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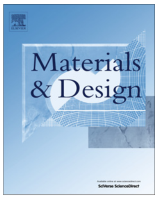

Technical Report

Effect of nanomodified polyester resin on hybrid sandwich laminates

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ABSTRACT

Effect of nanoclay modified polyester resin on flexural, impact, hardness and water absorption properties of untreated woven jute and glass fabric hybrid sandwich laminates have been investigated experimentally. The hybrid sandwich laminates are prepared by hand lay-up manufacturing technique (HL) for investigation. All hybrid sandwich laminates are fabricated with a total of 10 layers, by varying the extreme layers and wt% of nanoclay in polyester resin so as to obtain four different combinations of hybrid sandwich laminates. For comparison of the composite with hybrid composite, jute fiber reinforced composite laminate also fabricated. X-ray diffraction (XRD) results obtained from samples with nanoclay indicated that intergallery spacing of the layered clay increases with matrix. Scanning electron microscopy (SEM) gave a morphological picture of the cross-sections and energy dispersive X-ray spectroscopy (EDS) allowed investigating the elemental composition of matrix in composites. The testing results indicated that the flexural properties are greatly increased at 4% of nanoclay loading while impact, hardness and water absorption properties are increased at 6% of nanoclay loading. A plausible explanation for high increase of properties has also been discussed.

1. Introduction

In recent years, there has been a renewed interest in hybridization of natural fibers with synthetic fibers as reinforcement in composite materials. In hybrid composites, two different fibers are combined in a single matrix in order to compensate the drawback of one fiber by the other. These hybrid composite materials provide high specific stiffness, strength and lightweight which makes them attractive materials for secondary load bearing applications [1–3]. The properties of composites are significantly related to the properties of composite constituents, i.e., fiber, matrix and the interphase between them [4].

The utilization of nanoclay as fillers in polymer composites has attracted considerable attention due to the improved mechanical, thermal, flame retardant and gas barrier properties of the resulting composites. Because of the extremely high surface to volume ratios and the nanometer size dispersion of nanoclays in polymers, they exhibit improved properties as compared to the pure polymers.

Clays used in preparing polymer–clay nanocomposites is a montmorillonite (MMT) layered aluminoclay in the family of smectite clays. Each layer consists of two sheets of silica tetrahedral with an edge shared octahedral sheet of either aluminoclays or magnesium clays [5]. These layers are hold together with a layer of charge-compensating cations such as Li^+, Na^+, K^+, and Ca^+. Generally the surface of the clay needs to be modified to improve the wettability and dispersibility of hydrophilic clay. The charge compensating cations can be easily exchanged with surfactants including alkyl ammonium cations.

Since natural fibers offer significant cost advantages and benefits associated with processing as compared to synthetic fibers such as glass, nylon and carbon, during the last few years, a series of works have been done to replace the conventional synthetic fiber with natural fiber composites [6–8]. However, mechanical properties of natural fiber composites are much lower than those of synthetic fiber composites. Hence, use of natural fiber alone in polymer matrix is inadequate in satisfactorily tackling all the technical needs of a fiber reinforced composite. In an effort to develop a superior but economical composite, a natural fiber can be combined with a synthetic fiber in the same matrix material so as to take the best advantage of the properties of both the fibers [9–12]. Incorporation of nanoparticles (clays, carbon nanotubes, etc.) in the matrix system for fiber reinforced composites has been recently studied by several groups [13–15]. Kornmann et al. [16] developed glass fiber reinforced laminates with a matrix of layered clay/epoxy system and their results revealed that flexural strength of the composites is increased due to the presence of the nanoparticles in the matrix. Fraga et al. [17] studied the immersion of isophthalic polyester/glass composites in water at 80 °C. They

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observed that a degradation of the fiber/matrix interphase due to oligomer extraction and hydrolysis of silane coupling agent of the fibers. Huang and Netravali reported that the flax fibers/soy-protein nanoclay green composites produces better tensile and flexural properties compared to conventional composites [18].

Miyagawa et al. [19] studied the effect of biobased clay/epoxy nanocomposites as a matrix for carbon fiber composites. They reported that the addition of nanoclay has no effect on the flexural strength and modulus. Sundaram et al. [20] studied the mechanical properties of FRP with nanocomposites in the combination of polyester resin, E-glass fiber and nano-montmorillonite (nanoclay). It results in increase of tensile strength, percent of elongation and yield strength, moderate increase in Poisson ratio and reduced area. Chandradass et al. [21] have studied the hybridization effect of nanoclay dispersion in vinyl ester–fiber composites and they have observed that mechanical, thermal and vibration properties were improved in nanoclay dispersed composites over vinyl ester–glass fiber composites. Jeena Jose Karippal et al. [22] have studied the mechanical properties of epoxy/glass/nanoclay hybrid composites. They concluded that the mechanical properties such as ultimate tensile strength, Youngs modulus, flexural strength, flexural modulus, and interlaminar shear strength of the hybrid composites increased with increase in nanoclay loading up to 5 wt%. Levent Aktas and Cengiz Altan [23] have presented a novel method to prepare prepregs from aqueous dispersion of nanoclay, and used this method to investigate the utility of natural nanoclay with E-glass/waterborne epoxy composites. They concluded that 13.5% decrease in interlaminar shear strength and the flexural stiffness was observed to increase by more than 26% over the range of nanoclay loading. Faguaga et al. [24] studied the effect of water absorption on the dynamic mechanical properties of composites used for windmill blades. They found that nanoclay incorporated unsaturated polyester matrix system showing a detrimental effect in degradation resistance, probably because of the degree of hydrophilicity of the selected clay which produces a weak interphase with the polymeric matrix. Meguid and Sun [25] investigated the tensile debonding and shear properties of composite interfaces reinforced by two different homogeneously dispersed nanofillers, carbon nanotubes and alumina nanopowder. The results revealed that varying the weight percentage of the nanofillers into the epoxy matrix adhesive favorably influences the debonding and shear characteristics of the interface. Arun et al. [26] investigated the Morphology of nanoclay dispersed in resin and suspended in acetone thro scanning electron microscopy (SEM) and transmission electron microscopy (TEM). Further, they used vacuum assisted wet lay-up (VAWL) process for the inclusion of nanoclay in conventional fiber reinforced composites and this specimen has shown improvement in compressive strength for nanoclay enhanced fiber composites and also they developed an elastic–plastic model to predict the compressive strength of fiber reinforced composites based on the matrix properties and the predicted values are close to the experimental results. Hossain et al. [27] performed Flexure tests on the GRPC, 0.1–0.4 wt% CNF-filled GRPC showed up to 49% and 31% increase in the flexural strength and modulus, respectively, compared to the conventional one with increasing loading of CNFs up to 0.2 wt% and the quasi-static compression properties. SEM evaluation revealed relatively less damage in the tested fracture surfaces of the nanophased composites in terms of matrix failure, fiber breakage, matrix–fiber debonding, and delamination, compared to the conventional one. Further, the effects of carbon nanofibers on tensile and compressive properties of hollow particle filled composites were studied by Momchil Dimchev et al. [28]. Their results revealed that that addition of 0.25 wt% carbon nanofibers results in improvement in tensile modulus and strength compared to similar syntactic foam compositions (without nanofibers).

The mechanical and thermal properties of non-crimp glass fiber reinforced clay/epoxy nanocomposites were investigated by Emrah Bozkurt et al. [29]. They reported that that clay loading has minor effect on the tensile properties and the Flexural properties were improved by clay addition due to the improved interface between glass fibers and epoxy and Incorporation of surface treated clay particles increased the dynamic mechanical properties of nanocomposite laminates. Hassan Mahfuz et al. [30] stated that in a sandwich structure, the core plays an important role in enhancing the flexural rigidity and by controlling the failure mechanisms. They made attempt to investigate performance of the sandwich by strengthening the core by infusing nanoparticles into the parent polymer of the core material (polyurethane foam made from polymeric isocyanate (Part A) and reacting with polyol (Part B)). They observed that the flexural strength of nanophased (core) sandwich composites has been found to be significantly higher than with core materials. Although, the application of glass fabrics is being increased in composite fabrication, there is limited study reporting the properties of glass–jute fiber reinforced sandwich composites. Moreover, up to date there is no study carried out on the characterization of glass–jute fiber reinforced sandwich composites laminates with nanoclay matrix.

In this study, clay/polyester nanocomposite systems were prepared to use as matrix material for fabrication of glass–jute fiber reinforced sandwich composite laminates. The structure of clay and clay containing laminates were investigated by X-ray diffraction (XRD) and scanning electron microscopy (SEM). Flexural, impact, hardness and water absorption behavior of sandwich laminates manufactured with modified clay (OMMT) containing polyester resin were investigated.

2. Materials and methods

2.1. Materials

The plain weave glass fabric 600 g/m^2 supplied by Binani industries limited, Mumbai, India is used as reinforcing materials for preparation of hybrid composites. Isothalic polyester was used as resin. Methyl ethyl ketone peroxide and cobalt naphthanate were used as catalyst and accelerator respectively. Woven jute fabric 22 × 12 (22 yarns of Tex 310 in warp direction and 12 yarns of Tex 280 in weft direction, per inch) having an average weight of 367 g/m^2 and an average thickness of 0.8 mm is directly procured from Kolkata, West Bengal, India. The commercial nanoclay used in this study is provided by Southern Clay Products, Na$^+$ Montmorillonite (unmodified having CEC 92.6 meq/100 g clay).

2.2. Preparation of organic montmorillonite (OMMT)

Na$^+$–MMT was dispersed in distilled water with some concentration and octadecyl trimethyl ammonium chloride was vigorously stirred for a few times at a given temperature. The white precipitates were washed with hot distilled water (above 80 °C) until no bromide ion was detected with a 0–1 mol/l AgNO$_3$ solution. The product obtained was then vacuum-dried at 70 °C to a constant weight and then ground and screened with a 300-mesh sieve to get the modified clay (OMMT).

2.3. Preparation of nanocomposites

Molding box was prepared with the required size and use wax polish and polyvinyl alcohol which acts as a releasing agent. Mixture of OMMT nanoclay and polyester resin (2, 4, and 6 wt% of clay) is applied over the fiber mat of 300 cm square for a setting period of 1 h. After curing the laminate was removed from the mold and cured at room temperature for 48 h. Then samples were carefully cut from the laminates using a diamond saw with sufficient allowance for finishing. Final dimensions are obtained by finishing the samples using medium grade emery paper. Table 1 shows various combinations of polyester resin, glass fiber, jute fiber and nanoclay in wt%. All laminates were made with total 10 plies by varying the number and position of glass plies to obtain all jute laminates and hybrid sandwich laminates. Table 2 shows some of physical properties of resin and fibers which were taken from supplier's data sheet. Fig. 1 shows preparation of nanocomposite laminate by hand lay-up process.

All the laminates are processed at a total fiber volume fraction of 33%. The total fiber volume fraction is calculated using Eq. (1) [31].

$$V_f = \frac{(w_j/\rho_j) + (w_g/\rho_g)}{(w_j + \rho_j) + (w_g/\rho_g) + (w_r/\rho_r)} \tag{1}$$

where W_g, W_j and W_r are the known weights of the glass, jute and resin, respectively, and ρ_g, ρ_j and ρ_r are the densities of the glass, jute and resin respectively.

2.4. Characterization

2.4.1. Three point bending flexural test

Flexural samples are taken for flexural test under three point bending using the universal testing machine (UTM) LR-100K (Lloyd Instrument Ltd., UK). The flexural samples were prepared as per ASTM: D790 standards. Samples of length 130 mm and width 10 mm were cut from the laminates. Then the samples were loaded with a recommended span ratio 16:1, as shown in Fig. 2. The rate of loading applied on the samples was 3.5 mm/min.

The laminate maximum flexural stress in the outer fibers was calculated using the equation $\sigma_m = 3PL/2bt^2$ where P is the load at a given point on the load deflection curve, L is the support span length and b and t are the width and depth of the beam respectively. The flexural modulus was calculated from the slope of the initial portion of the load–deflection curve. The flexural modulus of elasticity is given by $E = L^3m/4bd^3$, Where m is the slope of the tangent to the initial straight-line portion of the load–deflection curve. Five replicate samples were used for each test and the data reported are the average of five tests.

2.4.2. Impact and hardness testing

The impact test samples are prepared according to the required dimension following the ASTM: D6110 standard. The square cross-sectional samples were impacted by a 10 mm hemispherical head. The impact velocity was 0.75 m/s for all jute and hybrid sandwich laminates. During the process of impact testing, the sample must be loaded in the position of simply supported beam in the machine and allows release of pendulum until it breaks. The toughness of the material (impact strength in kJ/m^2) can be measured easily by using the energy needed to break the material. Digital durometer for Shore D hardness testing pocketsize model with integrated probe has been used to measure the hardness of the samples following standards ASTM: D2240.

Table 1
Hybrid combination used for the fabrication process.

Sample code	Wt% of clay	Wt% of fibers		Total volume fraction (%)
		Jute	Glass	Fiber
S1	0	100	0	37
S2	0	60	40	35.6
S3	2	60	40	33.3
S4	4	60	40	33.6
S5	6	60	40	33.2

Table 2
Physical properties of polyester resin, jute fiber and glass fiber.

Physical property	Polyester resin	Jute fiber	Glass fiber
Density (g/cm^3)	1.1	1.4	2.55
Young's modulus (N/mm^2)	2.1–3.45	20	72.4
Tensile strength (MPa)	34.5–103.5	400–800	3.45
Elongation at break (%)	1–5	1.8	4.8
Diameter (μm)	–	160–185	10

2.4.3. Water absorption testing

Since jute is a permeable fiber, it has the tendency to absorb moisture when exposed to water. It results in poor mechanical properties. Water absorption testing was carried out with jute and hybrid sandwich laminates as per ASTM: D570 to study the effect of nanoclay loading on the water absorption behavior of laminates. Samples with 76.2 × 25 mm dimension were cut from the jute and hybrid sandwich laminated sheet. In order to avoid direct contact with water, neat resin coating was applied to all the edges of the samples S1 and S2. Nanopolyester resin coating was given to all the edges of the samples S3, S4 and S5. The samples were then dried in an oven at 75 °C for 24 h. These samples were weighed immediately in a single precision electronic balance with an accuracy of 0.0001 g. Three samples from each group were then immersed in water at room temperature. The immersed samples were taken out after 24 h. The water adhering on the surface of the samples was wiped off using a soft dry cloth. Again the samples were weighed using the same electronic balance and these samples were immersed again in water. The same procedure was carried out till the saturation period was reached. The weight gained by the samples was monitored with utmost care and proper attention was given to change water periodically. The water absorption percentage is calculated using the equation $M\ (\%) = (W_1 - W_2)/W_1$, where W_1 and W_2 are weights of dry and wet samples respectively.

2.4.4. Microstructural characterization

Samples with and without nanoclay particles obtained from laminates manufactured with different concentrations (0, 2 and 4 wt%) were analyzed by X-ray diffraction (XRD) technique using Rigaku smart lab-9 kW, with Cu Kα radiation. The samples were scanned in the interval of $2\theta = 2$–10 at 40 kV and 30 mA. Using XRD, intercalation behavior of clay particles loaded to matrix with different concentration was analyzed.

Scanning electron microscopy is utilized to analyze the dispersion of clay and fractured surfaces of the nanocomposites. The samples were given gold vapor deposition onto the fractured surface of tensile specimens to have a conductive layer over the samples. All samples were examined with CARLZEISS high resolution microscope at different level of magnifications. In addition to the polished surfaces, the fractured surfaces of the mechanically tested samples were also studied under SEM to identify any change in adhesion between matrix and glass fibers because of nanoclay. Elemental composition analyses of the nanoclay were carried out using energy dispersive X-ray spectroscopy (EDS).

3. Results and discussion

3.1. Three point bending flexural testing

Flexural tests of hand-layup samples were performed to evaluate the flexural strength and modulus of jute and nanoclay dispersed polyester hybrid sandwich laminates. Typical load–

Fig. 1. Preparation of nanocomposites by hand lay-up process.

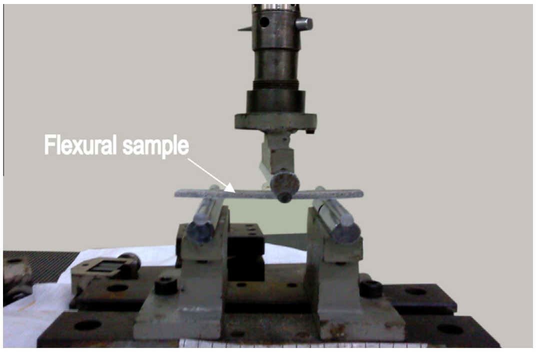


Fig. 2. Flexural test experimental arrangement.

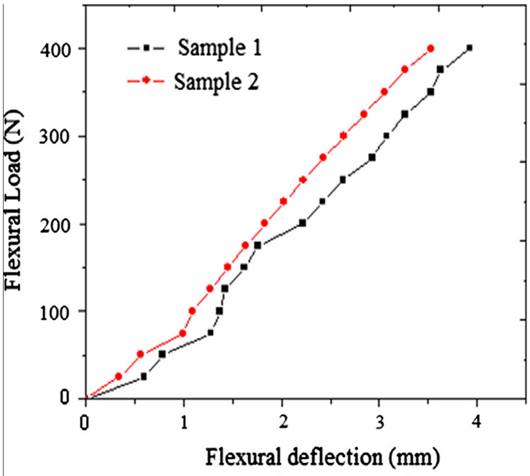
deflection behaviors for various samples from the flexural tests are shown in Fig. 3a and b. All the curves indicate nonlinear behavior. The failure initiation due to development of crack on the lower skin is the indication of point of deviation from linearity.

Flexural modulus and strength for laminates for different samples are compared in Figs. 4 and 5 respectively. Flexural strength and flexural modulus are improved up to 4 wt% of nanoclay loading. However, no further increase is noticed with the increase in nanoclay loading to 6% (S5). This reveals that loading of nanoclay at the polyester resin leads to considerable improvement in the flexural properties of jute/glass fiber hybrid sandwich laminates.

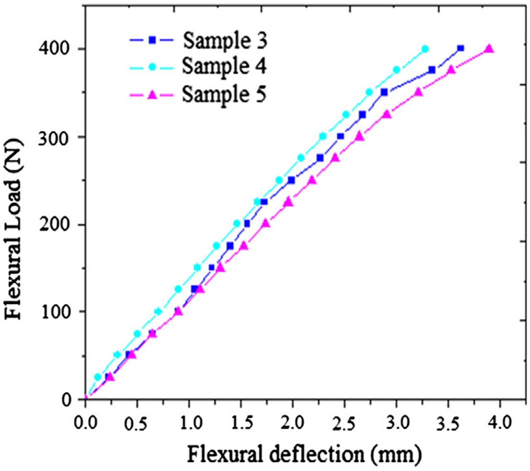
The hybrid sandwich laminate S4 is found to have the highest flexural strength of 162.89 MPa and modulus of 13.63 GPa, which is 90% and 67% higher than the strength and modulus of the jute laminate respectively. By loading nanoclay as in the cases of S5, no improvement in the flexural properties is achieved. The sample S5 exhibits the lowest flexural strength and modulus of 113.67 MPa and 10.35 GPa respectively, among all hybrid sandwich combinations. The flexural strength of various sandwich laminates are reported in Refs. [31–34]. The studies reveal that the flexural strength of nanoclay modified polyester hybrid sandwich laminates is superior to other sandwich laminates. Flexural properties of laminates were improved by clay addition due to the improved interface between glass fibers and nanoclay modified polyester and homogeneous dispersion of nanoclay.

3.2. Impact testing

For analyzing the impact capability of the jute and nanopolyester hybrid sandwich laminates the Charpy impact test is carried out. Fig. 6 shows the variation of impact strength of the different samples with respect to various clay combinations. The impact strength for all jute laminates is found to have the lowest impact strength of 25.87 kJ/m^2. The impact strength of the hybrid sandwich laminate is 57.80 kJ/m^2. When nanoclay loading is increased, its impact strength of the S5 hybrid sandwich increases to 140.4 kJ/m^2. It is observed that for 6 wt% of nanoclay loading, the impact strength is increased by 5.5 times of the impact strength of all jute samples. Achieving improvement in impact strength also suggests the possibility of having uniformly dispersed, submicron nanoclay clusters, as mechanical performance is known to be highly dependent on the particle size [36]. The impact strength of the sandwich samples were compared with [31] which shows comparatively



(a) Laminates S1 and S2



(b) Laminates S3, S4 and S5

Fig. 3. (a and b) Flexural load deflection curves.

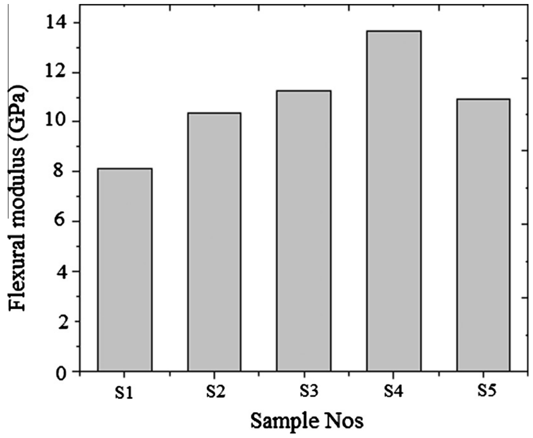


Fig. 4. Flexural modulus of laminates with respect to different samples.

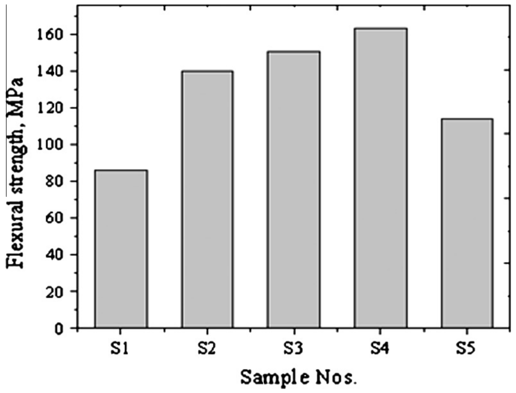


Fig. 5. Flexural strength of laminates with respect to different samples.

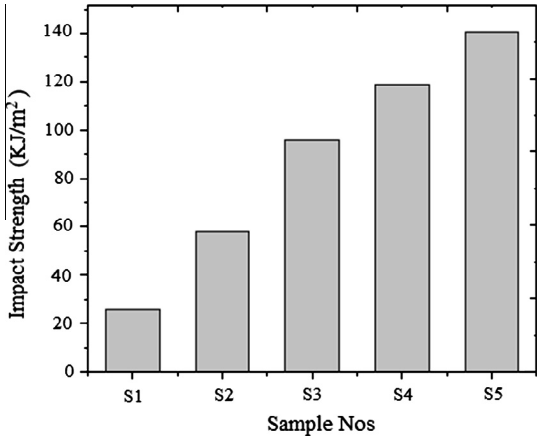


Fig. 6. Impact strength of laminates with respect to different samples.

more values than the present study. However, the nanomodified polyester sandwich samples used in the present study yields greater impact strength values than the other sandwich samples [32–33].

3.3. Hardness testing

The variations of shore D hardness of samples prepared with and without nanoclay particles were shown in Fig. 7. Each datum in the figure is the mean of three measurements. As observed from Fig. 7, the hardness of samples increases with increasing nanoclay content. The measured hardness of sample without nanoclay is 85, while the hardness of sample with nanoclay of 6 wt% is 117. An improvement of 27% in the hardness has been achieved by adding 6 wt% nanoclay to the composite. This behavior may be retained to the uniform distribution of nanoclay which taken high size of the

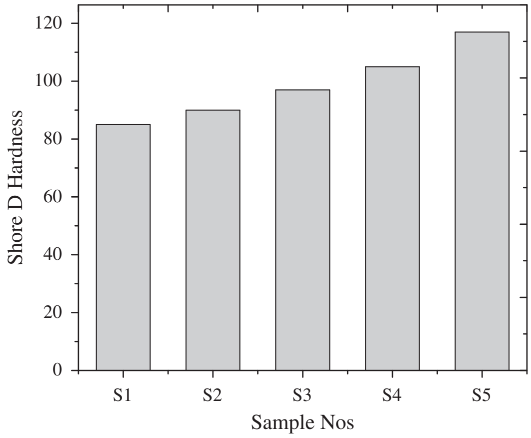


Fig. 7. Shore D hardness of laminates with respect to different samples.

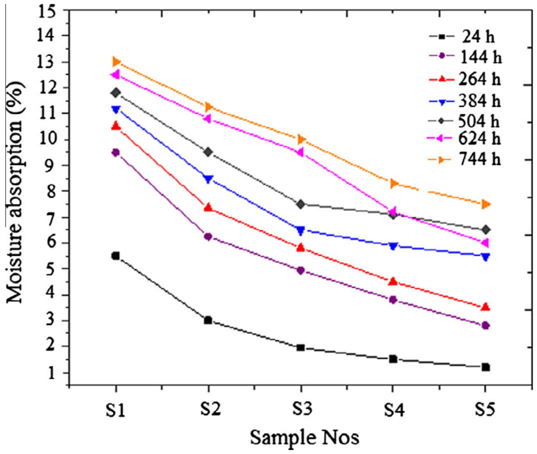


Fig. 8. Percentage of water absorption of laminates with respect to different samples.

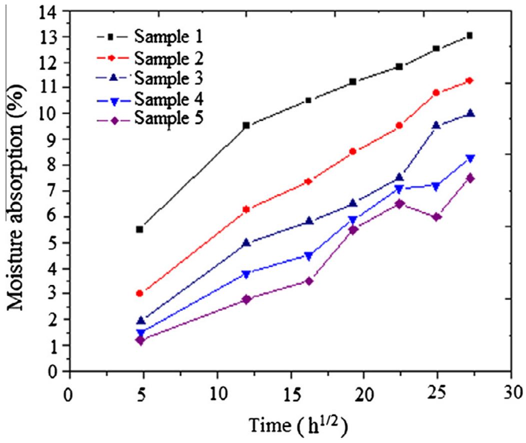


Fig. 9. Percentage of moisture absorption vs square root of time.

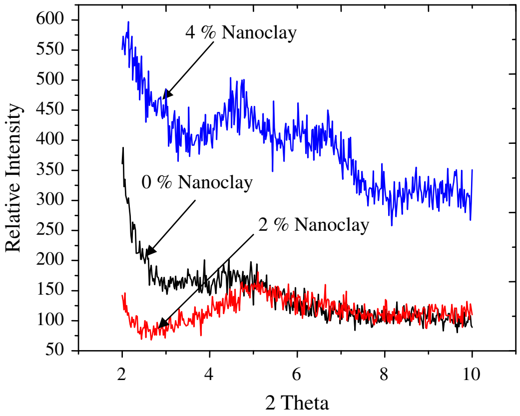


Fig. 10. X-ray diffractograms of laminates with respect to different samples.

composite surfaces so the applied stress is spread through distributed fibers so high hardness is obtained. Further, it is observed that the shore D hardness of current sandwich samples were compared with Ref. [35] in which, the observed hardness values of shore D hardness is more. The reason being the variation is due to the processing conditions, curing nature, environment, etc.

3.4. Water absorption testing

The water absorption behavior of neat polyester all jute laminates and nanopolyester hybrid sandwich laminates was studied. Since jute fabric used in this study is untreated, in the case of neat polyester all jute laminates poor adhesion of jute fiber with neat polyester is attributed to the hydrophilic nature of jute fiber. Nature of this hydrophilic is more responsible for the increasing water uptake percentage in neat polyester all jute laminates. In this connection water absorption reduces considerably for neat polyester hybrid sandwich laminates (glass layers on extreme surfaces). Further adding nanoclay in the neat polyester hybrid sandwich laminates, water absorption again decreases considerably. Fig. 8 shows water absorption percentage as a function of nanoclay loading in hybrid sandwich laminates for various periods of immersion.

It can be seen from the figure that for all periods of immersion, water absorption decreases with the increase clay loading in polyester system. Further, the comparison of the result with Ref. [31] reveals that the water absorption behavior of glass–jute sandwich laminates decreases with the increase in glass fiber content. This is because of impermeable fillers like clay and glass fibers act as barriers and prevent direct contact between jute and water. Fig. 9 depicts moisture absorption percentage as a function of square root of the time in hours for all jute and nanopolyester hybrid sandwich laminates. Each data point presented in the graph is average of the three data points. From the Fig. 8 it is observed that the initial portion of the curve is linear and level of saturation have attained after 744 h of soaking for all samples. The maximum percentage of moisture absorption for S1, S2, S3, S4 and S5 were found to be 13, 11.25, 10, 8.3 and 7.5 respectively of the samples.

3.5. Microstructure analysis

3.5.1. XRD analysis

Since X-ray diffraction is a widely accepted method of measuring the changes in gallery spacing over a nanoclay loading in polymer matrix system, the gallery spacing of the nanoclay in the composite is measured and compared with the gallery spacing of the natural nanoclay which is provided by material supplier, Southern Clay Products Inc. The results of the X-ray diffraction study are shown in Fig. 10. Sample with nanoclay particles have

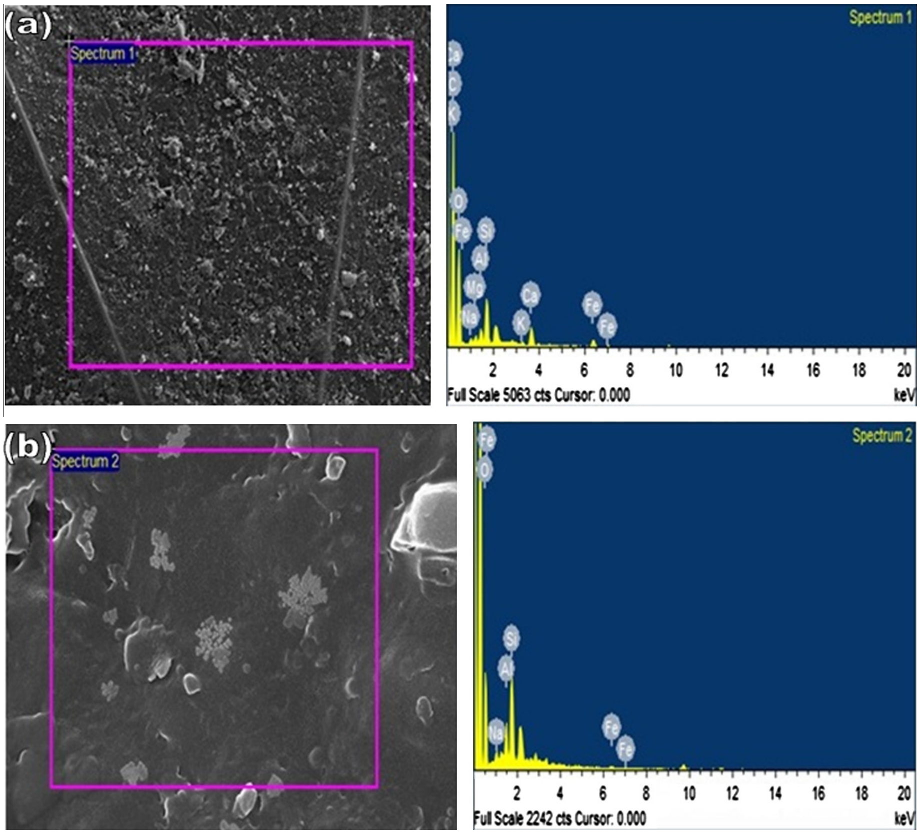


Fig. 11. (a – b) SEM Images and its EDS analysis of (a) Sample without nanoclay and (b) Sample with 4% of nanoclay.

Table 3
Quantitative elemental analysis data of 0% and 4% nanoclay sample.

Sample	Elements	Elements (%)	Atomic (%)
0% Nanoclay	Calcium (Ca)	1.52	0.53
	Sodium (Na)	0.31	0.19
	Aluminum (Al)	0.60	0.31
	Silicon (Si)	2.06	1.02
	Iron (Fe)	1.41	0.35
	Oxygen (O)	36.78	31.85
4% Nanoclay	Oxygen (O)	64.41	76.42
	Sodium (Na)	3.07	2.54
	Aluminum (Al)	8.20	5.77
	Silicon (Si)	20.87	14.10
	Iron (Fe)	3.44	1.17

a *d*-spacing of 18.6 Å, while the d-spacing of natural nanoclay particle is 11.7 Å. This 49% increase in gallery spacing of nanoclay is a clear indication of intercalation. The polyester resin molecules must have penetrated between the clay sheets and result in the expansion in gallery spacing. The characteristic peaks of clays illustrated in Fig. 10 are not visible for the composites. This may be due to further intercalation of the clays during the polymerization of the resin. However, the characteristic peaks from any agglomerated clay layers may not be in the detectable level due to the presence of high fraction of glass fibers and polyester matrix as compared to the fraction of the clay particles in the composites. To reveal the agglomeration tendency of nanoclay particles, backscattered SEM images from the smooth and fracture surfaces of sample with and without nanoclay particle were obtained. Corroborating our findings, the XRD spectrum of the samples with identical glass fiber reinforced in clay modified matrix was measured by Emrah Bozkurt et al. [29].

3.5.2. EDS analysis

Fig. 11a and b illustrates the SEM image of a polished cross section of the 0% and 4% nanoclay sample with EDS distribution of material composition in the same image. The results of EDS investigations highlighted are summarized in Table 3. The element (%) and atomic (%) of the 0% and 4% nanoclay sample are in good agreement with those of their respective components. We can see that 4% nanoclay sample containing more of Silicon and Aluminum due to nanoclay loading in the matrix.

3.5.3. SEM analysis

The scanning electron micrographs of before and after fracture surface of the composite samples are shown in Fig. 12a–d. It is often not possible to see individual nanoclay platelets embedded in a polymer matrix system using scanning electron microscopy. However, the image observed in nanocomposite samples is an indication of the homogeneity of the nanoclay dispersion. Compared with the sample without nanoclay, samples containing 4 wt% nanoclay display a granular surface topology with geometric features at smaller length scales as shown in Fig. 12b. These Microstructural differences similar to the ones observed herein have been reported elsewhere for hand lay-up glass/epoxy composites [23]. Similar to the surfaces of sample before fracture, scanning electron micrographs of the sample after fracture surfaces are notably different. A fiber bundle from the fracture surface of the composite sample without nanoclay is shown in Fig. 12c. Matrix residues that are observed on the fiber surfaces and between fibers show poor signs of good fiber–matrix adhesion. Fig. 12d also shows the fracture surfaces of the composite samples with 4 wt% nanoclay. It is interesting to note that the fiber matrix interface contains more matrix material compared to the sample without nanoclay. Especially the buildup of nanomodified matrix residues around the fibers is notable. Existence of nanomatrix material around the fibers after fracture indicates that effective fiber–matrix adhesion is maintained after the addition of nanoclay.

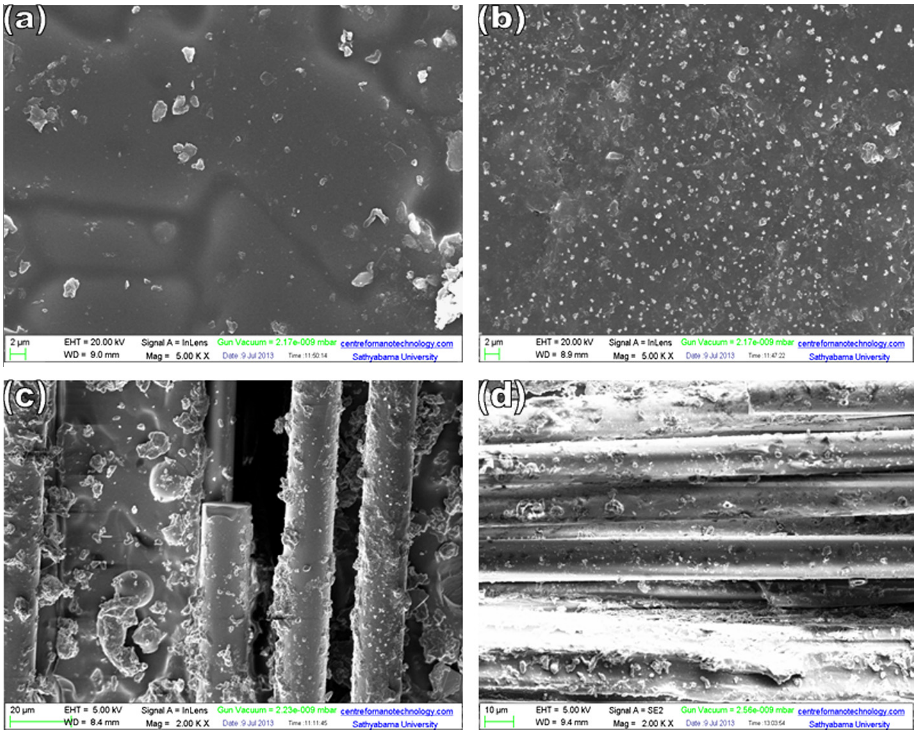


Fig. 12. (a–d) Scanning electron micrographs of composite samples with 0 and 4 wt% nanoclay. (a) Images taken from the polished surfaces of 0% nanoclay sample. (b) Images taken from the polished surfaces of 4% nanoclay sample. (c) Image taken from fracture surface of 0% nanoclay sample. (d) Image taken from fracture surface of 4% nanoclay sample.

4. Conclusions

The effect of nanoclay particle infused polyester resin woven jute – glass hybrid sandwich laminates on flexural, Charpy impact, hardness and water absorption properties have been experimentally studied. Microstructural characterization was carried out through X-ray diffraction, scanning electron microscopy and energy dispersive X-ray spectroscopy analysis. The following are the summary of results of the above investigation:

- Incorporation of nanoclay in glass–jute fiber hybrid sandwich laminates enhances the properties of resulting nanocomposites.
- The nanophased hybrid sandwich laminates has sufficiently high flexural strength and modulus improvement at 4 wt% of nanoclay.
- 4 wt% nanoclay seems to be an optimum loading for glass–jute hybrid sandwich polyester laminates in terms of flexural properties 6 wt% nanoclay seems to be an optimum loading for impact, hardness and water absorption respectively properties of same combination.
- From the impact test results, it is seen that Charpy impact strength increased by significant amount at 6 wt.% of nanoclay.
- The hardness of fabricated nanocomposite was significantly increased with 6% nanoclay loading.
- X-ray diffraction studies of the composite samples revealed a 49% increase in the gallery spacing of the nanoclay, thus indicating effective intercalation of nanoclay platelets by the polyester matrix. .
- Scanning micrographs also revealed improved adhesion of fibers to the matrix material with nanoclay content.
- The studies of above parameters which can predict the influence of nanoparticle in sandwich composite greatly increase mechanical properties.

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