Effect of silica nanoparticles on mechanical and thermal properties of intra-inter ply hybrid laminated composites

Bharathi M, S Senthil Kumaran and P Edwin Samson

1 Research Scholar, Department of Mechanical Engineering, Anna University, Chennai, India
2 Department of Mechanical Engineering, Anna University, Chennai, India

E-mail: m.bharathi1219@gmail.com

Keywords: mechanical properties, dynamic mechanical analysis (DMA), FESEM

Abstract

Emissions coming out from the automobile accounts for significant universal carbon emission. The reduction in the weight of the vehicle even by a kilogram can lead to a significant reduction in the carbon emissions, the use of natural fibre composites reduces the weight of the vehicle to a larger extent and minimises the problems associated with the disposal of the vehicle after its service life. The main objective of the work is to develop a light weight, comparatively eco-friendly natural fibre hybrid composite reinforced with intraply carbon + E-glass plies and unidirectional sunn hemp mat interplies and nano silica particles and to evaluate its mechanical and thermal properties for possible application in automobiles. The addition of nano silica was varied between 1wt% to 4wt%. Mechanical properties investigation through (tensile and impact tests) and thermo mechanical investigation through dynamic mechanical analysis (DMA) and heat deflection temperature (HDT) were carried out. Activation energy of the nano composites was determined using Arrhenius model. Failure analysis of the composites was carried out with field emission scanning electron microscopy (FESEM). Mechanical and thermal properties was found to be higher for the intra-interply polymer composite reinforced with carbon + E-glass fibres and unidirectional sunn hemp mats with 3wt%, nano silica particles addition. The results obtained in this work will be useful in designing comparatively environmentally friendlier composite structures

Nomenclature

C Carbon bidirectional mat
EG E-Glass bidirectional mat
Intra\textsuperscript{C}_{\text{EG}} Intraply (Carbon + E-Glass bidirectional mat)
UDSH Uni-directional Sunn Hemp mat
NS Nano Silica
EPOXY Resin LY556 and Hardener HY951
FRP-1 UDSH + Epoxy
FRP-2 Interply Hybrid composite (C + EG/USH/C + EG/USH/EG/C)
FRP-3 Intra-interply Hybrid composite (Intra\textsuperscript{C}_{\text{EG}}/Intra\textsuperscript{C}_{\text{EG}}/UDSH/
Intra\textsuperscript{C}_{\text{EG}}/Intra\textsuperscript{C}_{\text{EG}}/UDSH/Intra\textsuperscript{C}_{\text{EG}}/Intra\textsuperscript{C}_{\text{EG}})
FRP-4 Intra-interply Hybrid composite (Intra\textsuperscript{C}_{\text{EG}}/Intra\textsuperscript{C}_{\text{EG}}/UDSH/Intra\textsuperscript{C}_{\text{EG}}/Intra\textsuperscript{C}_{\text{EG}}/UDSH/Intra\textsuperscript{C}_{\text{EG}}/Intra\textsuperscript{C}_{\text{EG}})+1% NS
FRP-5 Intra-interply Hybrid composite (Intra\textsuperscript{C}_{\text{EG}}/Intra\textsuperscript{C}_{\text{EG}}/UDSH/Intra\textsuperscript{C}_{\text{EG}}/Intra\textsuperscript{C}_{\text{EG}}/UDSH/Intra\textsuperscript{C}_{\text{EG}}/Intra\textsuperscript{C}_{\text{EG}})+2% NS

© 2021 The Author(s). Published by IOP Publishing Ltd
1. Introduction

Last few decades have witnessed tremendous growth of composites in the various fields of engineering such as aerospace, automobile, marine and transportation of fluids in oil and gas industries due to their inherent advantages such as high strength to weight ratio, excellent corrosion resistance, etc., [1–4]. In spite of the advantages offered by the composites, disposing the obsolete composite products is a serious problem as it usually results in landfill, it has been pointed out that toxic gases are released into the air and water bodies, which can lead to cancer and respiratory diseases [5–8]. It is observed from the literature [1, 2] that very fine synthetic particles produced during the fabrication of synthetic fibre composites, are airborne and can lead to occupational health hazard. Hence, it is necessary to develop materials which will have lesser impact on the environment [9, 10].

In the recent years, plenty of research is done in the area of natural fibre hybrid composites [11–13] where the matrix is reinforced with natural fibre and synthetic fibre. Reinforcing in the aforesaid manner allows to combine the advantages of natural fibre and synthetic fibre used. The reduction in the quantum of synthetic fibre in the natural fibre hybrid composite results in low cost, comparatively environmentally friendlier composite structures. It is well known that carbon fibres have higher modulus, higher strength and lower failure strain whereas E-glass fibre have comparatively lower modulus and higher failure strain, thus by hybridising carbon and E-glass fibres, it is possible to mitigate the less desirable properties of these fibres. Among the natural fibres, hemp fibres exhibit tensile strength of the order 1100 MPa and is one of the strongest natural fibres [14]. Moreover, its flexural strength is almost equivalent to that of E-glass fibres [15].

Although research works are found in the area of interply composites made of carbon and E-glass [16–19], much of the research work is not available in the area of intraply composites made of carbon + E-glass. It is well known that energy absorption capability of the intraply composites is higher than interply composites, which can be attributed to the higher inter locking effect of the former [16, 18]. It has been pointed out that when natural fibres are hybridised with synthetic fibres, the energy absorption capability of the natural fibre hybrid composite is enhanced [11, 12].

The thermal stability of a composite decides the applicability of the same at a specific temperature; hence its evaluation is imperative. The thermal stability can be assessed with the tests such as dynamic mechanical analysis (DMA) and heat deflection temperature (HDT). Ilangoan et al [19] have found that the addition of nano silica particles increases the thermal properties of the fibre reinforced polymer (FRP) composites [19].

By hybridising intraply carbon + E-glass mats with interply unidirectional sunn hemp mats and by dispersing nano silica particles it will be possible to develop a composite structure with better thermal stability along with enhanced load bearing capability. Studies on the effect of hybridisation of intraply synthetic fibres and interply natural fibres with nano fillers in composites have not been addressed by the earlier researchers.

It has been pointed out that emission coming out from the automobile’s accounts for significant universal carbon emission. The reduction in the weight of the vehicle even by a kilogram can lead to a significant reduction in the carbon emissions, the use of natural fibre composites reduces the weight of the vehicle to a larger extent and minimises the problems associated with the disposal of the vehicle after its service life [20, 21].

This work aims at developing light weight comparatively ecofriendly natural fibre hybrid composite reinforced with intraply carbon + E-glass plies, unidirectional sunn hemp mat interplies and nano silica particles and to assess its tensile, impact properties and thermal stability by conducting DMA, HDT and activation energy calculated through Arrhenius model.

2. Materials selection and specimen preparation

In this work, materials such as bidirectional mats of carbon, E-glass, intraply carbon + E-glass mats and unidirectional woven sunn hemp mat and nano silica particles of size 40 microns were used as reinforcing materials. Each strand in the bidirectional carbon mat, bidirectional E-glass mat and carbon + E-glass intraply mat were of 3000 Tex. Epoxy (LY 556) and hardener (HY 951) was used as the matrix material. Ratio between the epoxy and the hardener was maintained as 10:1, by weight. Composite specimens were fabricated with hand layup technique and further compressed in a hydraulic press. Post curing of the composite specimens was carried out for 24 h at room temperature. The mould and hydraulic press used for fabricating the composite
laminate is shown in figure 1. Natural fibre hybrid composite panels of size 300 × 300 mm were fabricated, and standard specimens were cut from the laminates using table circular saw. Seven different composites were prepared and the stacking sequence adopted in the various composites is shown in figures 2(a)–(g).

While cutting the specimens from interply composites, care was taken to see that carbon fibres, E-glass fibres and unidirectional sunn hemp mats were parallel oriented in the loading direction and while cutting the specimens from the intra–interply composites care was taken to see that carbon fibres and unidirectional sunn hemp fibres were parallel oriented along the loading direction.

The stacking sequence of plies in the various composites is shown in figure 2.

3. Material testing

3.1. Tensile
Instron make universal testing machine model number 3382 was used to conduct the tensile test. The tensile test was carried out by adopting ASTM D3039 standard. Standard specimens of dimension 20 × 250 mm were cut from the laminates and tensile test was carried out with a cross head displacement rate of 2 mm min⁻¹.

3.2. Impact
Tinius Olsen make, impact testing machine was used to conduct the angular (izod and charpy) impact tests. For carrying out the izod test ASTM D256 standard was adopted, standard specimens of dimension 20 × 150 mm with a ‘V’ notch of 2 mm and angle of 45° were cut from the laminates and were used to assess the izod impact strength. For conducting the charpy impact test ASTM D 6110 standard was adopted, specimens of dimension 20 × 150 mm with a ‘V’ notch of 2 mm and angle of 45° were cut from the laminates and were used to assess the charpy impact strength.

3.3. Field emission scanning electron microscopic (FESEM) analysis
To understand the failure mechanism of the composite specimens failed under tensile test, field emission scanning electron microscopic (FESEM) analysis was carried out with Zeiss sigma make Field Emission Scanning Electron microscope. Before FESEM analysis, the composite specimens were coated with gold to have a better image.

3.4. Dynamic mechanical analysis (DMA)
DMA on the fabricated composites was carried out with Seiko make, model number DMA 6100 dynamic mechanical analyser by following ASTM standard D7028. Specimens of dimension 50 × 10 × 3.85 mm were cut from the laminates and were used in the DMA. A dual cantilever fixture was used to support the specimens. The DMA was carried out over a temperature 34° to 160 °C at different frequencies 0.2, 0.5, 1, 2 and 5 Hz and the dynamic mechanical properties like storage modulus, loss modulus, loss factor and glass transition temperature were estimated.

3.5. Heat deflection temperature (HDT)
The HDT is the temperature at which a composite deforms to a specified distance under a constant load. The heat deflection test is used to measure the thermal stability of the composite [22]. The heat deflection temperature was assessed with Instron HDT apparatus. The heat deflection temperature assessment was carried out in accordance with ASTM standard D648. Composite sample of size 127 × 13 × 12 mm was immersed in a
4. Results and discussion

4.1. Tensile properties

The results of the tensile test of the fabricated composites FRP 1, FRP 2 and FRP 3 are shown in figures 3(a) and (b).

From figure 3, it can be identified that the tensile strength of FRP 3 is 270.33 MPa which is marginally higher than the tensile strength 265.11 MPa exhibited by FRP 2. Therefore, it can be stated that reinforcing the composite with intraply carbon + E- glass bidirectional plies and unidirectional sunn hemp interplies has resulted in marginal improvement in the tensile strength when compared with the composite reinforced with
carbon, E-glass bidirectional interplies and unidirectional sunn hemp interplies. The increase in strength can be attributed due to the presence of high strength carbon fibres and E-glass fibres present in the same ply, this provides an interlocking arrangement between the fibres, enabling better load transfer\cite{16, 18}. Similar kind of observation were made by\cite{23, 24}.

Further the improvement in strength exhibited by the intra-inter ply composites can be attributed to the presence of larger amount of high strength carbon fibres present along the loading direction than the interply composites considered in the study.

It has been pointed out by Raj purohit\cite{23} that the E-glass fibres present in carbon+E-glass intraply composite impede the development of clump of fibre cracks in the carbon when subjected to load. The intra ply arrangement in the intra-interply hybrid composite helps to decrease the concentration of carbon fibres in a given volume and results in the increased strength of intra-interply hybrid composites. In the intra-interply

![Figure 3. (a) Tensile strength of FRP 1, FRP 2 and FRP 3 composites (b) Tensile strain of FRP 1, FRP 2 and FRP 3 composites.](image)
The results of the FESEM analysis of the FRP 1, FRP 2 and FRP 3 composite specimens failed under tensile test is shown in [119x427]Figure 4.1. FESEM analysis

The lower strength exhibited by interply composites can be attributed to the weak interfacial regions present between carbon woven mats, E-glass woven mats and sunn hemp mats [25].

From Figure 3 it can be identified that the tensile strain of FRP 3 is 2.96% and FRP 2 is 2.91%. The tensile strain exhibited by the composites is in the order of 2.9% which is reasonable. There is no major difference in the tensile strain between interply composite FRP 2 and intra-interply FRP 3 composite considered in the study.

4.2. Angular impact properties

The angular impact strength of the fabricated composites FRP 1, FRP 2 and FRP 3 were assessed by izod and charpy tests and is shown in the figures 4(a) and (b).

From figures 4(a) and (b), it can be identified that, FRP 3 exhibits an impact strength 66.82 kJ m$^{-2}$ in izod impact test and 65.82 kJ m$^{-2}$ in charpy impact test, the values are higher than the impact strength exhibited by FRP 2 in izod and charpy impact tests.

The difference in impact strength between FRP 3 and FRP 2 is 1.29 kJ m$^{-2}$ in both the tests, which is marginal. The increase in the impact strength of FRP 3 is due to the presence of stiff, high strength carbon fibres and ductile E-glass fibres present in the same ply in the weft and warp directions and sunn hemp fibres. In the intra-inter ply composites, synergistically along with the synthetic fibres, sunn hemp fibres have taken approximately 21% of the total impact load [26].

Further, it has been pointed out that the energy absorption capability of the intraply composites is higher than interply composites, which can be attributed to the higher interlocking effect of the former [16, 18]. It has been pointed out that when natural fibres are hybridised with synthetic fibres the ability of the natural fibre hybrid composites to withstand the shock load is enhanced [11, 12]. The hybridisation of intraply carbon + E-glass plies and unidirectional sunn hemp interplies has enhanced the load bearing ability of the FRP 3 composite.

4.3. FESEM analysis

The results of the FESEM analysis of the FRP 1, FRP 2 and FRP 3 composite specimens failed under tensile test is shown in figure 5(a)-(c).

The FESEM images of FRP 1 composite failed under tensile test shows the presence of the failure mechanisms such as matrix cracking, fibre bundle pull out and fibre pull out. In the FESEM images of FRP 2 composite failed under tensile test, failure mechanisms such as fibre breakage and matrix cracking were observed and in the FESEM images of FRP 3 composite failed under tensile test, failure mechanisms such as fibre breakage, matrix cracking and matrix ripple were observed. By comparing the FESEM images, it can be stated that the magnitude of fibre breakage and matrix cracking is lesser in FRP 3 when compared with FRP 1 and FRP 2, this further strengthens the statement FRP 3 intraply-interply composites are stronger when compared with FRP 2 and FRP 1 composites.

5. Dynamic mechanical properties

The results of the Dynamic Mechanical Analysis (DMA) of the fabricated composites FRP 1, FRP 2 and FRP 3 is shown in figures 6(a)-(c). The glass transition temperature based on loss modulus and loss tangent is presented in table 1.

5.1. Storage modulus

From figure 6(a) by observing the initial storage modulus exhibited by the various composites at 0.2 Hz, it can be stated that FRP 3 exhibits an initial storage modulus of 39550.3 MPa which is higher than 39309.4 MPa the initial storage modulus exhibited by FRP 2, the difference in storage modulus between FRP 3 and FRP 2 is 240.9 MPa. Similar kind of trend was observed in the other trials conducted at 0.5, 1, 2 and 5 Hz. Higher storage modulus is an index of higher energy absorption capability of the composite; therefore, it can be stated that FRP 3 has higher energy absorption capability than FRP 2, this can be attributed to the presence of carbon and E-glass fibres present in the same ply which promotes better load transfer [27]. The increase in storage modulus can also be attributed to the minimisation of concentration of cracks in carbon fibres in the intra-inter ply arrangement. The weak interface present in inter ply composites between carbon bidirectional mats and E-glass bidirectional mats reduces the effectiveness of load transfer and hence interply composites have lower storage modulus when compared with intraply composites.

In the intra-interply composites, synergistically along with the synthetic fibres, sunn hemp fibres have contributed approximately 50.50% of the total storage modulus.
5.2. Loss modulus
From figure 6(b), by observing the peak loss modulus exhibited by the various composites at 0.2 Hz, it can be stated that FRP 3 exhibits a peak loss modulus of 10351.96 MPa which is higher than 10224.19 MPa the peak loss modulus exhibited by FRP 2, the difference in loss modulus between FRP 3 and FRP 2 is 127.77 MPa. Similar kind of trend was observed in the other trails conducted at 0.5, 1, 2 and 5 Hz. Higher loss modulus is an index of energy spent by the composite during deformation, therefore it can be stated that when subjected to deformation FRP 3 will dissipate more energy than FRP 2, this can be attributed to the presence of carbon and E-glass fibres present in the same ply which promotes better load transfer \[28\] the relatively ductile E-glass with higher failure strain aids intra-intraply composites to carry more load when subjected to deformation \[20\]. The increase in storage modulus can also be attributed to the minimization of concentration of cracks in carbon fibres in the intra-inter ply arrangement.
Figure 5. (a) FESEM of FRP 1 specimens failed under tensile test. (b) FESEM of FRP 2 specimens failed under tensile test. (c) FESEM of FRP 3 specimens failed under tensile test.
Figure 6. (a) Storage Modulus versus Temperature (b) Loss Modulus versus Temperature (c) Loss Tangent versus Temperature of Epoxy, FRP 1, FRP 2 and FRP 3 composites at 0.2 Hz, 0.5 Hz, 1 Hz, 2 Hz and 5 Hz.
In the intra-interply composites, synergistically along with the synthetic fibres, sunn hemp fibres have contributed approximately 35.18% of the total loss modulus.

5.3. Loss tangent
From figure 6(c), by observing the peak loss tangent exhibited by the various composites at 0.2 Hz, it can be stated that FRP 3 exhibits a peak loss tangent of 0.26 which doesn’t differ much with the peak loss tangent exhibited by FRP 2. Similar kind of trend is observed in the other trails conducted at 0.5, 1, 2 and 5 Hz.

5.4. Glass transition temperature
By observing the table 1 it can be stated that \( T_g \) values exhibited by FRP 3 and FRP 2 dose not differ much. Glass transition is a material property and the inter, intra-intra ply arrangement of the plies does not have much influence on the glass transition temperature.

6. Heat deflection temperature (HDT)
The heat deflection temperature of the fabricated composite FRP 1, FRP 2 and FRP 3 was carried out in accordance with ASTM standard D648 and the results are shown in the table 2.

From the table 2 it can be identified that the heat deflection temperature between FRP 3 and FRP 2 is negligible and it can be stated that heat deflection temperature is in significant to the intraply and interply arrangement of the plies does not have much influence on the glass transition temperature.

7. Addition of nano silica particles in the composite reinforced with intraply carbon + E-glass mats and interply sunn hemp mats to enhance the mechanical and thermal properties.

Based on the evaluation of mechanical and thermal properties of the FRP 1, FRP 2 and FRP 3, the composite with the superior properties is alone considered for further study. Accordingly, intra-interply composite reinforced with carbon + E-glass mats and sunn hemp mats were found to be better and were further reinforced with nano silica by 1 wt %, 2 wt %, 3 wt % and 4 wt % respectively and their mechanical and thermal properties were estimated.

For fabricating the intra-interply composite reinforced with carbon + E-glass mats and sunn hemp mats with varying levels of nano silica, the fabricating procedure mentioned earlier was followed. The schematic arrangement of the various plies in the composites reinforced with nano silica is shown in figures 2(d)–(g)

7.1. Tensile properties of the intra–interply composites reinforced with carbon + E-glass mats, sunn hemp mats and nano silica particles
The results of the tensile tests of FRP 3, FRP 4, FRP 5, FRP 6 and FRP 7 is shown in the following figure 7.

| Material | Heat deflection Temperature °C |
|----------|--------------------------------|
| Epoxy    | 115.5 °C                      |
| FRP 1    | 185.3 °C                      |
| FRP 2    | 278.5 °C                      |
| FRP 3    | 279.5 °C                      |

In the intra-interply composites, synergistically along with the synthetic fibres, sunn hemp fibres have contributed approximately 35.18% of the total loss modulus.

Table 1. Glass transition \( T_g \) values of FRP 1, FRP 2 and FRP 3 Composites observed at 0.2, 0.5, 1, 2 and 5 Hz frequencies.

| Material | 0.2 Hz | 0.5 Hz | 1 Hz | 2 Hz | 5 Hz |
|----------|--------|--------|------|------|------|
| FRP 1    | T\(_g\) \( ^\circ \)C based on Loss Modulus | 83.35 | 83.60 | 84.14 | 84.29 | 84.53 |
|          | T\(_g\) \( ^\circ \)C based on Loss Tangent    | 89.46 | 89.71 | 90.25 | 90.30 | 90.63 |
| FRP 2    | T\(_g\) \( ^\circ \)C based on Loss Modulus    | 84.48 | 84.84 | 85.48 | 85.66 | 85.99 |
|          | T\(_g\) \( ^\circ \)C based on Loss Tangent    | 90.59 | 90.96 | 91.60 | 91.78 | 92.01 |
| FRP 3    | T\(_g\) \( ^\circ \)C based on Loss Modulus    | 84.78 | 85.23 | 85.54 | 85.72 | 85.99 |
|          | T\(_g\) \( ^\circ \)C based on Loss Tangent    | 90.89 | 91.34 | 91.66 | 91.83 | 91.99 |
From Figure 7, it is identified that the progressive addition of nano silica particles from 1 wt% to 3 wt% has resulted in progressive increase in the tensile strength, when the addition of nano silica particles exceeds 4 wt% there is reduction in the tensile strength, this could be due to the agglomeration effect of the nano silica particles. 

From Figure 10 it is identified that FRP 6 exhibited a tensile strength of 310.76 MPa which is higher than the tensile strength 270.33 MPa exhibited by FRP 3, the difference in tensile strength between FRP 6 and FRP 3 is 40.43 MPa. By the addition of 3 wt% nano silica, the tensile strength increases by 13%, which is significant. This increase in strength can be attributed to increase in the bonding strength between the matrix and the fibres by the addition of nano silica particles. Further the addition of nano silica particles strengthens the matrix by dispersion strengthening. Therefore, it can be stated that the addition of nano silica particles plays a crucial role in the tensile strength of the intra–interply composites considered in the study.

From Figure 7, it is identified that FRP 6 exhibits a tensile strain of 2.72 and FRP 3 exhibits a tensile strain of 2.96. With respect to the increase in the addition of nano silica particles there is a marginal reduction in the tensile strain of the composites and this can be attributed to the stiffening of the composite by the addition of nano silica particles.

7.2. Angular impact properties of the intra–interply composites reinforced with carbon + E–glass mats, sunn hemp mats and nano silica particles

The results of the angular impact tests of FRP 3, FRP 4, FRP 5, FRP 6 and FRP 7 are shown in the following figures 8(a) and (b).

From figures 8(a) and (b) it can be identified that the progressive addition of nano silica particles from 1 wt% to 3 wt% has resulted in progressive increase in the impact strength, when the addition of nano silica particles exceeds 4 wt%, there is reduction in the impact strength, this could be due to the agglomeration effect of the nano silica particles.

Further, from figures 8(a) and (b) it can be identified that FRP 6 exhibits an impact strength of 75.69 kJ m$^{-2}$ in izod and 75.54 kJ m$^{-2}$ in Charpy impact tests, the values exhibited by FRP 6 composite in these tests are higher than 66.82 kJ m$^{-2}$, 65.82 kJ m$^{-2}$ the impact strength exhibited by FRP 3 in izod and Charpy impact tests. The difference in impact strength between FRP 6 and FRP 3 is 8.85 and 9.72 kJ m$^{-2}$ in izod and Charpy tests. It can be stated that by the addition of 3 wt% nano silica particles, the impact strength increases by 11.7% in izod impact test and 12.86% in Charpy impact test, which is significant. This increase in strength can be attributed to increase in the bonding strength between the matrix and the fibres by the addition of nano silica particles [30, 31]. Further the addition of nano silica particles strengthens the matrix by dispersion strengthening which increases the load bearing capability. Therefore, it can be stated that the addition of nano silica particles plays a crucial role in the impact strength of the Intra–interply composites considered in the study.

7.3. FESEM analysis of the intra–Interply composites reinforced with carbon + E–glass mats, sunn hemp Mats and nano silica particles

The results of the FESEM analysis of the FRP 3, FRP 4, FRP 5, FRP 6 and FRP 7 composite specimens failed under tensile test is shown in figures 9(a)–(d).
The FESEM images of FRP 4 composite failed under tensile test shows the presence of the failure mechanisms such as matrix cracking, ductile fracture of natural fibres and fibre bridging. In the FESEM images of FRP 5 composite failed under tensile test, failure mechanisms such as matrix cracking and fibre pull out are observed.

The FESEM of FRP 6 composite failed under tensile test shows the failure mechanism delamination which is not predominant, therefore it can be stated that good fibre matrix interfacial bonding exists in FRP 6 composite and in the FESEM images of FRP 7 composite failed under tensile test, failure mechanisms such as brittle fracture are observed. By comparing the above FESEM images shown in figures 9(a)–(d) it can be stated that good fibre matrix interfacial bonding is there in FRP 6 than the other composites considered in the study.
7.4. Dynamic mechanical properties of the Intra–Interply composites reinforced with carbon + E–glass mats, Sunn Hemp mats and nano silica particles

The results of the dynamic mechanical analysis of the fabricated composites FRP 4, FRP 5, FRP 6 and FRP 7 in figures 10(a)–(e), 11(a)–(e), 12(a)–(e). The glass transition temperature based on loss modulus and loss tangent for these composites is presented in tables 3 and 4.

7.4.1. Storage modulus of the intra–interply hybrid composites reinforced with varying levels of nano silica particles

By observing figure 10(a) Storage modulus versus Temperature curves plotted for the FRP 3, FRP 4, FRP 5, FRP 6 and FRP 7 composites at 0.2 Hz over a temperature range varying from 34 °C to 160 °C it can be stated that FRP 6 exhibited an initial storage modulus of 42513 MPa which is higher than the initial storage modulus 39550.3 MPa exhibited by FRP 3, the difference in initial storage modulus between FRP 6 and FRP 3 is 2962.7 MPa and it can be stated that by the addition of 3 wt % nano silica particles, the storage modulus increases by 6.99%.

Further by observing figure 10(a) it can be stated that the progressive addition of nano silica particles from 1 wt % to 3 wt % has resulted in progressive increase in the storage modulus, further from the graphs it is identified that when the addition of nano silica particles exceeds 4 wt %, there is reduction in storage modulus, this could be due to the agglomeration effect of the nano silica particles. Similar kind of trend is observed in the other trails conducted at 0.5, 1, 2 and 5 Hz. The trails conducted confirmed that the addition of nano silica particles play a crucial role in improving the energy absorption capability of the intraply–interply composites reinforced with carbon + E- glass mats and sunn hemp mats.

7.4.2. Loss Modulus of the intra–interply hybrid composites with varying levels of nano silica particles

By observing figure 11(a) Loss modulus versus Temperature curves plotted for the FRP 3, FRP 4, FRP 5, FRP 6 and FRP 7 composites at 0.2 Hz over a temperature range varying from 34 °C to 160 °C it can be stated that FRP 6 exhibited a maximum loss modulus of 10892.74 MPa which is higher than the initial loss modulus 10351.96 MPa exhibited by FRP 3. The difference in loss modulus between FRP 6 and FRP 3 is 540.78 MPa and it can be stated...
that by the addition of 3 wt % nano silica particles, the loss modulus increases by 4.96%. Further by observing figure 5(a) it can be stated that the progressive addition of nano silica particles from 1 wt % to 3 wt %, has resulted in progressive increase in the loss modulus. Further, from the graphs it is identified that when the addition of nano silica particles exceeds 4 wt % there is reduction in loss modulus, this could be due to the agglomeration effect of the nano silica particles. Similar kind of trend is observed in the other trials conducted at 0.5, 1, 2 and 5 Hz. Higher loss modulus is an index of energy spent during the deformation of the composite, the presence of

Figure 10. (a)–(e) Storage Modulus versus Temperature curves at 0.2 Hz, 0.5 Hz, 1 Hz, 2 Hz, 5 Hz.
nano silica particles in the intraply-interply composites have resisted the molecular movement of the polymer resulting in higher loss modulus [32].

From table 3 it is found that FRP 6 at 0.2 Hz exhibited a glass transition temperature of 85.09°C, the value is marginally higher when compared with the glass transition temperature 84.78°C exhibited by FRP 3 composite at 0.2 Hz, the difference in glass transition temperature between FRP 6 and FRP 3 is 0.31°C and it can be stated that by the addition of 3 wt% nano silica particles, the glass transition temperature increases marginally by 0.36%. Similar kind of trend is observed in the other trails conducted. Therefore, it can be stated that there is no

---

**Figure 11.** (a)–(e) Loss Modulus versus Temperature curves at 0.2 Hz, 0.5 Hz, 1 Hz, 2 Hz and 5 Hz.
Figure 12. (a) Loss Tangent versus Temperature curves at 0.2 Hz, 0.5 Hz, 1 Hz, 2 Hz and 5 Hz.

Table 3. Glass transition $T_g$ values (based on loss modulus) of FRP 4, FRP 5, FRP 6 and FRP 7 Composites observed at 0.2, 0.5, 1, 2 and 5 Hz frequencies.

|       | 0.2 Hz | 0.5 Hz | 1 Hz  | 2 Hz  | 5 Hz  |
|-------|--------|--------|-------|-------|-------|
| FRP-4 | $T_g$ °C | 84.83  | 85.31 | 85.88 | 86.15 | 86.57 |
| FRP-5 | $T_g$ °C | 84.95  | 85.62 | 85.98 | 86.34 | 86.78 |
| FRP-6 | $T_g$ °C | 85.09  | 85.76 | 86.04 | 86.49 | 86.99 |
| FRP-7 | $T_g$ °C | 83.56  | 84.57 | 85.84 | 86.84 | 86.74 |
major difference in T_g values between intra–interply composites reinforced with nano silica particles and intra-interply composites without nano particle addition considered in the study.

Higher loss modulus is an index of energy spent by the composite during deformation. Therefore, it can be stated that FRP 6 has higher capability to dissipate energy when subjected to deformation than FRP 3 and it can be stated that the addition of nano silica plays a crucial role in improving the energy dissipating characteristics of the composite.

7.4.3. Loss tangent of the intra–interply hybrid composites with varying levels of nano silica particles

By observing table 4 and figure 12(a)–(e) Loss tangent versus Temperature curves plotted for the FRP 4, FRP 5, FRP 6 and FRP 7 composites at various frequencies over the temperature range 34 °C to 160 °C it can be stated that the loss tangent values marginally increases with increase in the percentage of addition of nano silica. For FRP 6 and FRP 7 higher loss tangent values are observed at 1, 2 and 5 Hz. Loss tangent is an index of higher energy dissipation characteristics of a composite. Therefore, it can be stated that the addition of nano silica particles increases the energy dissipation characteristics of the composite.

From tables 4 and 1 it is found that FRP 6 at 0.2 Hz exhibited a glass transition temperature of 91.19 °C the value is marginally higher when compared with the glass transition temperature 90.89 °C exhibited by FRP 3 composite at 0.2 Hz, the difference in glass transition temperature between FRP 6 and FRP 3 is 0.3 °C and it can be stated that by the addition of 3 wt % nano silica particles the glass transition temperature increases by 0.33%. Similar kind of trend is observed in the other trials conducted. Therefore, it can be concluded that the addition of nano silica particles doesn’t play a major role in increasing the T_g value of the intra–interply composites reinforced with nano silica particles.

7.5. Heat deflection temperature (HDT) of the Intra–Interply hybrid composites reinforced with varying levels of nano silica particles

The heat deflection temperature observed for the intra–interply hybrid composites reinforced with varying levels of nano silica is shown in the following table 5.

| Material | Heat deflection Temperature °C |
|----------|--------------------------------|
| FRP 4    | 289.9 °C                       |
| FRP 5    | 294.7 °C                       |
| FRP 6    | 299.3 °C                       |
| FRP 7    | 264.3 °C                       |

7.6. Activation energy of the Intra–interply composites FRP 4, FRP 5, FRP 6 and FRP 7

Linear regression lines are plotted between frequency and temperature (shown in figure 13) and the slope of the plotted regression lines is found out and multiplied with gas constant to find out the activation energy. In table 6 the maximum loss tangent, glass transition T_g values and activation energy of the FRP4, FRP5, FRP 6 and FRP 7 are shown.

The slope of the regression lines is substituted in the following equation for the calculation of activation energy.
Where R is gas constant. The calculated activation energy for the various intra-interply composites FRP 4, FRP 5, FRP 6 and FRP 7 is shown in the table 6. From the table 6 it can be identified that the activation energy of FRP 6 is higher than the other intra-interply composites considered in the study. Higher activation energy is an index of better thermal stability of the composite. There is a progressive increase in the activation energy with progressive increase in the percentage addition of nano silica particles up to 3 wt%. When the percentage of addition of nano silica in the intra-interply composites exceed 3 wt %, the composite becomes weaker due to the agglomeration effect and the activation energy also decreases.

8. Conclusions

The salient findings of the present work are summarised below
1. Mechanical and thermal properties of intraply interply composite reinforced with carbon + E-glass intraply and sunn hemp mat interplies are higher when compared with interply composite reinforced with carbon, E-glass and sunn hemp mats.

2. The addition of nano silica particles has profound influence on the tensile and impact strength of the intra interply composites reinforced with carbon + E-glass fibres and sunn hemp fibres, composites reinforced with 3 wt % nano silica particles exhibits maximum tensile and impact strength.

3. Visco elastic properties of the intra–interply composites reinforced with carbon + E-glass and sunn hemp interplies are higher when compared with interply composite reinforced with carbon, E-glass and sunnhemp mats.

4. The addition of nano silica up to 3 wt % in the intra–interply composite improves the storage and loss modulus, higher storage modulus is an index of the ability of the composite to absorb energy when subjected to loads such as impact, higher loss modulus is an index of energy spent by the composite during deformation. In lieu of the capabilities such as high energy absorption and dissipation of energy to a larger extent by deformation, it will be a better candidate for the structures which are susceptible to impact.

5. The loss tangent observed confirms the addition of nano silica particles improves the energy dissipation characteristics.

6. The calculated activation energy of the intra–interply composite reinforced with carbon + E-glass, sunn hemp interplies and 3 wt % nano silica particles is higher and this confirm its higher thermal stability.

7. The results obtained in this study will be useful in designing comparatively environmentally friendlier composite structures.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

ORCID iDs

Bharathi M https://orcid.org/0000-0002-4677-8729
P Edwin Samson https://orcid.org/0000-0002-6302-0557

References

[1] Sarasini F, Tirillo J, Sergi C, Seghini M C, Cozzarini I and Graupner N 2018 Effect of basalt fibre hybridisation and sizing removal on mechanical and thermal properties of hemp fibre reinforced HDPE composites Compos. Struct. 188 394–406
[2] Mochane M J, Mokhena T C, Mokhothu T H, Mtibe A, Sadiku E R, Ray S S, Ibrahim I D and Daramola O O 2019 Recent progress on natural fibre hybrid composites for advanced applications: a review Express Polym Lett 13 159–98
[3] Deniz M A, OkanOzdemir M, Ozan and Karakuzu R 2013 Failure pressure and impact response of glass–epoxy pipes exposed to seawater Composites Part B: Engineering 53 355–61
[4] Pickering K L, Elendy M G A and Le T M 2016 A review of recent developments in natural fibre composites and their mechanical performance Composites Part A: Applied Science and Manufacturing 83 98–112
[5] Vijay N, Rajkumara V and Bhattacharjee P 2016 Assessment of composite waste disposal in aerospace industries Procedia Environmental Sciences 35 563–70
[6] Cholake S T, Rajarao R, Henderson P, Rajagopal R and Walla. V S 2017 Composite panels obtained from automotive waste plastics and agricultural macadamia shell waste J. Clean. Prod. 151 163–71
[7] Santini A, Passarini F, Vassura I, Serrano D, Dufour J and Morselli L 2012 Auto shredder residue recycling: mechanical separation and pyrolysis Waste Manage. (Oxford) 32 852–8
[8] Kurasińska M, Barczewski M, Urani K, Lewandowski K, Prociak A and Michalowski S 2019 Basalt waste management in the production of highly effective porous polyurethane composites for thermal insulating applications Polym. Test. 76 90–100
[9] 2017/2018 Ford Motor Company Sustainability Report 2017/2018www.sustainability.ford.com
[10] Adeniyi A, George D V, Onifade J O, Ighalo and Adeoye A S 2019 A review of coir fibre reinforced polymer composites Composites Part B: Engineering 176 107305
[11] Mohan T P and Kanny K 2019 Compressive characteristics of unmodified and nano clay treated banana fibre reinforced epoxy composite cylinders Composites Part B: Engineering 169 118–25
[12] Alkahash Z F and Ansari M N M 2017 Investigation on energy absorption of natural and hybrid fibre under axial static crushing Compos. Sci. Technol. 151 32–61
[13] Scherer H F and Bom R P 2019 Determination of shear modulus in bamboo fibres composite in torsion tests Mater. Res. Express 6 035310
[14] Sair S, Oushabi A, Kammouni A, Tanane O, Abboud Y and El A 2018 Bouari. ‘Mechanical and thermal conductivity properties of hemp fibre reinforced polyurethane composites Case studies in construction materials 8 203–12
[15] Shahzad A 2012 Hemp fibre and its composites–a review J. Compos. Mater. 46 973–86
Vasudevan A, Senthil Kumaran S, Naresh K and Velmurugan R 2019 Layer-wise damage prediction in carbon/Kevlar/S-glass/E-glass fibre reinforced epoxy hybrid composites under low-velocity impact loading using advanced 3D computed tomography Int. J. Crashworthiness 259–23

Poyyathappan K, Bhaskar G B, Pazhanivel K and Venkatesan N 2014 Tensile and flexural studies on glass-carbon hybrid composites subjected to low frequency cyclic loading Int. J. Eng. Technol 6 85–90

Naresh K, Shankar K, Velmurugan R and Gupta N K 2018 Statistical analysis of the tensile strength of GFRP, CFRP and hybrid composites Thin-Walled Structures 126 150–61

Ilangovan S, Senthil Kumaran S, Vasudevan A and Naresh K Effect of silica nanoparticles on mechanical and thermal properties of neat epoxy and filament wound E-glass/epoxy and basalt/epoxy composite tubes Mater. Res. Express 12 6

Akampumuzo O, Wambua P M, Ahmed A, Li W and Qin X-H 2016 Review of the applications of bio composites in the automotive industry Polym. Compos. 38 2553–69

Zah R, Hischier R, Leão A L and Braun I 2007 Curauá fibres in the automobile industry - a sustainability assessment J. Clean. Prod. 15 1032–40

Safri S et al 2019 Analysis of dynamic mechanical, low-velocity impact and compression after impact behavior of benzoyl treated sugar palm/glass/epoxy composites Compos. Struct. 226 111308

Raj Purohit A, Joannès S, Singery V, Sanial P and Laiarinandrasana L 2020 Hybrid effect in in-plane loading of Carbon/glass fibre based inter- and intraply hybrid composites Journal of Composites Science. 1 6

Arputhabalan J, Palanikumar K, Roche Adaikalaraj S and Sagan Priyan M 2019 Investigation of glass fibre influence on mechanical characteristics and resistance to water absorption of natural fibre reinforced polyester composites Mater. Today Proc. 16 843–52

Tita V, de Carvalho J and Vandeputte D 2008 Failure analysis of low velocity impact on thin composite laminates: experimental and numerical approaches Compos. Struct. 83 413–28

Barouni A K and Dhakal H N 2019 Damage investigation and assessment due to low-velocity impact on flax/glass hybrid composite plates Compos. Struct. 226 111224

Devil U, Bhagawan S S and Thomas S 2009 Dynamic mechanical analysis of pineapple leaf/glass hybrid fibre reinforced polyester composites Polymer Composites, 31 956–65

Le Guen M J, Newman R H, Ferny Hough A, Emms G W and Staiger M P 2016 The damping–modulus relationship in flax–carbon fibre hybrid composites Composites Part B: Engineering 89 27–33

Alsaadi M, Erkilğ A and Abbas M 2020 Effect of clay nanoparticles on the mechanical and vibration characteristics of intraply aramid/carbon fibre reinforced epoxy composite Polym. Compos. 41 2704–12

Ramu P, Jaya Kumar C V and Palanikumar K 2019 Mechanical characteristics and terminological behavior study on natural fibre nano reinforced polymer composite - a review Mater. Today Proc. 16 1287–96

Ye Y, Chen H, Wu J and Chan C M 2011 Evaluation on the thermal and mechanical properties of HNT-toughened epoxy/carbon fibre composites Composites Part B: Engineering 42 2145–50

Jyoti J, Singh B P, Arya A K and Dhakate S R 2016 Dynamic mechanical properties of multiwall carbon nanotube reinforced ABS composites and their correlation with entanglement density, adhesion, reinforcement and C factor RSC Adv. 6 3997–4006