Effect of fiber orientation on dynamic mechanical properties of PALF hybridized with basalt reinforced epoxy composites

Parameswara Rao Venkata Doddi, Ratnam Chanamala and Siva Prasad Dora

1 Department of Mechanical Engineering, Andhra University, Visakhapatnam, India
2 Department of Mechanical Engineering, GITAM (Deemed to be University), Visakhapatnam, India
E-mail: paramesh.dv@gmail.com

Keywords: damping, PALF, fiber orientation

Abstract
In this modern era, the natural fibers usage in automobile and construction sectors has been increased. The goal of the current work was to investigate the fiber orientation effect on dynamic mechanical properties of hybrid Pineapple Leaf Fibre (PALF) hybridized with basalt reinforced epoxy composite at changing vibration frequencies. Hand Lay-up technique was used to manufacture the composites by keeping the unidirectional basalt fabric as an outer layer by keeping PALF as inner layer followed by static compression method. Tensile and flexural moduli were also determined apart from storage modulus (\(E^\prime\)) and damping factor (\(\tan \delta\)) for different PALF fiber angles. The results exemplified that not only the storage modulus and loss factor but also glass transition temperature (\(T_g\)) as well found to increase with frequency and also the fiber orientation angle has a greater impact on dynamic and static properties.

1. Introduction
As of late, the aggressive market circumstance enhanced by exponentially augmenting innovative developments combined with environmental factors continues to push the demands for innovative combination of materials, that would result in an extraordinary unconfined characteristics not only as regards as high performance, high-strength and lightweight structures but also in the terms of dynamical, electrical or thermal ones. Advanced multilayered composite architectures give off an impression of being one of the appropriate answers, particularly for applications in structural engineering guided by design factors like weight, manufacturing cost, compatibility of materials coupled with environmental factors paved the way to an increasing interest in using hybrid composite materials, particularly with the combination of natural organic fibers. Hybrid composites fabrication is done by a combining two or more materials that are reinforced together in a single matrix. A new material structure with more fetching and enhanced properties than their constituent materials and offers an extent of properties that can’t be bring off by a single form of reinforcement, whilst reducing their disadvantages [1, 2].

Natural fiber composites have got a great attention and viewed as a superior option for artificial and synthetic fiber composites in civil, automobile, marine and aerospace applications due to their prevalent properties, for example low cost, low density, pollution free and adequate mechanical properties in spite of having the impediment of poor interfacial layer bonding with polymeric materials due to the hydrophilic character of materials rendering them incompatible with hydrophobic matrices [3]. The surface modification of natural organic fibers is needed to enhance the compatibility and it has been inferred that the interfacial bonding is increased b according to the results of the viscoelastic behavior of the composites [4–6]. To investigate the viscoelastic behavior and structural properties of polymeric and metal matrix composite materials with the aim of determination their relevant damping and stiffness characteristics in our regular applications, dynamic mechanical analysis (DMA) was employed [7–10]. These dynamic properties obtained over a range of temperatures and frequencies are noteworthy, studies showed that the stacking sequence and fiber orientation influences the dynamic mechanical characteristics of hybrid polymeric composites [11–15].
Many research works are accounted for the study of dynamic mechanical properties of various natural hybrid fibers reinforced thermo-setting polymer composites. However, very little work has been reported on dynamic behavior of PALF hybridized with other natural or synthetic fibers. The experimental study on dynamic mechanical properties of HDPE polymeric hybrid composite reinforced with kenaf and PALF for different fiber loading and fiber length was conducted by Aji et al [16] and demonstrated that increase of fiber content raised the peak of damping with respect to temperature and storage modulus was improved with increase in fiber length.

PALFs display superior mechanical characteristics in light of its cellulose content which is high (70%–82%), low lignin (5%–12%) and low microfibril fiber orientation (14°) in comparison; alkaline treatment is utilized with an end goal to the interfacial adhesion enhancement between the PALF and Epoxy [17, 18]. Asim et al [19] reported a brief review of the pineapple fibers and its composites. The tensile characteristics of Diglycidylether of bisphenol A (DGEBA) with triethylenetetramine (TETA) matrix composites with reinforcement of various amounts of long, aligned and continuous PALF fibers were assessed by Glória et al [20] and the outcomes indicated significant changes in the mechanical characteristics with the amount of PALF fibers. In another study by Gloria et al [21] on flexural properties of epoxy composites reinforced PALF revealed that aligned and continuous fibers increase the flexural strength significantly. Likewise, an increase in the length of fiber at room temperature up to about 650 °C improved the storage modulus and from there after, a negligible difference in loss modulus and almost no distinction in tan delta value was observed with variation in fiber length. The limited research on dynamic mechanical properties using long continuous PALF fibers especially for hybrid composites encouraged the author to consider the unidirectional mat of PALF fiber for current research. Varley et al [22] performed dynamic mechanical thermal tests on basalt reinforced epoxy composites and confirmed that the glass transition temperature remains unchanged regardless of the surface treatment process. Lopresto et al [23] studied the mechanical characteristic comparisons of plastic fiber composites with reinforced basalt and glass fibers and noticed that basalt was outmatch and had the prospect of glass being superseded. Investigation by Doddi et al [24] on PALF/Basalt hybrid epoxy composites has shown that PALF hybridization with basalt has an impact on mechanical properties and also demonstrated that hybrid composites with PALF as inner layers and basalt as external layers gives better properties when compared to hybrid composite with PALF as envelope and basalt as core. In their analysis, Todkar et al [25] stated that the fiber orientation effect plays a critical role and longitudinal fibers gives higher mechanical strength than crosswise and random direction. Ganeshan et al [26] found that the mechanical properties are greatly influenced by fiber length of the reinforced material and weight percentage while fabricating madar fiber reinforced polyester composites. Several investigations [27–31] on the usage of single reinforced PALF or Basalt in epoxy composites has been reported.

From the above literature to the best of the authors learning, limited exploration has been done on the study of dynamic properties of PALF hybridized composites and no work has been carried out yet on the impact of fiber orientation and frequency on the dynamic mechanical behavior of PALF and basalt fiber hybrid composites. Henceforth in continuation of earlier work [24] by the authors, hybrid composites were prepared with PALF and basalt fiber as reinforcements and epoxy as matrix by keeping basalt fiber (high modulus) as skin and PALF as core to study the impact of fiber orientation of PALF on dynamic mechanical properties of the hybrid composite at different frequencies and the tensile and flexural properties as well, with an objective to develop high performance composites with good damping properties coupled with increased stiffness.

2. Materials and methods

2.1. Composite fabrication

The properties of PALF, basalt and epoxy are presented in Table 1.

The unidirectional PALF fiber mat and Epoxy LY556 along with Hardener HY951 purchased from Go greens Ltd, Chennai, India and unidirectional basalt fabric purchased from Aero, Bangalore were used as materials in this work. The properties of PALF, basalt and epoxy are presented in Table 1. The PALF mat was soaked in a solution of sodium hydroxide (10%) at room temperature for 3 h to facilitate effective adhesion...

Table 1. Properties of PALF, basalt fiber and epoxy resin [17, 26].

| Properties               | PALF   | Basalt | Epoxy |
|--------------------------|--------|--------|-------|
| Diameter um              | 20–85  | 10–18  | —     |
| Density g cm⁻³           | 1.44–1.53 | 2.8  | 1.15  |
| Tensile strength (MPa)   | 413–1628 | 2800 | 55–66 |
| Elongation at break (%)  | 1.6–3.1 | 2.9  | 1.5–2.5 |
| Young’s modulus (GPa)    | 34.4–82.51 | 89   | 3.0–3.9 |
between the PALF and matrix and to expel the soluble extractives and then washed with distilled water till the alkali is removed. Subsequent to washing, the fiber was dried in air for 6 h and then in oven at 70 °C for 6 h. The samples were then fabricated by impregnating each fabric with a matrix of epoxy resin and hardener HY951 mixed in the ratio of 10:1 by volume and then cured at room temperature and a pressure of 0.1 MPa for 24 h using compression molding. After curing, the laminates were cut using water jet cutting into standard size specimen as per ASTM standards for mechanical testing. For current study, samples with approximately same thickness and different PALF fiber orientation i.e., 0°, 30°, 45°, 60° and 90°, keeping basalt as envelop and PALF as core were considered and table 2 displays the corresponding nomenclature. To keep a check for repeatability, the tests were carried out on a set of three different samples for each specimen.

### 2.2. Static mechanical tests

To study the effect of fiber orientation on the static properties of the composites, test specimens were cut for tensile and flexural tests as per ASTM D3039 and ASTM D790 respectively and the corresponding equipment along with samples are shown in figures 1(a)–(b) and 2(a)–(b) respectively. Servo-hydraulic operated universal testing machine INSTRON 8801 was used to conduct the tensile tests with the 5 mm min⁻¹ as crosshead speed whereas 2 mm min⁻¹ as feed rate was used to perform the flexural tests at room temperature.

### 2.3. Damping measurements

For a viscoelastic material, the properties such as storage modulus ($E'$), loss modulus ($E''$), and damping factor ($\tan \delta$) are temperature dependent and play a vital role to provide information on interfacial bonding between the reinforced fibre and polymer matrix of composite material. The storage modulus is directly related to Young’s modulus and is considered to be a material’s capacity to store the energy applied on it, and Loss modulus is the propensity of materials to dissipate the energy added to it whereas the ratio of later and former is regarded as loss factor ($\tan \delta$).

To assess the effect of fiber orientation and frequency on storage modulus and loss factor of the hybrid composites, dynamic mechanical analyzer (DMA 8000) was employed and the experiments were accomplished in dual cantilever mode at 0.1 Hz, 1 Hz and 10 Hz frequencies under a dynamic load of 2 N and at constant strain amplitude as shown in figure 3. The samples were assayed from room temperature to 120 °C with 3 °C min⁻¹ heating rate and for each PALF orientation.

**Table 2. Designation and thickness of specimen.**

| Specimen | Layer sequence and fiber orientation | Thickness (mm) |
|----------|--------------------------------------|---------------|
| Sample A | 2Bp2Pv2Bp | 2.87 |
| Sample B | 2Bp2Pv2Bp | 3.01 |
| Sample C | 2Bp2Pv2Bp | 2.98 |
| Sample D | 2Bp2Pv2Bp | 2.99 |
| Sample E | 2Bp2Pv2Bp | 3.12 |

**Figure 1.** (a) Tensile test specimen mounted on Instron 8801 (b) Fractured samples obtained during tensile test with PALF orientation (a) 0° (b) 30° (c) 45° (d) 60° (e) 90°.
3. Results and discussions

3.1. Static mechanical properties

Tensile testing of the specimens was done using Instron universal Testing Machine (UTM) and they were left up to fracture. The corresponding ultimate tensile strength and elastic modulus were determined and plotted with respect to fiber orientation in figure 4 and it is observed that there is a decrease in tensile strength with increase in fiber orientation up to 45° and found to increase on further increase in fiber orientation, the highest composite tensile strength being 262.1 MPa at 0° and a minimum value of 237.67 MPa at 45° which indicates that variation of tensile strength with the increase in fiber orientation follows a ‘U’ shape complimenting the results reported from similar research on other natural and synthetic fiber composites. The variation of elasticity modulus also follows the trend similar to tensile strength with a maximum modulus of 10.9 GPa at 0° fiber angle and a minimum value of 9.3 GPa at 60°. The microscopic structure of the fractured specimen is shown in figures 5(a) and (b). Figure 5(a) shows the fractured surface of the composite interface with basalt as outer layer and PALF as...
inner layer and figure 5(b) depicting the honeycomb structure of PALF presenting its energy absorption characteristics.

The average flexural strength and modulus are obtained for all the samples from the flexural test and their corresponding variation with fiber orientation are plotted in figure 6. The findings show an improvement in flexural strength with a rise in fiber angle up to 60° and decreases with further rise in fiber angle with maximum value of 292.23 MPa at 0° and minimum value of 240.71 MPa at 60° following a ‘U’ shape curve and similar trend is observed for flexural modulus also with a maximum value of 21.66 GPa and a minimum value of 18.35 GPa at 0° and 45° fiber direction respectively. From the results, it is detectable that the maximum strength and modulus values are obtained for the hybrid composite with basalt as envelop and PALF as a core with fiber orientation at 0°, complementing the results obtained during previous research on other fibers.

3.2. Dynamic mechanical properties

The damping measurements were done on three different samples and observed that less than 5% variation for each sample and hence the maximum values are reported and presented.

A comparison of storage modulus of composites for different fiber orientations (0°, 30°, 45°, 60° and 90°) at frequencies 0.1 Hz, 1 Hz and 10 Hz were presented in figures 7(a)–(c). In all the cases, it was evident that the storage modulus was decreased with increased in temperature which is due to a reduction in stiffness of epoxy with an increase in temperature. It was further spotted that for all frequencies, the storage modulus between the temperatures 65 °C and 80 °C dropped considerably and exhibits high at low temperatures as the components in the glassy state are strongly packed, have low mobility, and experience strong intermolecular forces contributing
to a high modulus value. Increase in temperature beyond the values of glass transition temperature \((T_g)\) triggers the composite laminates to change its state from glassy to rubbery and with rise in temperature, particularly beyond \(T_g\), there would be a gain molecular movement resulting low storage modulus due to loss in stiffness. Here decrease in storage modulus can also be imputed to the way that the bonding between various fiber layers gets affected because of the difference in thermal expansion coefficient of the fibers and the matrix under dynamic conditions. Further as the epoxy resin becomes unstable in the rubbery region appearing at and above 100 °C, the storage modulus of all the composites become very less.

### 3.2.1. Effect of fiber orientation

The orientation of fibers with reference to the direction of loading is one of the main important parameters influencing the dynamic mechanical properties of fiber reinforced polymeric composites. The variation of storage modulus with fiber angle is shown in figures 7(a)–(c), not surprisingly the storage modulus of the composites have shown remarkable dependence upon the fibers direction in reference to the orientation of load. It was seen that the storage modulus of the specimens is reduced as the fiber angle increases from 0° to 60° and on further increase in angle the storage modulus increases, which is analogous to the results obtained for flexural modulus. Briefly, the variation of storage modulus with fiber angle follows a ‘U’ shaped curve with the highest value of for sample A and lowest value of for sample D, following the order sample A > sample B > sample C > sample E > sample D as seen in figure 8(a). The reason for this trend is the stiffness of the specimen along the longitudinal direction relies on the alignment of fibers and it decreases as the offset of the fiber axis increases resulting in reduction of bending resistance of the composite.

The loss factor variation of the hybrid composite samples for different fiber angles as a function of temperature is shown in figures 9(a)–(c). It is seen from the plots that the value of loss factor is increasing with a rise in temperature; reaching a maximum value at the transition region and begins to decrease in rubbery area. The chain segments contained in the resin are in the frozen state below glass transition temperature \(T_g\), causing low tan \(\delta\) values in all laminates whereas, in the transition region, resin molecules achieve higher mobility resulting in high tan \(\delta\) values. From the table 3, maximum loss factor is observed for sample A i.e. for 0° PALF angle and is found to decrease with increase in PALF angle up to 60° as the fibers that are oriented closer to 0° degrees exhibits higher bending stress due to this more energy is lost as heat dissipation thereby implying that the material is exhibiting higher loss modulus which in turn causes to have higher loss factor. The glass transition temperature \((T_g)\) among hybrid samples shifted to the right as the fiber angle increases up to 60° reflecting good interfacial bonding. In addition to this, the variation in glass transition temperature is found to be ~6 °C for the frequencies of 0.1 Hz and 1 Hz and it is ~12 °C for 10 Hz. This is observed because with increase in frequency of vibration, the composite tends to lose more energy than usual and enters into the glassy region faster than normal. Also, for sample D, double peaks have been observed which can be attributed to the inter-phase or micromechanical transition. From the plots it can be seen that the loss factor is decreased with an increase in fiber angle and follows the order Sample A > Sample B > Sample C > Sample E > Sample D with maximum tan \(\delta\) peak for sample A and minimum for sample D, at all frequencies under consideration as shown in figure 8(b).
3.2.2. Effect of frequency

To study the impact of frequency on the variation of dynamical mechanical properties of the samples, experiments were carried out at frequencies of 0.1 Hz, 1 Hz and 10 Hz and the corresponding values were

Figure 7. Storage modulus with respect to temperature for different PALF fiber orientation at frequency (a) 0.1 Hz (b) 1 Hz (c) 10 Hz.
presented in table 2 and the plots obtained were shown in figures 10(a)–(e) and 11(a)–(e) for storage modulus and loss factor respectively.

From figures 10(a)–(e), it can be established that the storage modulus have been affected by frequency and in the process of increasing frequency from 0.1 to 10 Hz especially at high temperatures it was found to be more prominent as the measurement of modulus carried out over a range of high-frequency results in higher values but measurements which were carried out over a lower frequency range results in the lower values. Drop in modulus values was found to start at around 60°C and continued till the temperature reaches 80°C since the molecular motion is believed to set at 60°C material undergoes rearrangement inter-molecularly in an effort to mitigate the localized stresses [7] and the modulus values remain unchanged after 100°C. There is an improvement in storage modulus with increment in frequency for all samples irrespective of fiber orientation and it has been observed for sample A, the storage modulus at frequencies 1 Hz and 10 Hz were found to increase by 3.35%, and 6.56% when compared to modulus at 0.1 Hz. Similarly, modulus values were found to increase by 2.88% and 5.36%, 5.73% and 11.17%, 1.15% and 1.40%, 3.50% and 5.24% for sample B, sample C, sample D and sample E respectively. From the above data, it can be observed that the measurements made at higher frequencies result in higher values complementing the fact that the modulus measurements performed over short intervals result in higher values and vice-versa.

The effect of frequency on the loss factor was presented in figures 11(a)–(e), it was seen from the plot that the frequency has a direct impact on tan δ peak and found to increase with an increase in frequency due to the
formation of microscopic cracks and void at higher frequencies. At higher frequencies, heterogeneity in the polymer network structure causes a broadening in the loss factor curve and as the damping peak is correlated with the partial loosening of the structure of polymer so that the segments in the matrix can shift. From the

Figure 9. Loss factor with respect to temperature for different PALF fiber orientation at frequency (a) 0.1 Hz (b) 1 Hz (c) 10 Hz.
results, it is found that the tan δ peak which is an indicator of the glass transition temperature, as well as the extent of cross linking of the system, was shifted to a greater temperature with increase of frequency. In addition, the loss factor curve for sample D shows double peaks and this can be believed due to the micro-mechanical changes arising out of the inactive epoxy layer which functions as an interlayer.

Table 3. Maximum Storage modulus, maximum loss factor and maximum glass transition temperature of hybrid composites at 0.1 Hz, 1 Hz and 10 Hz frequencies.

| Specimen | 0.1 Hz | 1 Hz | 10 Hz | 0.1 Hz | 1 Hz | 10 Hz | 0.1 Hz | 1 Hz | 10 Hz |
|----------|--------|------|-------|--------|------|-------|--------|------|-------|
| Sample A | 6.25   | 6.46 | 6.65  | 0.397  | 0.407| 0.420 | 71.6   | 78.32| 78.32 |
| Sample B | 4.57   | 4.62 | 4.72  | 0.333  | 0.365| 0.396 | 75.56  | 83.00| 91.36 |
| Sample C | 3.56   | 3.73 | 3.92  | 0.363  | 0.365| 0.390 | 76.6   | 77.26| 92.56 |
| Sample D | 2.39   | 2.40 | 2.42  | 0.236  | 0.288| 0.329 | 72.47  | 83.57| 88.47 |
| Sample E | 3.44   | 3.59 | 3.64  | 0.305  | 0.382| 0.414 | 73.01  | 77.32| 89.08 |

Figure 10. Variation of storage modulus with respect to temperature of hybrid composites at various frequencies for different fiber orientations (a) 0° (b) 30° (c) 45° (d) 60° (e) 90°.
4. Conclusion

Dynamic mechanical properties of PALF hybridized with Basalt reinforced epoxy composites along with their tensile and flexural behavior with different fiber orientations was investigated. It was found that the change in fiber orientations will have a great influence on storage modulus and loss tangent along with other mechanical properties investigated in this study, as is evident from the table that maximum variance in storage modulus at frequencies of 0.1 Hz, 1 Hz and 10 Hz are approximately 3.86 GPa, 4.26 GPa and 4.23 GPa respectively and the corresponding variance in loss factor values are 0.16, 0.12 and 0.09 respectively. This is because of the reason that increase in fiber orientation leads to change in the area of contact between resin and reinforcement fibers which ultimately affects the effectual stress transfer between basalt fiber and PALF. The better damping properties were found for sample A and least for sample D and follows a similar pattern for Young’s modulus and flexural modulus. There was a shift temperature of glass transition towards the right with an increase in fiber angle of PALF. Increase in frequency causes the modulus and loss factor to increase and shift in glass transition temperature to the higher temperature as well.
References

[1] Dong C 2018 Review of natural fibre-reinforced hybrid composites J. Reinf. Plast. Compos. 37 331–48
[2] Singhia K and Short A 2012 Review on basalt fiber International Journal of Textile Science 1 19–28
[3] George J, Sreekala M S and Thomas S 2001 A review on interface modification and characterization of natural fiber reinforced plastic composites Polymer Engineering Science 41 1471–85
[4] Li X, Tabl J G and Panigrahi S 2007 Chemical treatments of natural fiber for use in natural fiber-reinforced composites: a review Journal of Polymers and Environment 15 23–33
[5] John M J and Anandjiwala R D 2008 Recent developments in chemical modification and characterization of natural fiber-reinforced composites Polym. Compos. 29 187–207
[6] Le Guen M, Newman R H, Fernyhough A and Staiser M P 2014 Tailoring the vibration damping behaviour of flax fibre-reinforced epoxy composite laminates via polyol additions Composites Part A: Applied Science and Manufacturing 67 37–43
[7] Prasad D S, Ebenezer N S, Shobha C and Pujiari S R 2018 Effect of nickel electroplating on the mechanical damping and storage modulus of metal matrix composites Mater. Res. Express 5 1–10
[8] Prasad D S and Shoba C 2015 Damping behavior of metal matrix composites Trans. Indian Inst. Met. 68 161–7
[9] Prasad D S, Radha P T, Shoba C and Rao P S 2018 Dynamic mechanical behavior of WC-Co coated A356.2 aluminum alloy J. Alloys Compd. 767 988–93
[10] Saba N, Jawaiddh M, Alothman O Y and Paridak M T 2016 A review on dynamic mechanical properties of natural fibre reinforced polymer composites Constr. Build. Mater. 106 149–59
[11] Gupta M K and Deep V 2017 Effect of stacking sequence on flexural and dynamic mechanical properties of hybrid sisal/glass polyester composite America Journal of Polymer Science and Engineering 5 53–62
[12] Portella E H, DiaimeRomaniinb, CoussiratAngriFanb C, Amicob S C and Zatteraa A J 2016 Influence of stacking sequence on the mechanical and dynamic mechanical properties of Cotton/Glass fiber reinforced polyester composites Mater. Res. 19 542–7
[13] Motoc D L, Ferrandizbou1 S and Gimeno R B 2015 Effects of fibre orientation and content on the mechanical, dynamic mechanical and thermal expansion properties of multi-layered glass/carbon fibre-reinforced polymer composites J. Compos. Mater. 49 1211–21
[14] Mengal A N and Karuppunan S 2015 Influence of angle ply orientation on the flexural strength of basalt and carbon fiber reinforced hybrid composites Composites Research 28 1–5
[15] Gupta M K 2017 Effect of frequencies on dynamic mechanical properties of hybrid jute/sisal fibre-reinforced epoxy composite Advances in Materials and Processing Technologies 3 651–64
[16] Lopattananon L, Payae Y and Seadan M 2008 Influence of fibre modification on interfacial adhesion and mechanical properties of pineapple leaf fibre-epoxy composites Journal of Polymers and Environment 110 433–43
[17] Motaleb K Z M A, SharifullahMadb and Hoose Mb 2018 Improvement of physic mechanical properties of pineapple leaf fibre reinforced composite International Journal of Biomaterials 2018 1–7
[18] Asim M, KhalidAbdab, Jawaid M, Nasir M, Dashizadeh Z, Ishak M R and EnamulHoque M B 2015 A review on pineapple leaves fibre and its composites Int. J. Polym. Sci. 2015 1–17
[19] Gloriatia G, Al佐e C R, Moraeas M M, Loyalab R L, Margem F M and Monteiro N S 2015 Tensile properties of epoxy composites reinforced with continuous PALF fibers Characterization of Minerals, Metals, and Materials (Cham: Springer) 139–44 Characterization of Minerals, Metals, and Materials
[20] Gloriatia G, Teles M C A, Cerqueiraa Neeve A C, Vieira C M F, Lopes F P D, de Almeida Gomes M, Muiylaett Margem F and Neves Monteiro S 2017 Bending test in epoxy composites reinforced with continuous and aligned PALF fibers Journal of Materials Research and Technology 6 411–6
[21] Varley R J, Tian W, Leong K H, Leong A Y, Fredo F and Quaresimin M 2013 The effect of surface treatments on the mechanical properties of basalt reinforced epoxy composites Polym. Compos. 34 320–9
[22] Lopresto V, Leone C and Iorio F 2011 Mechanical characterization of basalt fibre reinforced plastic Composites Part B: Engineering 42 717–23
[23] Doddi P R V, Chananal R and Dora S P 2019 Dynamic mechanical properties of epoxy based PALF/basalt hybrid composite laminates Mater. Res. Express 6
[24] Todkar S S and Patil S A 2019 Review on mechanical properties evaluation of pineapple leaf fibre (PALF) reinforced polymer composites Composites Part B 174 1–16
[25] Ganeshan P, Kumaran S S, Raja K and Venkateswarlu D 2018 An investigation of mechanical properties of madar fiber reinforced polyester composites for various fiber length and fiber content Mater. Res. Express 6
[26] Ma F, Yang M, Pu Y and Zhi Y 2018 Response of carbon-basalt hybrid fibre reinforcement polymer under flexural load Mater. Res. Express 5
[27] Bozkurt O Y, Eryüksel A and Bozkurt Y T 2019 Influence of basalt fiber hybridization on the vibration-damping properties of glass fiber reinforced epoxy laminates Mater. Res. Express 6
[28] Azghani M A and Esfahani-Farsani R 2018 The effects of stacking sequence and thermal cycling on the flexural properties of laminate composites of aluminum-epoxy/basalt-glass fibres Mater. Res. Express 5
[29] Krishnasamy S, Muthukumar C, Nagarajan R, Thigiamani S M K, Saba N, Jawaid M, Siengchin S and Ayrilmis N 2019 Effect of fibre loading and Ca(OH)2 treatment on thermal, mechanical, and physical properties of pineapple leaf fibre/polyester reinforced composites Mater. Res. Express 6
[30] Mittal M and Chaudhary R 2019 Biodegradability and mechanical properties of pineapple leaf/coir Fiber reinforced hybrid epoxy composites Mater. Res. Express 6