal Chips (Mild Steel) was sourced from Air Force Institute of Technology Kaduna Central Workshop. The chips were taken to Chemical Engineering for Milling using Ball Milling Machine to particle sizes of 0.03mm in ABU Zaria. The Chips were further subjected to mechanical impact force using piston, in Building Technology Department of the same Institution which reducing the particle sizes to $0.075\mu\text{m}$. Aluminium Silicate (Al_2SiO_5) was sourced from Kaduna Metropolis where the particle sizes were reduced using hammer to the particle sizes of 0.01mm . The particle sizes were further reduced using Ball Milling Machine to $0.075\mu\text{m}$ from ABU Zaria Kaduna. Ceramic- Alumina (Al_2O_3) was sourced from Nigerian Research Institute of Metals and Mineral resources (Malani) in Kaduna. The material was milled with Ball Mill Machine in Chemical Engineering Department to the particle sizes of $0.04\mu\text{m}$. The Ultra-High Density Polyethylene was bought from the National Institute of Leather and Polymer Technology Zaria. It was smelted using two roll mill after ten (10) minutes Table 1 shows the materials description. Table 1 shows the materials description.

Table 1. Materials Description

S/N	Material description	Particle size (μm)	State
1	Ultra-high-density polyethylene		Smelted
2	Aluminum silicate (Al_2SiO_5)	0.075	Particulate
3	Alumina (Al_2O_3)	0.04	Particulate
4	Metal chip (Mild steel)	0.075	Particulate
5	Carbon fibre		woven mat

2.1 Sample Preparation of the Materials for Mechanical Test

The percentage weight of aluminium silicate, alumina, metal chips (mild steel), polyethylene and carbon fibre each are measured with a digital weighing balance. The required pellets of polyethylene were smelted and the quantities of these particulates were added to the TwoRoll Mill and rolled for ten (10) minutes for proper mixing of the particulates. The composites were layed into the mould and were placed in a compressive machine at a holding temperature of 120°C for 15 minutes. The laminates produced is cooled in the air for about 30minutes before the mechanical test was carried out.

2.2 Mechanical Test

Sample specimen preparation for bending strength of $(30 \times 30 \times 100) \text{mm}^3$, tensile strength of $(100 \times 15 \times 10) \text{mm}^3$, impact strength of $(100 \times 10 \times 10) \text{mm}^3$ and hardness strength of $(30 \times 30) \text{mm}^2$ were carried out.

The tensile test was carried out using Universal Electronic Testing Machine in Metallurgical and Material Engineering Department laboratory, ABU Zaria, with model WDW-100KN 190536. The test samples were placed and gripped in between the jaws of the machine. The load was gradually

applied through a hydraulic press until deformation occurred and the result was displayed digitally [12] Ultimate tensile strength stresses were calculated using equations 1 and 2.

$$\sigma = \frac{P}{A} \quad (1)$$

$$A = \frac{\pi d^2}{4} \quad (2)$$

Where P is the maximum applied load; A is the cross-sectional area of the machine sample; d is the diameter of the machined samples.

The impact test was carried out on the Charpy impact testing Machine in accordance to HD96QD (15J and 25J) present in the Metallurgical and Material Engineering Department ABU Zaria. The machine consists of tops between which the test sample is inserted. With the specimen positioned in the vice, a blow was stroked by two released pendulums in opposite directions from their calibrated standard height to fracture off the specimen. The energy retained was determined by the height rise of the pendulum as indicated by the dial gauge. The difference between the energy input and energy retained gave the energy absorbed [13].

The hardness values of the hybrid fibre/particulates composites were determined in accordance with the ASTM E140 standard using the Vickers Hardness testing machine present in the shell office, department of Mechanical Engineering A.B.U., Zaria. The machine consists of a digital display reading HV and HB., 0.42cm steel ball indenter with a load of 0.3kgf. The specimens prepared to a good finish of perfectly horizontal surface were indented. The depth of indentation indicated the hardness of the laminates [14].

The machine used for the flexural test is a universal tester of model Nr. 261. It has a hydraulic press that actuates the pressure of the machine to grip the load and the result of the force is displayed digitally on the machine of the composite materials. The Universal Material Testing Machine is situated in Mechanical Engineering Department, ABU Zaria [15].

3 RESULTS AND DISCUSSION

3.1 Thermal Analysis- Dynamic Mechanical Analysis

The Dynamic Mechanical Analysis apparatus is so-called resonant system i.e. the measuring frequency is not constant. The Dynamic Mechanical Analysis systems are nearly always fixed-frequency systems operating at frequencies between 0.01 and 100 Hz. It requires a temperature region ranging from -150°C to 300°C. The Dynamic Mechanical Analysis of the polymer composites preferred the frequency of 2.5Hz, 5Hz and 10Hz, recommended for polymers. From Dynamic Mechanical Analysis, it uses storage modulus (E'), the loss modulus (E'') and the damping factor ($\tan \delta$) for the evaluation of the material properties.

3.2 Storage Modulus (E')

The storage modulus is the measure of the elastic energy stored in a material that can be recovered. It is used to evaluate the elastic behaviour of a material subjected to sinusoidal loading by [16] In fibre reinforced polymer composite, the storage and loss modulus behaviour is governed by the matrix type, fibre loading, fibre length, fibre dispersion and fibre matrix adhesion by [17]. From the graph shown in Figure 1, it can be seen that the higher the temperature the lower the storage modulus of the composite accepts for the percentage by weight of 60wt% polyethylene that has its value almost the same. The percentage by weight of 68wt% polyethylene in the composite has the highest storage modulus while 76wt% has the lowest storage modulus at the elevated temperature.

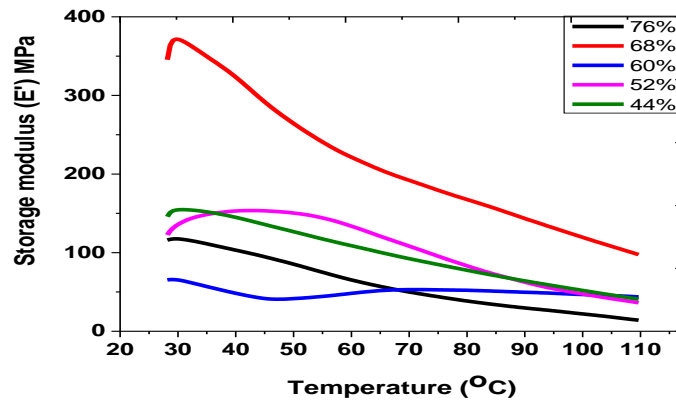


Figure 1. Variation of the storage modulus (E') of the percentage by weight of resin in composite

3.3 Loss Modulus (E'')

The loss modulus is a measure of the energy loss due to the viscous flow of the polymer molecules in a material subjected to sinusoidal loading by [5]. Normally, the loss modulus is dependent on the frictional resistance between the fibre reinforcement and the matrix. It describes the energy dissipated (lost as heat) during a deformation cycle. A high loss modulus indicates viscous behavior and hence marked damping properties. When the timescale of molecular motion coincides with that of mechanical deformation, each oscillation is converted into the maximum-possible internal friction and non-elastic deformation. The loss modulus, which is a measure of this dissipated energy, also reaches a maximum and is denoted as the glass transition (T_g) temperature of the system by [16]. The highest loss modulus was obtained from Figure 2, except for 60wt% polyethylene in the composite, all loss modulus can be observed to decrease with an increase in temperature because, as the temperature increases, the value of loss modulus goes through the maximum in the transition region and then decreases in the rubbery region. The percentage by weight of 68wt% polyethylene of the composite has the highest loss modulus peak at a temperature of 114.9°C while 76wt% of polyethylene exhibited the least energy dissipation with a T_g at 115.4°C.

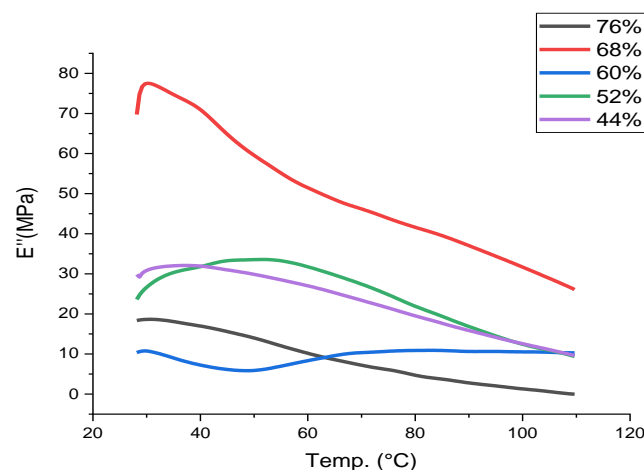


Figure 2. The loss modulus (E'') as a function of Temperature for 76%, 68%, 60%, 52% and 44% composite

3.4 Damping Factor or Phase Angle ($\tan \delta$)

The ratio of the storage modulus (E') to loss modulus (E'') of a material defines as the index of mechanical damping factor or the tangent of the phase angle ($\tan \delta$). It is a dimensionless parameter and a measure of the ability to dissipate energy through molecular movement when subjected to dynamic sinusoidal loading [7]. In fibre reinforced polymer composite, the material damping

behaviour is dependent on the friction between fibre and matrix, molecular movement in the polymer chain, fibre strength and the rate of crack propagation in composite system [5]. The height of the $\tan \delta$ is associated with the extent of energy dissipation as a result of polymer molecular chain movement. From Figure 3, the percentage by weight of 52wt% polyethylene of the composite has the highest damping factor while 76wt% has the lowest damping factor. All damping factor ($\tan \delta$) of the composite increases with temperature except the percentage by weight of 76wt% that decreases with the increase in temperature.

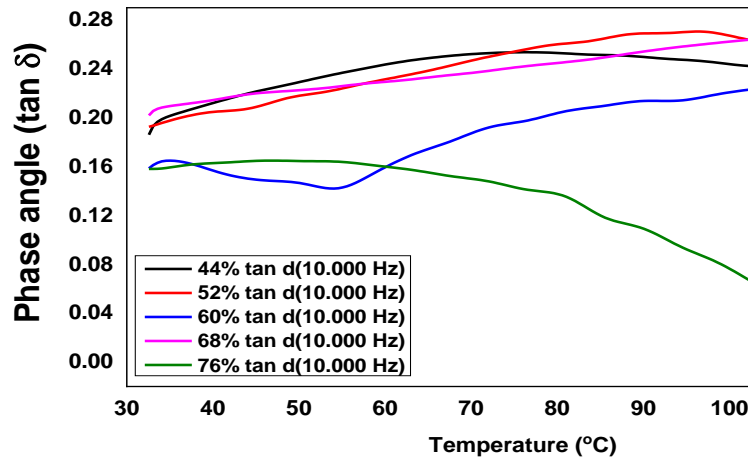


Figure 3. variation of the damping factor ($\tan \delta$) as a function of Temperature for 76%, 68%, 60%, 52% and 44% composite

The oscillating load for polymer of 76wt% was 100MPa, the peak temperature of 115.4°C and the damping factor or dissipation energy ($\tan \delta$) was 0.20. The oscillating load for polymer of 68wt% was 350MPa, the peak temperature of 114.9°C and the damping factor ($\tan \delta$) was 0.267. The oscillating load for polymer of 60wt% was 65MPa, the peak temperature of 115.4°C and the damping factor ($\tan \delta$) was 0.250. The oscillating load for polymer of 52wt% was 140MPa, the peak temperature of 115.9°C and the damping factor ($\tan \delta$) was 0.271. The oscillating load for polymer of 44wt% was 140MPa, the peak temperature of 89.1°C and the damping factor ($\tan \delta$) was 0.254.

4 CONCLUSIONS

From the results obtained the percentage by weight of 68wt% polyethylene has the highest storage energy of 350MPa therefore, it can withstand the impact energy of the projectile of 350MPa. The percentage by weight of 60wt% polyethylene has the lowest storage energy of 65MPa which means, it can only withstand the impact energy of the projectile of 65MPa was the smallest storage energy among the five samples composites. The percentage by weight of 52wt% has the highest projectile impact energy of temperature 115.9°C which signifies that it can withstand higher temperature and dissipation energy of 0.271.

REFERENCES

1. Tolera, A.N., Yusuf, P., Yasin, A., Ali, K. and Jawaid, M. (2021). Mechanical and dynamic mechanical thermal properties of ensete fibre/woven glass fibre hybrid composite. *Journal of Applied Polymer Science*, vol. 259, issue 1, pp. 11-16.
2. Solomon, U., Ridzuan, M.J.M., Abdu, M.S.M., Cheng, E.M. and Razlan, Z.M. (2021). Effect of thermal aging on the scratch resistance of natural fibre reinforced epoxy composites. *Composite Structures*, vol. 261, pp. 13-22.
3. Heltor, L.O.J., Alexandre, S.B., Rudinel, F., Ademir, J.Z. and Sandro, C.A. (2010). Mechanical and dynamic mechanical analysis of hybrid composites molded by resin molding. *Journal of Applied Polymer Science*, vol. 118, issue 2, pp. 887-896. <https://doi.org/10.1002/app.32388>.

4. Gupta, M.K. (2016). Thermal and dynamic mechanical analysis of hybrid jutes/sisal fibre reinforced epoxy composite. *Journal of materials; design and applications*, vol. 55, pp. 626-642. <https://doi.org/10.1177/1464420716646398>.
5. Ridzuan, M.J.M., Abdulmamid, M.S., Afendi, M., Mazlee, M.N. and Gibson, A.G. (2016). Thermal behavior and dynamic mechanical analysis of pennisetum purpureum/glass reinforced epoxy hybrid composite. *Composite Structures*, vol. 152, Issue 15, pp. 850-859. <https://doi.org/10.1016/j.comstruct.2016.06.026>.
6. Ahmad, M.A.A., Abdulmakid, M.S., Ridzuan, M.J.M., Mazlee, M.N. and Gibson, A.G. (2018). Dynamic mechanical analysis and effects of moisture on mechanical properties of interwoven hemp/polyethylene terephthalate (PET) hybrid composites. *Journal Construction and Building Materials*, vol. 179, issue 10, pp. 265-276. <https://doi.org/10.1016/j.conbuildmat.2018.05.227>.
7. Maries, I., Malhotra, S.K., Kuruvilla, J. and Sabu, T. (2005). Dynamic mechanical analysis of randomly oriented intimately mixed short banana/sisal hybrid fibre reinforced polyester composite. *Composite Science and Technology*, vol. 65, issue 7-8, pp. 1077-1087.
8. Anuar, H., Ahmad, S.H., Rasid, R., Ahmad, A. and Wanbusu, W.N. (2007). Mechanical properties and dynamic mechanical analysis of thermoplastic natural-rubber-reinforced short carbon fibre and kenaf fibre hybrid. *Composites Journal of Applied Polymer Science*, vol. 107, issue 6, pp. 4043-4052. <https://doi.org/10.1002/app.27441>.
9. Arulmurugan, M., Prabu, K., Rajamurugan, G. and Selvakumar, A.S. (2019). The influence of barium sulfate filler on the woven natural fibre alovera /hemp/flax hybrid composites behavior. *Bull. Mater. Sci.*, vol. 6, pp. 43-58.
10. Subhash, M. and Sarfaraz, A. (2012). Dynamic mechanical analysis and morphological studies of glass/bamboo fibre reinforced unsaturated polyester resin-based hybrid. *Composites Journal of Applied Polymer Science*, vol. 125, issue 1, pp. 382-387. <https://doi.org/10.1002/app.36304>.
11. Umar, L.D., Bhagawan, S.S. and Thomas, S. (2010). Dynamic mechanical analysis of pineapple leaf/glass hybrid fibre reinforced polyester composite. *Polymer Composite*, vol. 31, issue 6, pp. 956-965. <https://doi.org/10.1002/pc.20880>.
12. Asim, A. (2019). Comparism of tensile properties and impact damage tolerance of hemp and glass fibre composites. *Journal of Reinforced Plastic Composites*, vol. 30, issue 22, pp. 1877-1893.
13. Gabriel, O.G., Frederico, M.M. and Carolina, G.D. (2015). Charpy impact test of epoxy composites reinforced with giant bamboo fibres. *Material Research*, vol. 2, issue 18, pp. 178-184.
14. Beniwal, D., Singh, P., Gupta, S. and Kramer, M.J. (2022). Distilling physical origins of hardness in multi-principal element alloys directly from ensemble neural network models. *Computational Materials*, vol. 8, issue 22, pp. 153-159.
15. Satish, K. and Helminiak, T.E. (2011). Compressive strength of higher performance fibres material science and engineering of rigid-rod polymers, *Cambridge University Press*, vol. 134, pp. 134-363.
16. Venkarajan, S., Subbu, C., Athijayamani, A. and Muthuraja, R. (2015). Mechanical properties of natural cellulose fibres reinforced polymer composites. *Materials Today Proceedings*, vol. 47, issue 4, pp. 1017-1024.
17. Nair, K.C.M., Thomas, S. and Groeninck, G. (2001). Thermal and dynamic mechanical analysis of polystyrene composites reinforced with short sisal fibres. *Composites Science and Technology*, vol. 61, pp. 2519-2529.