Indian Journal of Engineering & Materials Sciences
Vol. 30, April 2023, pp. 331-337
DOI: 10.56042/ijems.v30i2.609

Tensile Behaviour of Natural Polymer Composite Materials at Ambient and Elevated Temperatures

Phani Prasanthi P[a], N Raghu Ram[a], V V Venu Madhav[b], Manoj Kumar Agrawal[c], Prasanta Kumar Mohanta[d], Kuldeep K Saxena[e],*, Ch Sri Chaitanya[b], Karrar hazim Salem[f], Barno Sayfutdinovna Abdullaeva[g]

[a]Department of Mechanical Engineering, Prasad V Potluri Siddhartha Institute of Technology, Kanuru, Vijayawada 520 001, India
[b]Department of Mechanical Engineering, Velagapudi Ramakrishna Siddhartha Engineering College, Vijayawada 520 001, India
[c]Department of Mechanical Engineering, GLA University, Mathura, UP 281 406, India
[d]Department of Aeronautical Engineering, Institute of Aeronautical, Engineering, Hyderabad 500 043, India
[e]Division of Research and Development, Lovely Professional University, Phagwara 144411, India
[f]Al-Mustaqbal University College, 51001 Hillah, Babil, Iraq
[g]Tashkent State Pedagogical University, Tashkent, Uzbekistan

Received 15 September 2022; Accepted: 10 January 2023

The behaviour of materials can change significantly when they are exposed to high temperatures. Therefore, it is essential to understand how materials perform under elevated temperature conditions before recommending them for applications that involve exposure to high temperatures. The present work describes the preparation of composite materials using natural biodegradable waste materials such as groundnut shell powder and teak wood powder as reinforcement phases for a polyester matrix. The composites were tested for their mechanical properties such as tensile modulus, tensile strength, and percent of elongation, as well as their thermal conductivity at room temperature. Later, using the simulation studies, the experimental behaviour of natural composites at room temperature was validated and further extended to find the same composite behaviour at elevated temperatures. From the current studies, it is identified that teak wood powder reinforced composites experienced more stress than the ground nut shell powder reinforced composites at the selected elevated temperatures, such as 50 °C, 80 °C, 100 °C, 120 °C, and 150 °C respectively. At room temperature, the teak wood powder reinforced composites had a 60% higher tensile modulus, 97% higher tensile strength, and 12.5% greater thermal conductivity than the GNSP composite under similar particle loading, hosting medium, and environmental conditions.

Keywords: Biodegradable composite, Ground nutshell, Wood powder, Finite element method, Elevated temperatures, equivalent Stresses.

1 Introduction

Natural fiber-polymer composites are being used more often in a wide range of applications due to their affordability and environmental friendliness compared to traditional petroleum-derived materials[1]. Cotton stalk, pineapple leaf, rice straw, flax, hemp, soybeans, rice husk, garlic straw, potato peel, grape skin, wood powder [2], groundnut shell powder[3], walnut shell, hazelnut shell, and sunflower husk[4] and other agricultural waste materials can all be used to make the reinforcement. Agro-biomass can be used for many things, like making paper, textiles, composites, building materials, furniture, environmentally friendly products, and even medicine.

Natural biodegradable composites in automobile parts not only reduce the component's bulk by 80% but also the energy required for production[5]. Biodegradable fibres and polymers, primarily derived from renewable resources, are expected to play a significant role in the development of new industrial high-performance biodegradable composites. This will help to partially address the issue of waste management. A controlled industrial composting procedure can be used to crush and recycle a structural biodegradable composite after it has served its purpose[6].

Bamboo fibre polyester composites were studied at 40, 80, and 120 °C to understand the tensile and bending strengths and discovered a significant decrease in all mechanical properties for composites tested at 120 °C to promote the applications of natural fibre reinforced composites at elevated temperatures[7]. According to the results of the studies, the initial deformation resistance of the composite at room

---

*Corresponding author (E-mail: saxena0081@gmail.com)

temperature did not appear at high temperatures[8]. Curaus, hemp, and sisal fibres are believed to behave consistently between 100 and 200 degrees Celsius, but between 150 and 200 degrees Celsius, their mechanical behaviour is drastically impaired[9].

The current state of the art for wood particle-reinforced composites is demonstrated, including how they are described, chemically treated, manufactured, and used[10]. Many academics are fascinated by particulate wood polymer composites because they have good mechanical and physical qualities and are environmentally friendly. Thermal degradation of wood powder occurs at a relatively low temperature, around 200 °C[11]. As a result, the thermal properties of wood particle-reinforced composites must be investigated and forecasted. Using banana particulate reinforcement, a composite material is developed using polyvinyl chloride matrix and the composite showed better creep stability at elevated temperature than pure matrix material considered for the study[12].

Most of the work related to natural composites is limited to their mechanical properties at room temperature. To recommend these materials for use at temperatures other than room temperature, it is also important to know how they behave at higher temperatures. In this work, wood and ground nutshell powder is selected as two types of biodegradable agricultural waste that could be used to create a natural particle composite. The behaviour of a natural composite at ambient and increased temperatures is evaluated in this study by combining experimental and simulation research. Two distinct natural biodegradable agro-waste material-reinforced composites for static and thermal conductivity are developed and tested. The objective of the present work is to find the tensile behaviour of the natural agro-waster based particle reinforced composite at elevated temperatures using simulation studies. The input parameters required for the simulation studies are obtained by conducting suitable experimental studies. The param0eters required are tensile modulus, density, and thermal conductivity of the respective composite.

2 Materials and Methods

The natural composite material is prepared by selecting two different biodegradable waste materials, such as ground nut shell powder (GNSP) and teak wood powder (TWP), and a polyester matrix. The common polyester resin is used and combined with a catalyst Methyl Ethyl Ketone Peroxide (MEKP) and hardener (cobalt) for curing. The polyester resin, catalyst, and hardener are mixed in 100:1.5:1.5 proportions. The weight fraction of this ground nut powder and teak wood powder is maintained at 40%, as this is the maximum percentage of the filler in the matrix material[13]. The hosting medium (polyester resin) percentage is maintained at 60%. The glass transition temperature of the polyester is in the range of 100–150 °C. The natural composite specimens are prepared by adopting the hand layup technique. percentage is maintained at 60%. The glass transition temperature of the polyester is in the range of 100–150 °C. The natural composite specimens are prepared by adopting the hand layup technique. Two different agro-waste materials are chosen to prepare the natural composite, i.e., GNSP and TWP, which are collected from the local markets of Vijayawada, Andhra Pradesh, India. The polyester matrix, compatible catalyst, and hardener were purchased from Bindhu agencies in Vijayawada, Andhra Pradesh, India. The teak wood powder and ground nutshell powder are blended into a fine powder, and, using the particle filter mesh, uniform-sized particles of the teak wood powder and groundnut shell powder are collected. The size of the green powders is maintained at 0.3 mm in diameter.

2.1 Preparation of Samples for Tensile Tests

To prepare the teak wood powder mixed polyester composite, the required quantity of the TWP and GNSP are taken separately, and the polyester matrix is taken into a beaker along with the recommended percentage of catalyst and hardener. The size of the both the particles are 0.3mm found by using same mesh sieve. First the measured resin content is taken and measured quantity of GNSP and TWP are mixed in the resin and the resulting mixture is then stirred mechanically and sonicated for 30 minutes using an ultrasonicator to get a uni-form distribution of reinforcing particles. The mixture is poured in prepared mould and the mixture is kept in the mould for 24 hours for curing. The cured specimens are removed from the mould. As per the recommendations of the polymer suppliers, the curing time is fixed to 24 hours. The TWP-mixed polyester composite specimens are removed from the mould after curing. A similar procedure is followed for GNSP mixed with polyester matrix. In both cases, the weight fraction of TWP or GNSP is maintained at

40%. At this weight fraction of particle reinforcement, 5 specimens are prepared. The composite specimen is prepared as per ASTM D3039 standard. The digital universal testing machine shown in to perform the tensile test, 20 KN load cell is used. The load is applied at a crosshead speed of 5 mm/min. thermal conductivity apparatus is used to find the thermal conductivity of the prepared composites. Using the average of the five specimen results as the final result reduces the impact of individual differences, resulting in a more trustworthy depiction of the tested material's performance.

2.2 Preparation of Samples for Thermal Conductivity Tests

ASTM E1530-11 is used to make composite specimens that can be used to measure the thermal conductivity of the particulate composite. The test samples were circular in shape with a 50-mm diameter and a 10-mm thickness. The specimens prepared for the thermal conductivity are presented in the same image.

2.3 Finite element methodology

The majority of engineering problems are initiated with numerical simulation, design of experiments which has gained enormous appeal among designers [13-15]. Using the finite element method-based software ANSYS R19.2, the validation of tensile strength is performed, and further validated models are extended to explore the elevated temperature behaviour of respective composite materials. The geometrical models are generated by using the same dimensions as the specimens considered for experimental studies. As shown in Figure 1, the length of the model is 165 mm, the width is 15 mm, and the thickness is 3 mm. Using a solid 186 element, the geometrical model is converted into a finite element model. The total number of elements is 17928. The element sizes are carefully adjusted depending on the appropriate size and criticality of a particular component [26-27]. A SOLID186 element is used to perform static analysis to impose the temperature effect, and a SOLID90 element is used under thermal loading. It is a hexahedral element having eight nodes and three degrees of freedom (displacements in the x, y, and z dimensions) at each node. This element type can model huge deformations and geometric nonlinearities, as well as sophisticated material behaviour such as nonlinear material characteristics. The Finite Element (FE) Models are validated with experimental findings. The assumptions applied while performing the FE simulations are that the material is assumed to be isotropic and homogeneous.

2.4 Loading and boundary conditions for FE models

According to the experimental studies, both ends of the tensile specimens are gripped and a tensile load is applied to the one end of the specimens. The gripping conditions are implemented by fixing the gripping zone deformations in X,Y and Z directions. In this study, the tensile modulus, load verses displacement curve obtained from the experimental studies is given as input material properties and the maximum ultimate load is applied to the Finite element (FE) models and the equivalent stresses are identified from the FE studies under these conditions. The maximum ultimate load of the GNSP composite is 1088.9N. The equivalent stress is 12.805 MPa. The ultimate strength

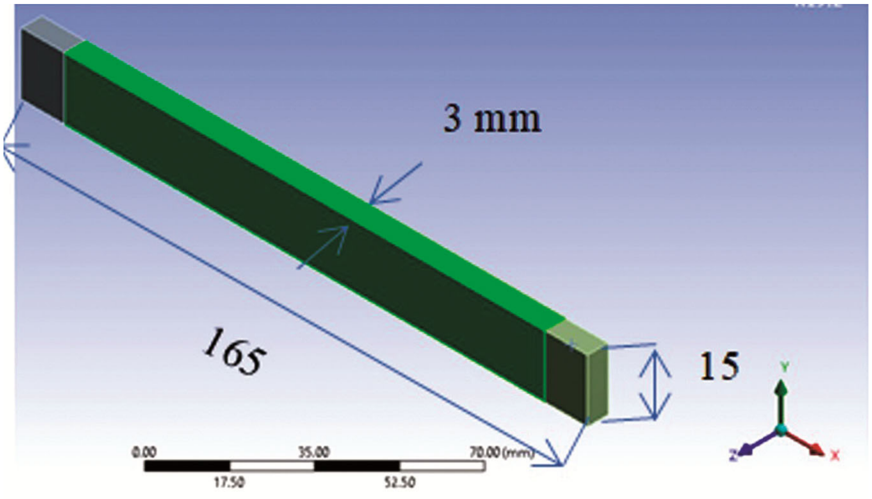

Fig. 1 — Geometrical model for finite element studies.

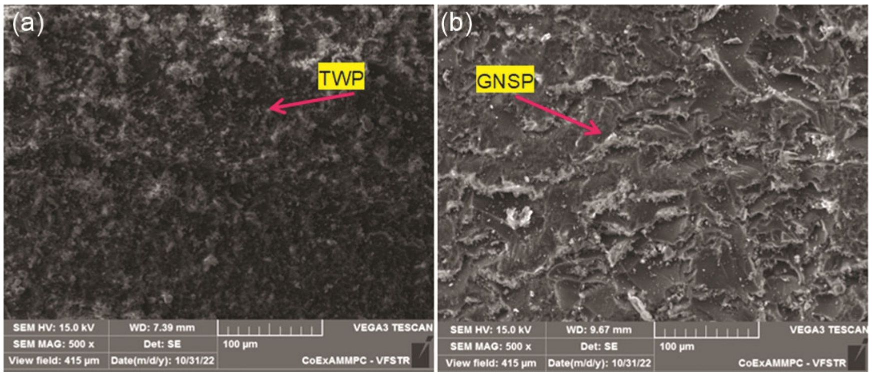

Fig. 2. (a) — SEM images of TWP composite, (b) SEM images of GNSP reinforced composite.

from experimental studies is 11.958MPa. The scanning electronic microscopic images (SEM) of TWP and GNSP-reinforced composites are presented in Fig. 2 (a) and Fig. 2 (b) respectively. The SEM image is captured at the failure zone of the composite, and perfect bonding between the constituents is observed in Fig. 2 (a and b). The percentage of error between the experimental and simulation studies for the GNSP composite is 7.808%, and for the TWP composite, the same percentage of error becomes 10.58%. The deviations in the experimental and simulation studies are attributed to many real-time parameters such as reinforcement particle distribution, bonding between the constituents, etc. which cannot completely implement in the simulation studies.

After validation of the FE models with the experimental findings, the same models are extended to reveal the effect of elevated temperature on the tensile behaviour of the same composite.

3 Result and Discussion

3.1 Tensile behaviour of particulate composite:

The tensile modulus of TWP reinforced polyester composite and GNSP reinforced polyester composite is identified from 5 composite specimens and the average value is taken as the final value[18]. The variation in the tensile modulus of two different particulate composites is presented in Figure 3. Compared to GNSP reinforced composite, the TWP reinforced composite showed higher tensile modulus due to the good bonding between TWP and polymer matrix[19]. The differences in the lumen percentages of GNSP and TWP also influence the tensile modulus of the resulting composite[19].

The tensile modulus of GNSP composite is recorded as 14801.4072 MPa, whereas at the same conditions such as particle loading (40%), hosting medium and particle size, and the TWP composite average tensile modulus is 23682.3178 MPa. Compared to GNSP composite, TWP reinforced composite is 60% higher. This is due to the load bearing capacity of TWP.

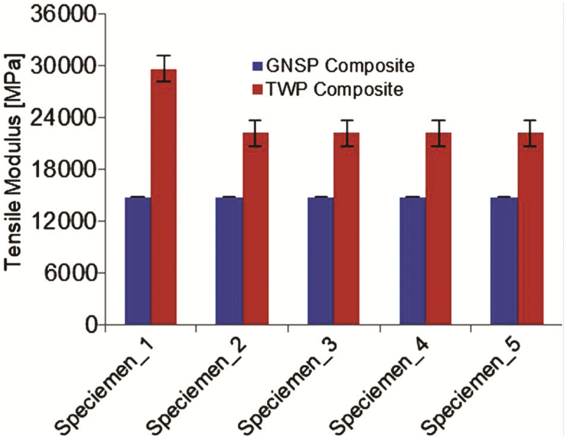

Fig. 3 — Variation of Tensile Modulus.

The average value of the tensile strength of the TWP reinforced composite is 22.098 MPa. For GNSP reinforced polyester composite, the tensile strength is 11.218 MPa. That means the percentage of enhancement of TWP reinforced composite is 97% higher than that of GNSP composite. This is due to the load-bearing capacity of TWP under tensile load.

The average percentage of elongation of GNSP reinforced composite is 0.24%, whereas this percentage is raised to 0.31% for the teak wood powder reinforced composite. The teak wood powder has taken more load and this is reflected in their percentage of elongation (0.31%), whereas the GNSP reinforced composite percentage of elongation is limited to 0.24%. Moreover the changes in the elongation is related to the built-in architecture and physical characteristics of the constituents[21]. The thermal conductivity of the prepared composite material is presented in Figure 4. The ability of the conductivity of the TWP reinforced composite is higher than the GNSP reinforced composite. The thermal conductivity of GNSP reinforced composite is 0.4 Wm-1K-1, whereas the thermal conductivity is 0.45 for TWP reinforced composite. The difference in these magnitudes is attributed to the differences in the cellulose, hemicellulose, and lignin percentages in teak wood powder and ground nut shell powder [22-23]. The biodegradability is the one of the benefits associated with this of composites [26].

3.2 High temperature behaviour of natural composites:

Coupled steady-state thermal and static structural analysis is used to investigate the behaviour of an agro-waster-based composite at elevated temperatures. The response of the material from the static tests is coupled with thermal analysis to predict the same material behaviour at higher temperatures. In static tests, the mechanical properties of the material, such as stiffness, strength, and deformation characteristics, are determined under ambient temperature conditions. However, the behavior of materials can change significantly when subjected to elevated temperatures due to thermal expansion, softening, or other thermal effects. The selected temperature for the present analysis is 30 °c, 50°C, 80°C, 100°C, 120°C and 150°C. The maximum temperature is limited to 150 °C based on the polyester matrix. Polyester matrices, have temperature constraints within which they can retain mechanical characteristics and structural integrity. Excessive temperatures can cause thermal degradation, softening, loss of stiffness, and failure of the composite material. The natural materials are commonly found in the transportation sector. Thermal and mechanical loads on these structural materials are substantial[23]. In the steady state analysis, the composite material is subjected to an isothermal state of temperature and the results of the analysis are coupled to the static structure. By applying the same ultimate load and boundary conditions, the tensile response is obtained.

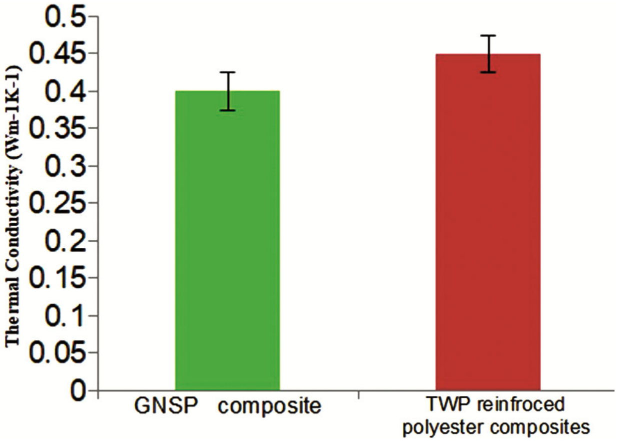

Fig. 4 — Variation of Thermal conductivity.

Figure 5 shows the variation of normal stress in X, Y, and Z directions with respect to the temperature. Increasing the temperature of exposure of the GNSP and TWP composites, the normal stress experienced by the material is also increasing. As the temperature increases, the mismatch in thermal expansion between these components can induce internal stresses, resulting in increased normal stress. Compared to GNSP, the TWP composite experienced more stress in all directions.

The stiffness and strength of the TWP composite is higher than that of GNSP composite. As a result, the TWP should present less stress. However, under the thermal loading, the thermal conductivity plays an important role in the generation of the stresses. The thermal conductivity of TWP is greater and this property conducts more heat energy. As a result, the material becomes soft and shows more stress than the GNSP composite.

Figure 6 presents the equivalent stresses of the two different composites at different temperatures. At lower temperatures, the difference in the equivalent stresses is minimal. However, increasing the temperature may increase the differences in the equivalent stresses of GNSP and TWP composites. The TWP presented more stresses in this case. The TWP composites showed higher tensile strength than GNSP composite at room temperature; as a result, these composites offer more resistance to the applied load even at high temperatures. As a result, the

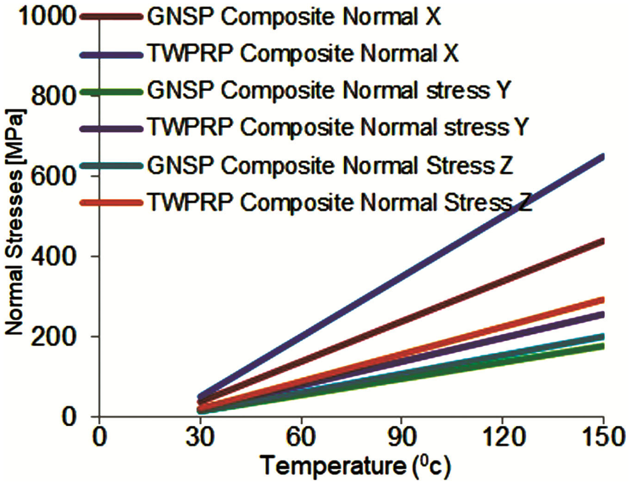

Fig. 5 — Normal stresses at elevated temperature.

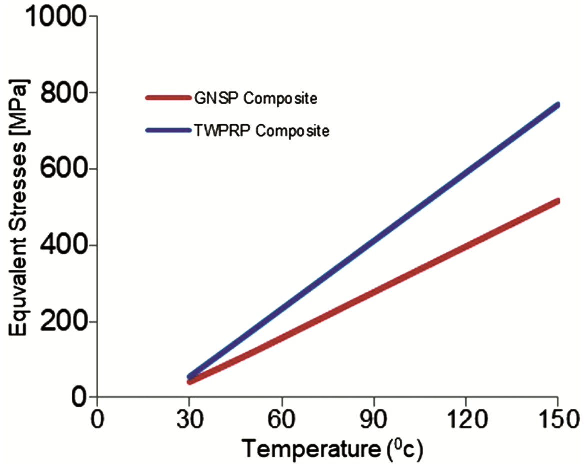

Fig. 6 — Equivalent stresses at elevated temperature.

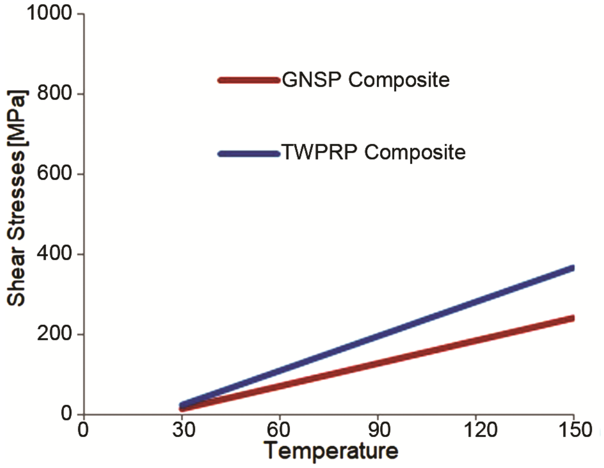

Fig. 7 — Shear stresses at elevated temperature.

equivalent stress magnitude is high for TWP composite. Figure 7 shows the shear stress of the biodegradable composite at different temperatures. Compared to normal and equivalent stresses, the magnitude of shear stresses is less under thermal and static loading. Up to 50°C, the materials' coefficients of thermal expansion may be equivalent or comparable, resulting in little changes in their response in strain energy. However, if the temperature rises over 50°C, the materials' expansion rates may differ, resulting in increased variances in their behaviour.

4 Conclusion

The tensile loading response of the natural agro-waster based particle mixed polyester composite is estimated at ambient and elevated temperatures by conducting experimental and simulation studies. The biodegradable waste materials considered for the present work are groundnut shell powder and teak wood powder. The following are the important highlights of the present work.

Under similar particle loading and hosting medium and environmental conditions, the TWPRP composite showed 60% higher tensile modulus, 97% higher tensile strength, and 12.5% more thermal conductivity than the GNSP composite at room temperature.

The equivalent stresses experienced by TWPRP are more than GNSP composite due to the higher thermal conductivity of the same composite at elevated temperatures.

Thermal conductivity is one of the deciding factors for the experience of stresses at elevated temperatures through the material, which possesses the highest strength and stiffness.

The strain energy of the considered natural composite is the same up to 50 °C, later the effect of elevated temperature is considerable on the strain energy.

References

1 Vickers N, J Curr Biol, 54 (2016) 62.
2 Malladi R, Nagalakshmaiah M, Robert M & Elkoun S, ACS Sustain Chem Eng, 6 (2018) 2807.
3 Nemaleu JGD, Belela EA, Nana A, Kaze RC, Venyite P, Yanou RN & Kamseu, Environ Sci Pollut Res, 29 (2022) 449.
4 Malkapuram R, Kumar V & Negi YS, J Reinf Plast Compos, 28 (2009) 1169.
5 Ouagne P, Bizet L, Baley C & Bréard J, J Compos Mater, 44 (2010)1201.
6 Manalo AC, Wani E, Zukarnain NA, Karunasena W& Lau KT, Compos B Eng, 80 (2015) 73.
7 Nakamura R, Goda K, Noda J & Ohgi J, J Express Polym Lett, 3 (2009) 19.
8 Keya KN, Kona NA, Koly FA, Maraz K M, Islam MN & Khan RA, Mater Eng Res,14 (2019)1494.
9 Tahir PM, Ahmed AB, SaifulAzry SO & Ahmed Z Bioresour, 6 (2011).
10 Khan MZ, Srivastava SK Gupta MK, Polym Test, 89 (2020) 106721.
11 Poletto M, Zattera AJ, Forte MM & Santana RM, Bioresour Technol, 109 (2012) 148.
12 Dan-Asabe B, J King Saud Univ Eng Sci, 30 (2018) 296.
13 Sundarababu J, Anandan SS & Griskevicius P, Mater. Today, 39 (4) (2021)1241.
14 Awasthi A, Saxena KK & Arun V, Mater Today, 44, (2021) 2069.
15 Bandhu D, Kumari S, Prajapati V, Saxena KK & Abhishek K Mater Manuf, 36 (2021)1524.
16 Agarwal KM, Tyagi RK & Saxena KK, Adv Materb Process, 8(2022) 828.
17 Sharma SK Saxena KK, Mater Today Proc, 56 (2022) 2278.

18 Dhawan A, Gupta N, Goyal R & Saxena KK, Mater Today 44 (2021)17.

19 Ichazo MN, Albano C, Gonzalez J, Perera R & Candal AM, Compos Struct, 54 (2001) 207.

20 Prasanthi P, Kondapalli SB, Morampudi NKSR, Vallabhaneni VVM, Saxena KK, Mohammed KA & Buddhi D, Mater 15(2022) 7032.

21 Nagaraja Ganesh B & Rekha B, Arch Civ Mech, 20 (4) (2020) 1.

22 Jain NK & Gupta MK, Mater Res Express 5(12) (2018) 125306.

23 Raju GU & Kumarappa SJ, Reinf Plast Compos 30(2011) 1029.

24 Madhav VV, Chaitanya CS, Prasanthi PP, Gupta AV SSKS, Spandana VV, Saxena KK & Prakash C, Interact Des Manuf, (2022) 1.

25 Kumar PSS & Allamraju KV, Mater Today (18) (2019) 2556.

26 Budarapu PR, YB SS & Natarajan R Front. Struct. Civ, (10) (2016) 394.

27 Sudhir Sastry YB, Krishna Y & Budarapu PR, Comput Mater, 96 (2015) 416.