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Investigation of Dynamic Mechanical Behavior of Nanosilica Filled Carbon-Kevlar-Epoxy Polymer Hybrid Nanocomposite

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ABSTRACT

Reinforcement of epoxy-carbon-Kevlar fabric composite with the addition of nanosilica has resulted in the evolution of new hybrid polymer nanocomposite, which results in the improved mechanical properties of polymer hybrid nanocomposite. The current investigation concentrated on the dynamic mechanical behavior of unfilled and nanosilica filled carbon-Kevlar-epoxy polymer composite with five and four layers of carbon and Kevlar woven fibers respectively with epoxy matrix (5C4K). Nanosilica was mixed into the epoxy at different weight percentages (wt.%) of 0, 0.5, 1.0, and 1.5. The laminates were fabricated using the vacuum-assisted resin infusion moulding (VARIM) technique. The dynamic mechanical properties, storage modulus, loss modulus, damping factor (tan delta), and glass transition temperature was investigated using a dynamic-mechanical analyzer at temperature ranging from 25 to 165 degrees Celsius. The test specimens were prepared in accordance with the ASTM D4065 standard to investigate dynamic mechanical analysis (DMA) of the hybrid polymer nanocomposite. The results of the tested specimens for dynamic mechanical behaviors of carbon-Kevlar-epoxy hybrid nanocomposites are very much influenced by the presence of nanosilica. The storage modulus, loss modulus for nanosilica added hybrid polymer composites were more than the unfilled ones and the damping factor (tan delta) was observed more in an unfilled composite.

1. INTRODUCTION

Polymer composites with nanofiller find extensive engineering applications in aerospace, space, automobile, marine, infrastructure, sports, oil and pipe industries due to enhancement in mechanical, electrical and thermal properties as compared with the conventional materials [1, 2]. These properties of polymer composites still can be enhanced by hybrid polymer composites with nanofillers. The selection of matrix material and reinforcement material plays an important role for the production of polymer composite material which will have higher mechanical, electrical and thermal properties than the conventional one.

The commonly used matrix material for the fabrication of polymer composite is epoxy resin, which has low shrinkage after curing, impact resistance, low weight, ease of manufacturing and processing, excellent chemical resistant, excellent adhesion, electrical resistant, and heat resistant properties. Reinforcement of epoxy matrix with nanofillers improves crack propagation resistance as well as the thermomechanical properties of nanocomposites [3].

Fibers are a powerful strengthening material in polymer composites. Carbon fibers has good properties like high strength, high modulus, good electrical and thermal properties. Kevlar fibers possess better properties like good impact resistance, low density and good toughness. These fibers are hydrophobic, the moisture absorption content is low [4-6].

A composite with at least two different types of fibres reinforced in a single matrix is referred to as a "hybrid polymer composite", which provide a synergistic effect such as enhanced mechanical properties. Hybrid composites offered, strength and stiffness, reduced weight/cost, better fatigue resistance, balanced thermal stability, fracture toughness, impact resistance compared to mono fiber composite [6, 7].

Hybrid Polymer nanocomposites have received very much attention from nanoscience academics and industries due to their great physical, mechanical, and tribological properties. The addition of nano-sized inorganic fillers such as silica, titania, aluminium oxide, multiwall carbon nanotube, halloysite, nanoclay has reformed the mechanical and physical properties of the hybrid polymer composites extensively [8-17].

Nanosilica is white and comes in crystalline and amorphous forms. Nanosilica is porous, has a large surface area, containing several hydroxyl groups as well as unsaturated residual bonds. The addition of nanosilica can enhance the strength, flexibility and durability of polymers composite [18-20].

The mechanical properties of polymer composites are significantly influenced by manufacturing procedures. The methods like hand layup, vacuum bagging method, vacuum assisted resin infusion molding, autoclave are mainly used for manufacturing the polymer composite. Among these methods, the mechanical properties are found to be high in autoclave method, but it is an expensive method of manufacturing. On the other hand, vacuum assisted resin infusion molding technique produces the polymer composite with similar mechanical properties like autoclave in a reasonable cost of manufacturing the polymer composite [17].

Certain factors like aging in the type of liquid, aging time, type of polymer and reinforcement, curing rate of resin, filler content and diffusion coefficients are very much influence for the degradation of the polymer composite. The hybridization of polymer composites provides good resistance to the degradation of the properties as compared to normal composites [6]. The flexural properties of hybrid polymer nanocomposite having five layer of carbon and four layers of Kevlar with addition of nanosilica with 0.5 wt.% to epoxy matrix enhance the flexural properties as compared to unfilled nanosilica [20].

Presently dynamic mechanical analysis is more predominantly used to analysis viscoelastic properties, storage modulus, loss modulus, damping factor (tan delta) and glass transition temperature of the polymer composites. Dynamic mechanical analysis entails applying an oscillatory force to the test specimen to generate sinusoidal stress and strain. Which provides complex modulus, with storage modulus as real part and loss modulus as imaginary part. The real part corresponds to elastic portion and imaginary part corresponds to viscous portion of the polymer composite. The applied force leads in a sinusoidal strain that lags the force applied by a phase angle, and its measurement helps in finding the damping property of the polymer composite. This test also provides a safe range of working temperature with the help of the glass transition temperature (Tg) of the material. These measurements form the dynamic mechanical analysis help in assessing the composite material's capability to recover from the deformation and their damping property in the form of dissipating the energy as heat, to a sinusoidal force as a function of time and temperature. Also, the variations in the viscoelastic properties of polymer composites allows for the measurement of long-run changes that may take place in polymer composite material structures subjected to raised temperatures under the dynamic loading condition [21-23].

Sudarsharao [24] studied the addition of nanofiller graphite for dynamic mechanical behavior of carbon-epoxy polymer composite. The graphite filler was added in different wt. % 0, 2, 4 and 6. The presence of nanofiller influences the dynamic mechanical behaviour of the polymer composite. The storage as well as loss modulus increases as weight % of graphite increases and the highest value of tan delta are observed in an unfilled composite. Bommegowda et al. [1] The impact of micro and nanofiller hybrids on the dynamic mechanical behaviour of glass-reinforced epoxy polymer composites has been investigated. The micro and nanofillers used in the research work were aluminas, silica, graphite, silicon carbide, molybdenum disulfide and cenosphere. The test results show that the storage and loss modulus in the composites without micro and nanofiller have a minimum value as compared to those with micro and nanofiller. When hybrid cenosphere and molybdenum sulphide fillers are added to a base epoxy composite, the glass transition temperature rises by 2℃. Muralidhara et al. [25] focused on the effect of graphene nanoplatelets on dynamic-mechanical analysis of carbon-epoxy polymer composites. The test results reveled that the addition of graphene nanoplatelets influences storage modulus, loss modulus, and damping factor (tan delta) as compared to base composite. Ahmad et al. [26] studied the influence of graphene nanoplatelets/glass-reinforced epoxy polymer composite on dynamic mechanical analysis. The composite laminates were fabricated by adding graphene nanofiller to the epoxy matrix with 0.5 and 1.5 wt.%. The results revealed that 1.5 wt.% of graphene with glass-epoxy composite shows better dynamic mechanical properties due better interfacial bonding between the graphene nanofiller with epoxy matrix.

Present work investigating the significance of adding different weight % 0, 0.5, 1.0 and 1.5 nanosilica into carbon-Kevlar reinforced epoxy polymer composite on dynamic mechanical properties.

2. EXPERIMENTAL DETAILS

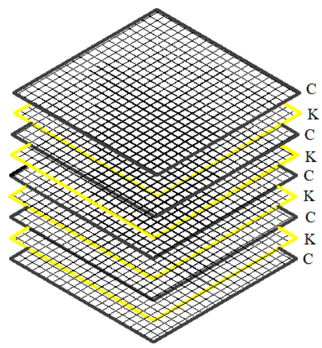
2.1 Materials

As reinforcement, 200 GSM and 220 GSM plain weave (0/90°) carbon and Kevlar were employed. Epotec-YD535LV epoxy resin, hardener TH7257C as a matrix material. The nanosilica having average particle size of 30-50nm used as nanofiller in the present work.

2.2 Composite fabrication

Table 1. Fiber stacking sequence were used in fabricating the hybrid polymer nanocomposite laminates

Laminate	Sequence of fiber
5C4K	C/K/C/K/C/K/C/K/C



C: Carbon layer K: Kevlar layer

Figure 1. Fiber stacking sequence of 5C4K

Table 2. The Hybrid polymer nanocomposites with nanosilica

Laminate	Laminates containing nanosilica wt.%
5C4K-NS0	Laminate unfilled with nanosilica.
5C4K-NS0.5	Laminate filled with 0.5 wt. % of nanosilica.
5C4K-NS1.0	Laminate filled with 1.0 wt. % of nanosilica.
5C4K-NS1.5	Laminate filled with 1.5 wt. % of nanosilica.

Hybrid polymer nanocomposites laminates were made up of five and four layers of carbon and Kevlar woven fiber respectively with epoxy matrix (5C4K), along with nanosilica weight percents of 0, 0.5, 1.0, and 1.5. Table 1 and Figure 1 show the fiber stacking sequence used in the present research work and Table 2 provides the polymer hybrid nanocomposites employed in the current study. The mixing ratio of YD535LV epoxy resin, and hardener TH7257C is 100:35 is used in the present fabrication process, as per the standards recommended by the Epotec for resin infusion technique [27]. The nanosilica was mixed with matrix material by high-speed shearing method. Vacuum-assisted resin infusion moulding (VARIM) technique was used to fabricate the hybrid polymer nanocomposite laminates. The hybrid polymer nanocomposite laminates were first cured at room temperature for 24 hours before being post-cured in an oven at 80 degrees Celsius for 5 hours [20]. The ASTM D 4065 standard was used to prepare the DMA test specimens [28].

2.3 Dynamic Mechanical Analysis (DMA) Test

DMA is popularly used technique to measure the viscoelastic properties of polymer composite [21]. The analysis was carried with DMA instrument ''TA instruments Q800''. with the dual cantilever method. The samples were prepared and the test was conducted according to ASTM D4065 standard. The dimensions of the test specimens used in the present work were 50mm x 10mm x 2.3mm. Initially, the test samples were kept at an isothermal temperature for five minutes, to achieve the thermal stabilization at 1Hz. The viscoelastic properties were found by heating samples from 25℃ to 165℃, at frequency of 1 Hz with 4℃/min heating rate and the flow rate of nitrogen 20 ml/min. The five test specimens were tested and the mean values were considered to discuss in the present work.

3. RESULT AND DISCUSSION

3.1 Storage modulus (E')

Storage modulus (E') is a measure of a material's elastic response that indicates the material's potential to the store energy elastically. The storage modulus curves for the hybrid nanocomposite 5C4K with different wt.% 0, 0.5, 1.0 and 1.5 of nanosilica varying with temperature from 25℃ to 165℃ is shown in the Figure 2. The storage modulus of the polymer hybrid nanocomposites gradually decreases as the increase in temperature. The polymer hybrid nanocomposites undergo a three-phase change as the temperature rises, which can be explained as a glassy, a transition, and a rubbery region [21]. Figure 2 is divided into three regions: the first glassy region, which ranges from room temperature to 60℃, the second transition region, which ranges from 60℃ to 110℃, and the third rubbery region, which is above 130℃. It is observed that from the Figure 2, the storage modulus is almost constant until 60℃, then starts decreasing. The decreasing curve indicates that with an increase in temperature, the composites change their state from glass to rubber region. The temperature at which the storage modulus decreases give an indication of the polymer hybrid nanocomposite's glass transition temperature. This temperature represents the polymer hybrid nanocomposite's transition from a glassy to a rubbery state, or vice versa [1]. High storage modulus in the range of 7709 to 11546 MPa was observed in the glassy region for the polymer composites, since the molecules are closely packed with a less mobility. The storage modulus increases by the addition of nanosilica as compared to unfilled composite. The highest storage modulus was found in 0.5 wt.% of nanosilica addition polymer hybrid nanocomposite as compared to 0, 1.0 and 1.5 wt. % nanosilica filled polymer hybrid nanocomposite. The storage modulus trend in the polymer hybrid nanocomposites is as follows 5C4K-NS0.5>5C4K-NS1.0>5C4K-NS1.5>5C4K-NS0.

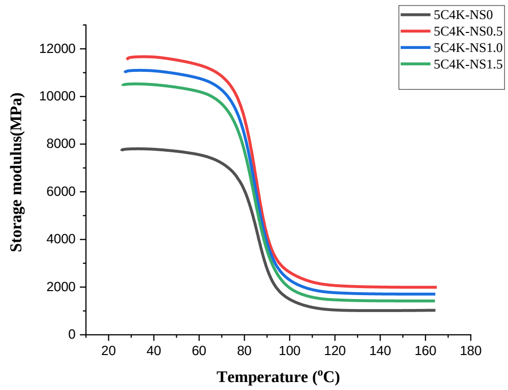


Figure 2. Storage modulus of 5C4K with different wt.% of Nanosilica

The enhance in storage modulus could be related to the presence of nano silica, which increases the surface area between fibers and epoxy, and the blending effect of nano-silica surface on the motion of the matrix molecular chain, as well as the friction between them increased. As the temperature starts increasing, the molecular motion also starts to increase, which results in, loss of stiffness, hence reducing the storage modulus of the polymer hybrid nanocomposite is observed after the glassy region [24, 26, 29].

3.2 Loss modulus (E")

The loss modulus (E") is a measure of the polymer composite's viscous response. Which mainly influenced by the interfacial bonding between the matrix and fiber. With temperature fluctuations, the loss modulus can be used to determine the glass transition temperature (Tg). At Tg, polymer hybrid nanocomposite changes its state from glassy to rubbery region, and temperature at the peak of loss modulus, corresponds to the temperature at which the glass transition occurs (Tg) [1]. Figure 3 shows, loss modulus of polymer hybrid nanocomposite for 5C4K with different wt.% of nanosilica varying with temperature from 25℃ to 165℃. From the graph, the loss modulus in polymer hybrid composites is minimum at room temperature, as the temperature rises the loss modulus also increases up to glass transition temperature and then it starts to decrease. It has been observed that the loss modulus for nanosilica filled composites shows better values as compared to unfilled ones in the entire temperature range. This indicates that the energy dissipation capacity of the polymer hybrid nanocomposite increases with the addition of nanosilica into the carbon-Kevlar-epoxy polymer composite. The highest value of loss modulus of 1518.351 MPa was found in 0.5wt.% of nanosilica added polymer hybrid nanocomposite due to strong interfacial adhesion and the lowest 1084.763 MPa in unfilled nanosilica composite. According to the graph, the loss modulus values are nearly constant at lower temperatures, but after 60℃, until the peak value, a steep increase can be seen. After reaching the peak value, a sharp decrease is observed until the very low loss modulus values which are maintained until 165℃. The loss modulus trend in the polymer hybrid nanocomposites is observed as follows 5C4K-NS0.5>5C4K-NS1.0>5C4K-NS1.5>5C4K-NS0.

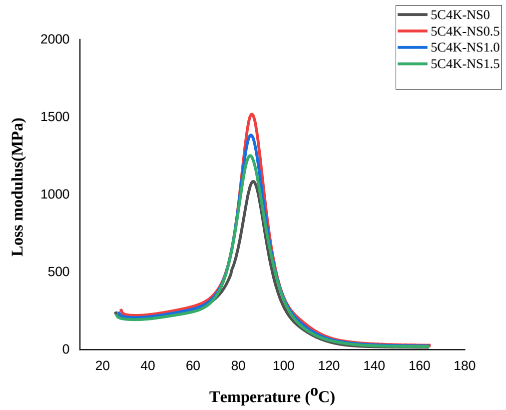


Figure 3. Loss modulus of 5C4K with different wt.% of nanosilica

3.3 Damping factor (tan delta)

The damping factor, is the ratio of loss modulus to storage modulus of a polymer composite. It is a method for determining the energy dissipation of a material as well as its energy absorbing capacity. Figure 4 depicts the fluctuation of damping factor with temperature. Up to 60℃, the damping factor (tan delta) is practically constant, then it begins to increase, reaches a peak value at the transition temperature, and then begins to decline. Which is the most common behaviour of epoxy in the transition state. The value of the damping factor is heavily influenced by interfacial bonding and reinforcements. The glass transition temperature (Tg) can also be computed by plotting the damping factor (tan delta) as a function of temperature [1].

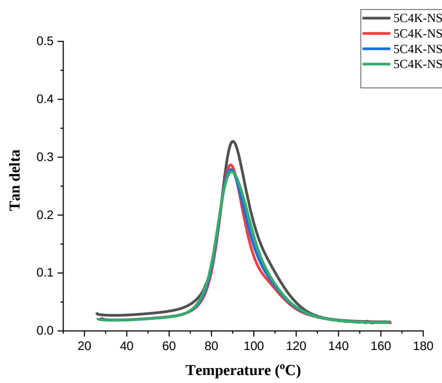


Figure 4. Damping factor (tan delta) of 5C4K with different wt.% of nanosilica

From the graph, the higher value of tan delta was observed in unfilled nanosilica composite and the lower value in 1.5 wt. % nanosilica filled composite. The tan delta peak, and the lower values exibit, the non-elastic, and the elastic behavior of the hybrid polymer nanocomposites respectively. The glass transition temperature is considered at the peak point in the curve, many researchers proposed which is the best way to get the Tg [25]. The glass transition temperature and corresponding damping factor for 5C4K-NS0, 5C4K-NS0.5, 5C4K-NS1.0, 5CK4-NS1.5 are 90.12℃, 89.13℃, 89.05℃, 89.44℃, and 0.327, 0.286, 0.279, 0.274 respectively. By adding the nanosilica, the damping factor decreases. The unfilled nanosilica polymer composite has higher damping factor results in higher energy dissipation capacity, the addition of nanosilica to the polymer composite reduces the damping factor results in lower energy dissipation capacity, which means the addition of nanosilica to the polymer composite acts like an elastic to store the load rather dissipating it and also restrict the molecular movement during the transition [30].

3.4 Cole-Cole plot

The Cole-Cole graph depicts the relationship between the heat energy stored and dissipated by the viscoelastic material. The cole-cole graph is based on the variation of loss modulus to storage modulus. The graph depicts the homogeneous and non-homogeneous properties of a hybrid polymer nanocomposite structure. The polymer nanocomposite is homogeneous with a well-dispersed nanofiller, if the Cole-Cole graph remains smooth and a semi-circular arc forms. Conversely, the divergence from the semi-circular arc shape to the irregular shapes indicates that the nanofiller has not been dispersed uniformly, also an indication of the existence of phase heterogeneity, phase segregation, and nanofiller particles aggregation due to immiscibility [1].

Cole-Cole plot helps in analysing the structural changes in the polymer nanocomposite due to the addition of nanosilica. The nature of the polymer nanocomposite can be analysed based on the shape of the curve. Figure 5 shows the cole-cole plot for the polymer nanocomposite 5C4K with different wt.% of nanosilica. The results reveal that, adding nanosilica to epoxy reduces the imperfections in the polymer hybrid nanocomposite, which can be observed in cole-cole plot. This indicates that the interfacial bonding between fibers and epoxy is enhanced due to the addition of nanosilica and also it depends on the weight percentage of nanosilica.

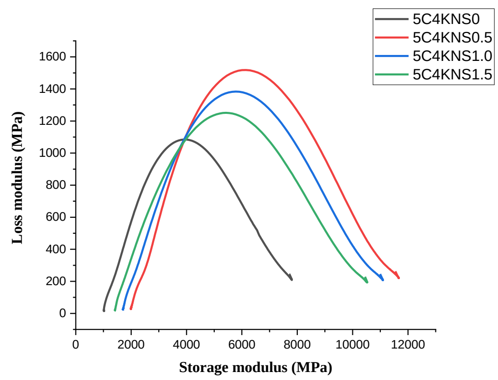


Figure 5. Cole-Cole graph of 5C4K with different wt.% of nanosilica

4. CONCLUSION

The dynamic mechanical behaviour of an unfilled and nanosilica filled polymer hybrid nanocomposite containing five and four layers of carbon and Kevlar woven fibre respectively with epoxy (5C4K) was investigated in this study.

i) In the glassy area, the storage modulus of the hybrid polymer nanocomposites ranges from 7709 to 11546 MPa, with the basic hybrid polymer composite having the minimum value and the maximum value in hybrid polymer nanocomposite contains 0.5 wt.% nanosilica.

ii) The highest value of loss modulus of 1518.351 MPa was observed in 0.5wt.% of nanosilica filled composite and the lowest 1084.763 MPa in unfilled nanosilica composite.

iii) Glass transition temperature and damping factor values were greater in unfilled composites as compared to nanosilica filled ones.

REFERENCES

[1] Bommegowda, K.B., Renukappa, N.M., Rajan, J.S. (2021). Effect of micro-and nanofiller hybrids on the dynamic mechanical properties of glass reinforced epoxy composites. Polymer Composites, 42(5): 2252-2267. https://doi.org/10.1002/pc.25974

[2] Goertzen, W.K., Kessler, M.R. (2007). Dynamic mechanical analysis of carbon/epoxy composites for structural pipeline repair. Composites Part B: Engineering, 38(1): 1-9. https://doi.org/10.1016/j.compositesb.2006.06.002

[3] Shukla, M.K., Sharma, K. (2019). Effect of carbon nanofillers on the mechanical and interfacial properties of epoxy based nanocomposites: A review. Polymer Science, Series A, 61(4): 439-460. https://doi.org/10.1134/S0965545X19040096

[4] Bhatt, P., Goe, A. (2017). Carbon fibres: Production, properties and potential use. Mater. Sci. Res. India, 14(1): 52-57. https://doi.org/10.13005/msri/140109

[5] Rajesh, S., VijayaRamnath, B., Sudharsanan, V., Yuvaraj, K., Daniel, R.S. (2016). Investigation of flexural response of Kevlar composite. Indian Journal of Science and Technology, 9: 1. https://doi.org/10.17485/ijst/2016/v9iS1/108441

[6] Somaiah Chowdary, M., Raghavendra, G., Niranjan Kumar, M.S.R., Ojha, S., Om Prakash, M. (2020). A review on the degradation of properties under the influence of liquid medium of hybrid polymer composites. SN Applied Sciences, 2(10): 1-12. https://doi.org/10.1007/s42452-020-03502-7

[7] Saba, N., Jawaid, M. (2017). Epoxy resin based hybrid polymer composites. Hybrid Polymer Composite Materials, 57-82. https://doi.org/10.1016/B978-0-08-100787-7.00003-2

[8] Patel, K.K., Purohit, R. (2018). Dispersion of SiO_2 nano particles on epoxy based polymer nano composites and its characterization. Oriental Journal of Chemistry, 34(6): 2998-3003. https://doi.org/10.13005/ojc/340641

[9] Rahman, G.T., Meem, M.T., Gafur, M., Mahmud, A., Hoque, M. (2020). Preparation of TiO_2 and SiO_2 nanoparticles and their effect on epoxy resin nanocomposites. Micro and Nanosystems, 12(2): 135-141. https://doi.org/10.2174/1876402911666190809141557

[10] Suresha, B., Divya, G.S., Hemanth, G., Somashekar, H. M. (2021). Physico-mechanical properties of nano silica-filled epoxy-based mono and hybrid composites for structural applications. Silicon, 13(7): 2319-2335. https://doi.org/10.1007/s12633-020-00812-8

[11] Yadav, P.S., Purohit, R., Kothari, A., Rajput, R.S. (2021). Effect of nano SiO_2 on mechanical and thermal properties of polymer matrix nanocomposites. Advances in Materials and Processing Technologies, 1-17. https://doi.org/10.1080/2374068X.2021.1939559

[12] Nayak, R.K., Dash, A., Ray, B.C. (2014). Effect of epoxy modifiers ($Al_2O_3/SiO_2/TiO_2$) on mechanical performance of epoxy/glass fiber hybrid composites. Procedia Materials Science, 6: 1359-1364. https://doi.org/10.1016/j.mspro.2014.07.115

[13] Alsaadi, M., Bulut, M., Erkliğ, A., Jabbar, A. (2018). Nano-silica inclusion effects on mechanical and dynamic behavior of fiber reinforced carbon/Kevlar with epoxy resin hybrid composites. Composites Part B: Engineering, 152: 169-179. https://doi.org/10.1016/j.compositesb.2018.07.015

[14] Islam, M.E., Mahdi, T.H., Hosur, M.V., Jeelani, S. (2015). Characterization of carbon fiber reinforced epoxy composites modified with nanoclay and carbon nanotubes. Procedia Engineering, 105: 821-828. http://dx.doi.org/10.1016/j.proeng.2015.05.078

[15] Fathalian, M., Ghorbanzadeh Ahangari, M., Fereidoon, A. (2019). Effect of nanosilica on the mechanical and thermal properties of carbon fiber/polycarbonate laminates. Fibers and Polymers, 20(8): 1684-1689. https://doi.org/10.1007/s12221-019-1158-0

[16] Ayatollahi, M.R., Barbaz Isfahani, R., Moghimi Monfared, R. (2017). Effects of multi-walled carbon nanotube and nanosilica on tensile properties of woven carbon fabric-reinforced epoxy composites fabricated using VARIM. Journal of Composite Materials, 51(30): 4177-4188. https://doi.org/10.1177/0021998317699982

[17] Nagaraja, K.C., Rajanna, S., Prakash, G.S., Rajeshkumar, G. (2020). Improvement of mechanical and thermal properties of hybrid composites through addition of halloysite nanoclay for light weight structural applications. Journal of Industrial Textiles, 1528083720936624. https://doi.org/10.1177/1528083720936624

[18] Nemati Giv, A., Ayatollahi, M.R., Ghaffari, S.H., da Silva, L.F. (2018). Effect of reinforcements at different scales on mechanical properties of epoxy adhesives and adhesive joints: A review. The Journal of Adhesion, 94(13): 1082-1121. https://doi.org/10.1080/00218464.2018.1452736

[19] Pranesh, K.G., Channabasavaraj, S. (2020). Effect of nanomaterials on mechanical properties in fiber reinforced polymer composite-a review. International Research Journal of Engineering and Technology (IRJET), 7(5): 2727-2730.

[20] Pranesh, K.G., Channabasavaraj, S. (2022). Investigation of flexural properties of hybrid woven Carbon-Kevlar-epoxy composites added with nanosilica filler. Materials Today: Proceedings, 62(8): 5347-5350. https://doi.org/10.1016/j.matpr.2022.03.484

[21] Nagamadhu, M., Jeyaraj, P., Mohan Kumar, G.C. (2020). Influence of textile properties on dynamic mechanical behavior of epoxy composite reinforced with woven sisal fabrics. Sādhanā, 45(1): 1-10. https://doi.org/10.1007/s12046-019-1249-z

[22] Priyanka, P., Mali, H.S., Dixit, A. (2021). Dynamic mechanical behaviour of Kevlar and carbon-Kevlar hybrid fibre reinforced polymer composites. Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science, 235(19): 4181-4193. https://doi.org/10.1177/0954406220970600

[23] Mat Yazik, M.H., Sultan, M.T.H., Jawaid, M., Abu Talib, A.R., Mazlan, N., Md Shah, A.U., Safri, S.N.A. (2021). Effect of nanofiller content on dynamic mechanical and thermal properties of multi-walled carbon nanotube and

montmorillonite nanoclay filler hybrid shape memory epoxy composites. Polymers, 13(5): 700. https://doi.org/10.3390/polym13050700

[24] SudarshanRao, K. (2021). Dynamic mechanical behavior of unfilled and graphite filled carbon epoxy composites. In IOP Conference Series: Materials Science and Engineering, 1126(1): 012033. https://doi.org/10.1088/1757-899X/1126/1/012033

[25] Muralidhara, B., Babu, S.P., Suresha, B. (2020). Studies on the role of graphene nanoplatelets on mechanical properties, dynamic-mechanical and thermogravimetric analysis of carbon-epoxy composites. Journal of The Institution of Engineers (India): Series D, 1-7. https://doi.org/10.1007/s40033-020-00219-0

[26] Ahmad, M.A.A., Ridzuan, M.J.M., Majid, M.A., Cheng, E.M., Sulaiman, M.H. (2021). Dynamic mechanical analysis of graphene nanoplatelets/glass reinforced epoxy composite. In Journal of Physics: Conference Series, 2051(1): 012046. https://doi.org/10.1088/1742-6596/2051/1/012046

[27] Epotec® Epoxy Systems – Composites: Brochure. (2010). Aditya Birla Chemicals (Thailand) Limited.

[28] ASTM, I. (2007). Standard test method for plastics: Dynamic mechanical properties: In flexure (three-point bending). ASTM D5023-07. PA 19428-2959, United States.

[29] Lu, H., Xu, X., Li, X., Zhang, Z. (2006). Morphology, crystallization and dynamic mechanical properties of PA66/nano-SiO_2 composites. Bulletin of Materials Science, 29(5): 485-490. https://doi.org/10.1007/BF02914079

[30] Kumar, G.M., Jeyaraj, P., Nagamadhu, M. (2019). Dynamic mechanical analysis of glutaraldehyde cross linked polyvinyl alcohol under tensile mode. In AIP Conference Proceedings, 2057(1): 020017. https://doi.org/10.1063/1.5085588