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A Review on Mechanical Properties of Epoxy-Glass Composites Reinforced with Nanoclay

Shanti Kiran Zhade, Syam Kumar Chokka, V. Suresh Babu and K.V. Sai Srinadh

Abstract

Polymer nanocomposites are currently one of the most rapidly growing families of materials, and they are finding use in a wide range of industrial applications, including aerospace and defense. The broad usage of composites is because of their consolidated mechanical properties. Glass fiber reinforced epoxy composites are available for the last few decades. The idea of adding nano clay into it has emerged in the late first decade of this century. This study is aimed at reporting the effects of the addition of nano clay into GFRP on its mechanical properties. The new composite formed is epoxy-glass composites reinforced with nano clay (EGCN). Nano clay has a crystal structure that facilitates the formation of intercalated and exfoliated mixture with liquid epoxy during mixing which results in good dispersion of Nano clay thereby resulting in improved mechanical properties compared to GFRP. The work done by several researchers in this area and the results obtained are reported in this article. The improved mechanisms of failures were discussed with the addition of nano clays.

Keywords: nano clay particles, GFRP composites, mechanical properties, interlaminar shear strength

1. Introduction

In the current era, much effort is invested in developing new composite materials which are superior to existing materials in terms of their mechanical and physical properties. Quite a large number of studies have been published in the area of behavior, characterization, and modeling of composite materials, from metal matrix composites [1–3] to polymer matrix composites [4–7]. There are several definitions for composite materials, but the common feature of each definition is the presence of two or more constituents with an interface between them. Traditional metal matrix-based composites are made of heavy materials. In the aerospace and automobile sector, the fuel consumption is proportional to the weight of the body of the vehicle. A study by A. K. Dhingra [8] has shown that a minimum of 20% of the cost is saved if polymer composites (PMCs) replace the metal structures and the operating and

maintenance costs are also very low. Chakraverty AP [9] stated that Polymer composites are easy to repair, have good durability, and maintenance is simple. There is a consistent requirement for composites in the industries with the invention of new applications. Glass fiber-epoxy composites are widely used in the making of aircraft and automobile body parts and are not only limited to these fields but also used in ship building, structural applications in civil engineering, pipes for the transport of liquids, electrical insulators in reactors, etc. GFRPs have been in use since 1936. As the requirements for weight reduction continuously increase the mechanical properties of GFRPs can be tailored by adding micro fillers and it further evolved by adding nanofillers. The epoxy resin in GFRP firmly holds the fibers together and helps in uniform load distribution throughout the composite.

Nanocomposites are materials that are created by introducing nanoparticles into a matrix. There is a drastic improvement in mechanical properties with the addition of nanomaterials into various matrix materials. In general, the content of nanoparticles that can be added to the composite ranges between 0.5% and 5%. It is because of the high surface area of nanomaterials at a given weight content compared to the micron-sized powder of the same material. Plenty of research is in progress to develop nanocomposites with multiple functionalities. The term “polymer nanocomposite” broadly describes any number of multicomponent systems where the primary component is the polymer matrix and the filler material has at least one dimension below 100 nm [10]. Polymer nanocomposites are generally lightweight, require low filler loading, are often easy to process, and provide property enhancements extending orders of magnitude beyond those realized with traditional composites.

Filler is a term that encompasses a vast number of materials and plays a significant role in improving composite properties. Fillers help minimize cost, enhance properties, and improve the composites. Fillers also increase the mechanical properties and reduce shrinkage of the composites during curing. Proper selection of matrix and filler combination will lead to the creation of composites with high mechanical and thermo-mechanical properties which are comparable to metals.

Montmorillonite is natural clay with a high charge density. Charge density is the total number of cations in between the silicate layers of montmorillonite which can be substituted with organic cations. Montmorillonite nanoparticles are naturally hydrophilic but if treated with alkylammonium ions, the particles become organophilic. The organically treated montmorillonite when dispersed in liquids like epoxy forms gels [11, 12]. The length of the ammonium ions has a strong impact on the resulting structure of nanocomposites. Lan et al. [13] showed that alkylammonium ions with chain lengths larger than eight carbon atoms favor the synthesis of exfoliated nanocomposites, whereas alkylammonium ions with shorter chains led to the formation of intercalated nanocomposites. Alkylammonium ions based on secondary amines have also been successfully used [14]. A schematic diagram showing the substitution of alkylammonium ions in place of interlayer cations is shown in **Figure 1**. The structure of the organic cations between silicate layers depends on the charge density of clay [15]. In **Figure 1**, alkylammonium ions adopt a paraffin type of structure due to which the spacing between the clay layers increased by about 10 Å. Alkylammonium ions permit lowering the surface energy of clay so that organic species with different polarities can get intercalated between the clay layers.

Based on the above discussion, it is observed that out of the three types of surface modifiers alkyl ammonium ions are the most popular because they have a higher affinity with silicate layers compared to amino acids and silanes. Depending on the layer charge density of the clay, alkyl ammonium ions may adopt different structures

Figure 1.
The cation-exchange process between alkylammonium ions and cations initially intercalated between the clay layers.

between the clay layers. Alkyl ammonium ions reduce the electrostatic interactions between silicate layers thus facilitating the diffusion of a polymer molecule between clay platelets or galleries [16].

2. Mechanical properties

2.1 Tensile properties

EGCN exhibited 54% improvement in modulus at 10 wt% addition of octadecyl ammonium treated fluorohectorite (ME-ODA) but there was a 36% decrease in strength while ductility was also reduced (shown **Figure 2a**). The stress–strain curve of GRE exhibited ductile behavior, and the EGCN exhibited brittle behavior [17]. Bozkurt et al. [18] reported that when MMT is added to epoxy-noncrimp glass fabric composite, up to 6 wt% there was no improvement in strength and stiffness while both decreased beyond 6 wt%. This unchanging behavior is attributed to the dominant effect of noncrimp glass fibers over the nanoclay effect (shown **Figure 2b**). Shi et al. [19] reported the effect of “Magnetic stirring” and the high shear mixing technique (HSMT) on the tensile behavior of EGCN. When the magnetic stirring method was used, the increment in modulus of EGCN was about 19.4%, 22.2%, and 27.7% at 1, 2, and 3 wt% of nanoclay respectively. The increased modulus is credited to the good dispersion of clay layers. At 1 wt% nanoclay, the tensile properties were compared between composites; one composite consists of an epoxy-clay mixture processed by magnetic stirring, and the other by mechanical stirring. There was about a 7.9% and 5.7% increase in σ_{UTS} and modulus for the EGCN with matrix processed by mechanical stirring (shown **Figure 2c**). The epoxy molecular chains were prevented from moving when the load was applied. The clay layers hindered the molecular chains because of strong adhesion and chemical bond between organoions and epoxy, thereby enhancing the stiffness of the laminate. This mechanism of clay particles hindering epoxy molecular movement was also described by other researchers [20–22]. The formation of clay aggregates at low clay contents, i.e., at 2 and 3 wt% clay addition was also reported in some literature [23–25]. The increased tensile properties with the addition of various surface-modified nanoclays under different mixing conditions and composite making methods are given in **Table 1**.

Voids are formed while mixing nanoclay and hardener, and increase with clay content; due to an increase in the viscosity of the mixture, the removal of these gas bubbles becomes difficult when kept in degassing chamber. In addition to aggregates and voids, there is a possibility of a decrease in strength by other means, that is,

Figure 2.
Changes in tensile properties of EGCN'S at various conditions.

through interruption of crosslinking of chains by silicate layers as a result of the reaction of epoxy molecules with organoions, which breaks the continuity of the crosslinks, this claim is not yet fully established though [35, 36]. The laminate fabricated from the matrix which was prepared by HSMT provided the enhancement in strength and modulus by 7.9% and 5.7% as compared to the laminates made by using the matrix prepared by direct mixing technique (DMT) [19].

Gurusideswar and Velmurugan [29] carried out tension tests on laminates with the addition of Garamite-1958 (alkyl ammonium treated clay) at crosshead speeds of 0.5, 5, 50, and 500 mm/min. The stress-strain plot for EGCN at 1.5 wt% of nanoclay and a testing speed of 5 mm/min was linear elastic with 9.9% elongation and failed suddenly. At 500 mm/min there was a rise in strength, modulus, and ductility by about 17%, 10.7%, and 33.3% compared to the values at quasi-static loading, i.e., at 5 mm/min (shown **Figure 2d**). σ_{UTS} is more sensitive to strain rate compared to the modulus which is due to the dominant behavior of fibers in strength, whereas the modulus is influenced by clay. The same behavior was exhibited by glass/epoxy composite (GRE). The increase in clay content by up to 5 wt% did not change the elongation (i.e., 9.9%) at quasi-static loading, but at high strain rates.

Author, Year	Nanoclay	Nanoclay wt%	Glass Fiber	Observations
Haque et al. [26]	Nanomer I.28E	0, 1, 2, 5, 10 wt%	—	At 1 wt% nanosilicates, there was 44, 24, and 23% improvement in ILSS, σ_f , and fracture toughness compared to GRE.
Bozkurt et al. [18]	MMT	0, 1, 3, 6, and 10%wt	40 – 44 vol %	i. Up to 6 wt% nanoclay addition, σ_{UTS} and modulus were not changed. ii. At 6 wt% of nanoclay, σ_f and modulus were improved by 16% and 13%. iii. At 10 wt% of nanoclay, fracture toughness was improved by 5%
Shi et al. [19]	Cloisite 30B	0, 1, 2 and 3 wt%	55 – 58 vol%	At 1 wt% i. The tensile, flexural, and compressive modulus increased by 21%, 27%, 15% respectively. ii. The tensile, flexural, and compressive strength were increased by 18%, 25%, and 30% respectively. iii. ILSS was increased by 25% and Impact strength was increased by 6%.
Zulfli and Chow [27]	Nanomer 1.28E	0, 2, 4, 6, 8 wt%	4 layers	i. At 4 wt% of clay, σ_f and modulus were improved by 19% and 9%. ii. At 2 wt% of nanoclay, fracture toughness was improved by 111%. iii. At 4 wt% of nanoclay, impact strength was improved by 46%
Kanny and Mohan [28]	Cloisite 30B	0, 1, 2, 3, 4, 5 wt%	6 layers	i. At 3 wt.% of nanoclay, there was about a 9%, 21%, and 15% increase in tensile strength, modulus, and elongation.
Gurusideswar and Velmurugan [29]	Garamite_ 1958	1.5, 3, and 5 wt%	—	i. At 1.5% clay, the modulus and strength increased by 5%, 3% compared to neat epoxy. ii. The modulus and strength of 1.5 wt% EGCN with 1.5 wt% clay 5 mm/min crosshead speed increased by 8%, 1% compared to GRE.
Kornmann et al. [17]	ME-100	10 wt%	55 vol%	At 10 wt% of nanoclay. i. Flexural modulus increased by 8% ii. σ_f decreased by 27% iii. Flexural strain increased by 19%.
Sharma et al. [30]	Cloisite 30B	1, 3, and 5 wt%	—	i. Up to 3 wt% of clay, σ_{UTS} was increased and decreased beyond that. ii. σ_f was increased up to 5 wt% of nanoclay addition.
Manfredi et al. [12]	i) Cloisite 30B ii) Cloisite 10A	3, 5 wt%	30 vol%	a. At 30 vol% glass fiber, and 5 wt% of Cloisite 10A i. Flexural modulus and strength were increased by 20% and 29%. ii. ILSS was increased by 8% iii. The impact strength was improved by 23% b. The properties were not improved by the Cloisite 30B

Author, Year	Nanoclay	Nanoclay wt%	Glass Fiber	Observations
Gurusideswar and Velmurugan [31]	Garamite_1958	0, 1.5, 3 wt%	—	<p>a. At quasi static strain rate of 0.00167 s^{-1} with corresponding loading speed of 5 mm/min.</p> <p>i. 15% improvement in young's modulus was observed at 3 wt% of nanoclay</p> <p>ii. 9% improvement in σ_{UTS} at 1.5 wt% of nanoclay.</p> <p>b. At the strain rate of 445 s^{-1} and 1.5 wt% of nanoclay the strength was improved by 84%</p> <p>c. At 0 wt% clay and</p> <p>i. At 0.00167 s^{-1} strain rate the strength and modulus were 314.92 MPa, 18.09 GPa</p> <p>ii. At 315 s^{-1} the values were improved by 34%, 58%.</p> <p>iii. At 385 s^{-1} strain rate the values improved by 51%, 92%.</p> <p>iv. At 445 s^{-1} strain rate the values were improved by 67%, 106%.</p>
Krushnamurty et al. [32]	Nanomer I.30E	0, 3 wt%	40, 50, 60, 70	<p>At 3 wt% of addition of nanoclay, the σ_{UTS} was improved by</p> <p>i. 21% at 40% of fiber volume</p> <p>ii. 13% at 50% of fiber volume</p> <p>iii. 7% at 60% of fiber volume</p> <p>iv. -2% at 70% of fiber volume</p> <p>At 3 wt % addition of nanoclay, the σ_f was improved by</p> <p>i. 20% at 40% of fiber volume</p> <p>ii. 14% at 50% of fiber volume</p> <p>iii. 8% at 60% of fiber volume</p> <p>iv. 3% at 70% of fiber volume</p>
Jeyakumar et al. [33]	Cloisite 93	1, 3, 5, 7 wt%	—	<p>i. Maximum improvement in σ_{UTS} is 30% at 5 wt%.</p> <p>ii. Maximum improvement in tensile modulus is 32% at 5 wt%.</p> <p>iii. Maximum improvement in σ_f is 50% at 5 wt%.</p> <p>iv. The maximum improvement in flexural modulus is 116% at 5 wt%.</p> <p>v. The maximum improvement in impact strength is 42% at 3 wt%.</p> <p>vi. The maximum improvement in fracture toughness is 136% at 5 wt%.</p>

Author, Year	Nanoclay	Nanoclay wt%	Glass Fiber	Observations
Achutha et al. [34]	OMMT	0, 2, 4 wt%	40, 50, 60 wt%	<p>The maximum improvement in the property of EGCN with the addition of 4 wt% of OMMT and 60 wt% glass fiber compared to GRE with 60 wt% fiber</p> <p>i. σ_{UTS} improved by 11.5% at room temp</p> <p>ii. σ_f improved by 4.5% at room temp</p> <p>iii. For specimens soaked in cold water for 70 days, there was a 7.5% decrease in tensile strength</p> <p>iv. For specimens soaked in cold water for 70 days, there was a 10% decrease in σ_f</p> <p>v. For specimens soaked in boiling water for 2 hrs, there was a 9% decrease in tensile strength</p> <p>vi. For specimens soaked in boiling water for 2 hrs, there was a 12.5% decrease in σ_f</p>
Prabhakar et al. [11]	a. MMT b. Nanomer I.28E	3 wt%	40 wt%	<p>a. Improvement in tensile, flexural, and impact strength values of EGCN compared to GRE</p> <p>i. With the addition of MMT are -54.4%, -19.2%, -20.7%</p> <p>ii. With the addition of OMMT are -11.5%, -33.8%, -20.7%</p> <p>iii. With the addition of MMT and silane treated glass fiber are -25.36%, -9.2%, -59%</p> <p>iv. With the addition of OMMT and silane treated glass fiber are 6%, -9.9%, -1.8%</p> <p>v. With the addition of MMT and acid treated glass fiber are -30.7%, -28%, 2.2%</p> <p>With the addition of OMMT and acid treated glass fiber are -43%, -58.5%, -59.2%</p> <p>i. Improvement in tensile, flexural, and impact strength values of GRE with addition of silane treated glass fiber -16.6%, 12.5%, 33.75%.</p> <p>ii. Improvement in tensile, flexural, and impact strength values of GRE with the addition of acid treated glass fiber -26.5%, -5.3%, -40.3%</p>

Table 1.
Effect of Nano clay on various properties.

the elongation has reduced (i.e. 9.6% at 500 mm/min). This is attributed to the high brittleness induced at high clay addition. At 1.5 wt% of nanoclay addition, the inversely proportional behavior between elongation and strain rate was not observed, unlike the case of 5 wt% clay added composite. The increase in strength is mainly attributed to the presence of fibers and the increase in modulus is mainly attributed to the silicate platelets which restrict the movement of epoxy molecules [37–41].

The optimum value of clay content is 1.5 wt%, whereas all tensile characteristics were improved at a high strain rate, the slight decrease in properties above 1.5 wt% nanoclay is attributed to agglomeration and a weak interfacial bond between epoxy and clay. An increase in strain rate in the range of 0.0006 s^{-1} – 0.6 s^{-1} increased the strength and elongation of GRE. Okoli and Smith [42] reported that there was a decrease in percentage elongation when GRE specimens were tested at various strain rates. Okoli and Smith [42] added that the decrease in elongation at high strain rates is explained with the help of Eyring theory of viscosity; while formulating this theory, an assumption has been made which states that the molecules of polymer need to cross the potential energy barriers to deform when a load is applied. Based on this assumption a linear model is developed which states that the plot between yield stress and a logarithm of strain rate is linear. This increase in yield stress with the logarithm of strain rate implies decreased plastic deformation of the matrix due to decreased movement of crosslinked epoxy molecules at high strain rates. The constrained movement of molecules is ascribed to the lack of time available for the molecules to relax at high strain rates [43–45]. But according to Gurusideswar and velmurugan [29], this effect was absent at 500 mm/min as there was an increased elongation for GRE at 500 mm/min compared to the elongation at quasi-static loading rate, which implies that 500 mm/min is not high enough to restrict the molecules' relaxation. Hussain F [45] stated that the high modulus of clay is also one of the attributes for an increase in tensile properties and improved deformation mechanisms. Li X et al. [46] Reported that the exfoliated structures have a high surface area of contact between silicate platelets and resin; therefore the transfer of load to clay platelets also will be more compared to the load transferred in intercalated structures. Withers et al. [47] reported an 11.7%, 10.6%, and 10.5% increase in strength, modulus, and elongation with 2 wt% of Cloisite 30B loading into glass-epoxy due to exfoliated morphology (shown **Figure 2e**).

Gurusideswar and Velmurugan [31] reported the behavior of EGCN with the addition of GARMITE-1958 and testing speeds varying between quasi-static rate of 0.00167 s^{-1} to very high strain rates of 315 s^{-1} , 385 s^{-1} , 445 s^{-1} which are far higher compared to the strain rates in the range of 0.0001 – 0.1 s^{-1} . GRE exhibited about 106% and 67% improvement in modulus and strength at 445 s^{-1} compared to quasi-static conditions. EGCN exhibited about a 150% rise in modulus and 84% rise in strength at 1.5 wt% clay addition and 445 s^{-1} strain rate. This substantial rise in modulus and strength of EGCN is attributed to viscoelastic nature, damage accumulation behavior of epoxy which was also reported by Brown et al. [48] for GRE, restriction of polymers chain mobility in the matrix and at the fiber-matrix interface due to good adhesion between clay platelets and epoxy allowed better stress transfer to all the fibers. Similar findings were reported by many authors [49, 50]. Jeyakumar et al. [33] reported the mechanical properties of EGCNs with the addition of Cloisite 93A into epoxy-glass. Nanoclay was mixed into acetone using a mechanical stirrer for 30 min. Epoxy resin of the required weight was added to the acetone-clay mixture heated to 80°C and mixed for 1 hr. During this process, acetone gets evaporated and the epoxy clay mixture remains. The remaining mixture is ultrasonicated for uniform mixing.

The testing results of the prepared samples showed that the σ_{UTS} improved by 6.6%, 16.6%, and 23.58% at 1, 3, and 5 wt% of nanoclay, whereas tensile modulus improved by 8.4%, 14%, and 23.66%. With the further addition of nanoclay, the decreasing trend started (shown in **Figure 2f**).

Achutha et al. [34] attempted to optimize the parameters such as nanoclay wt% and glass fiber content in EGCN. In addition, the samples were also subjected to hydrothermal conditions. A set of samples were soaked in cold water for 70 days and dried and another set of samples was boiled in hot water for 2 hrs and dried. It was reported from these studies that hydrothermal aging conditions showed 42.69% contribution to tensile properties whereas nanoclay content showed 24.57% contribution and fiber content showed 30.23% contribution. Achutha et al. [34] reported that nanoclay does not act as a load-bearing instrument but it warrants load transfer to fibers as the interface between matrix and fiber becomes strong, which also hinders crack propagation. The samples treated with cold water exhibited lower σ_{UTS} and those treated with hot water exhibited the lowest strength due to the moisture absorbed at the interface which weakens the interface strength. Moisture absorption increases with temperature.

Prabhakar et al. [11] studied the effect of Nanomer I.28E on the mechanical properties of EGCN. In addition, the glass fiber was treated with silane and acid to check for the effects of both treatments. The results indicated that a combination of silane-treated glass fibers and Nanomer I.28E in the composite exhibited the highest σ_{UTS} which was 130% compared to EGCN with untreated glass fiber and unmodified MMT particles. Prabhakar et al. [11] showed that any increase in an interfacial bond due to the addition of nanoclay led to increases in both σ_{UTS} and hardness of the composite. The treatment of fibers and organic modifiers on MMT formed a strong interface.

2.2 Flexural properties

Haque et al. [26] reported 24% and 17% enhancement in flexural strength (σ_f) and modulus at 1 wt% addition of Nanomer 1.28E in EGCN (shown **Figure 3a**). Kornmann et al. [17] reported 6% and 27% improvement in flexural modulus and σ_f of EGCN at 10 wt% addition of ME-ODA (shown **Figure 3b**). The increase in σ_f is linked to the existence of nano-silicate layers at the interface of the fiber, which might have improved interfacial properties. Another possible illustration is the fact that the compressive strength of epoxy is enhanced by the presence of the silicate layers so that it in turn enhances the bending strength of the laminate. Bozkurt et al. [18] reported 16% and 13% improvement in σ_f and modulus at 6 wt% addition of OMMT (shown **Figure 3c**). It was observed from the fracture surface that fracture occurred along with the fiber-matrix interface and the fracture surface seems to have roughness indicating a strong interface. The laminate without clay showed a smooth fracture surface, which means the interface was weak. The increased flexural properties with the addition of various surface-modified nanoclays under different mixing conditions and making methods are given in **Table 1**.

Manfredi et al. [12] stated that the addition of Cloisite 10A in EGCN laminates caused the flexural modulus and strength to rise by 20% and 29%. The addition of Cloisite 30B did not cause any increment in the modulus of epoxy. It could be because of the collapse of clay particles, i.e. the particles were aggregated and the layers were not separated in the matrix. The modulus of clay nanoparticles is about 170 GPa (shown in **Figure 3d**). Therefore, when a strong bond is formed between matrix and clay it will result in an increased modulus of the laminate [51]. The increase in

bending strength is attributed to the presence of silicate layers upon the glass fiber surface which improves the adhesion between the interface of matrix and glass fibers. The other possible reason for the improvement in the bending strength of laminate could be the increase in compressive strength of the epoxy. Shi and Kanny [19] reported that EGCN showed about 23% and 14% enhancement in modulus and strength at 3 wt% of Cloisite 30B. This enhancement is ascribed to the presence of intercalated silicate platelets of clay which interrupted the molecular motion of epoxy [52, 53]. The composites consisting of matrix processed by HSMT have shown 9.7% and 8.5% improvement in strength and modulus at 1 wt% (shown **Figure 3e**).

Sharma et al. [30] observed improvement in σ_f up to 5 wt% addition of nanoclay (shown **Figure 3f**). This increment is attributed to the presence of layered silicates on the glass fiber surface enhancing the adhesive bond between the epoxy matrix and glass fibers. In the range of 6 – 8 wt% of OMMT σ_f is reduced which was attributed to the agglomeration of OMMT in the EGCN. The uniform distribution and dispersion of silicate layers in epoxy resin are limited by the weight content of OMMT, when this content exceeds its percolation threshold (the ability of the liquid resin to pass through clay particles so that all the particles get wetted) there is a tendency to form particle aggregates [27]. The increased viscosity hinders the dispersion and favors the formation of agglomerates [54]. The fracture surface of GRE has shown that the fibers pulled out from the matrix had a smooth surface texture, whereas EGCN showed less fiber pullout with rough surfaces of fiber and matrix indicating the strong bond between fiber and epoxy and improved stress transfer between fiber and matrix. At 8 wt% clay addition, there were agglomerates formed fully in the EGCN [55].

At 40% and 60% volume of glass fiber reinforcement into epoxy-clay matrix, there was about 20% and 8% improvement in σ_f at 3 wt% of Nanomer I.30E (shown **Figure 3g**) [32]. This increment is attributed to the ability of the matrix to transfer the load to all the fibers. When nanoclay is not present in the matrix, it cannot transfer the load to all fibers, and thus crack propagates along with the matrix, and there will be low resistance to crack propagation. At low fiber volumes, i.e., at 40%, GRE exhibited interlaminar fracture as the crack propagated through the matrix between fiber layers and confined itself to layers near the top of the composite where the loading point is located so that the load was not transferred to all the layers, whereas EGCN exhibited translaminar fracture as the fiber layers break vertically at the loading point which requires more energy because the load is transferred to all the fiber layers [56].

With the increase in V_f of fiber to 60%, there was a reduction in the effect of nanoclay and both GRE and EGCN have failed predominantly in translaminar fracture mode which should occur only for EGCNs. This is because, at higher V_f of fibers, the fabric layers are well compacted to fit in the same volume of the composite, thereby the crimp zones present in the fabric will get interlocked with adjacent fabric layers, thus strengthening the interlaminar regions. Hence the crack propagation is resisted along interlaminar regions by the interlocked crimp zones and fracture occurs by rupture of glass fibers along the translaminar direction. These interlocks could resist interface shearing; thus, at higher V_f , crack propagation proceeds with the rupture of fiber fabric layers [32]. Srikanth I et al. [23] stated that At further higher fiber volumes, i.e., at >60%, fiber wetting became difficult, so there is a chance of failure by both mechanisms, i.e., interlaminar and translaminar crack propagation, thereby decreasing strength.

Jeyakumar et al. [33] stated that with the addition of Cloisite 93A into EGCN there was a significant improvement in flexural properties. With the addition of 1, 3, 5 wt% of Cloisite 93A, there was about 10.4%, 41.2%, and 52.3% increase in σ_f and also

Figure 3.
Changes in flexural properties of EGCN'S at various conditions.

18.75%, 62.5%, and 118.75% improvement in flexural modulus. Beyond the 5 wt% addition of nanoclay, there was a decreasing trend (shown in **Figure 3h**). Najafi et al. [20] conducted experiments on EGCNs by adding pristine MMT and subjected some samples to hygrothermal conditions which consists of immersing the specimens in distilled water at 80°C for 10 weeks. The flexural curves for both neat GRE and EGCN exhibited linear behavior, EGCN subjected to hygrothermal conditions exhibited a gradual decrease in slope. At 3 and 5 wt% addition of MMT, there was about 8% and

12% improvement in flexural modulus, and 10.7% and 6.3% improvement in σ_f was observed. At 3 wt% of MMT addition, the properties were optimum. The samples treated by hygrothermal conditioning exhibited very poor flexural properties due to decreased interface bond strength caused by water absorption. Prabhakar et al. [11] stated that the addition of silane treated glass fiber in epoxy has resulted in improved flexural properties due to enhanced interface bonding between fiber and matrix compared to the composite reinforced with untreated fiber. The addition of Pristine MMT and Nanomer I.28E has not shown any considerable improvement but rather reduced the σ_f . There was about a 29% increase in σ_f of epoxy-silane treated fiber composite compared to epoxy-untreated fiber composite.

2.3 Fracture toughness

At 1 and 2 wt% addition of Nanomer I.28E, there was about 28% and 32% improvement in fracture toughness of clay-epoxy nanocomposite compared to NE, whereas EGCN exhibited about 20 and 23% improvement in fracture toughness for the same clay contents compared to GRE. Above 5 wt%, there was a decreasing tendency (shown **Figure 4a**) [26]. In the single edge notch bending test conducted by Bozkurt et al. [18], at 10 wt% addition of OMMT, the K_{IC} of EGCN improved by 5% but MMT did not show significant improvement (shown **Figure 4b**). The load applied is in the in-plane of the specimen. Therefore the fracture mechanism consisted of fiber-matrix debonding, fiber pullout, and fracture. The increased fracture toughness of the composites with the addition of various surface modified nanoclays under different mixing conditions and various making methods are given in **Table 1**.

Zulfli and Chow [27] stated that with the addition of nanoclay, K_{IC} improved. This improvement was ascribed to the strengthening of the interface between fiber and matrix by the presence of OMMT at the interface and increased resistance to crack propagation because of OMMT [55]. Swaminathan and Shivakumar [21] stated

Figure 4. Changes in fracture toughness of EGCN'S under various conditions.

that the major mechanism for increased toughness in composites was because of the deflection of the crack around clay tactoids. OMMT resists the crack from propagating because of which bowing and pinning of the crack take place [21]. The toughening effect of OMMT is limited by agglomeration. Tsai and Wu [22] reported a continuous decrease in Mode-I fracture toughness with the addition of nanoclay due to the brittleness induced in the composite which caused the crack to propagate at a faster rate, whereas pristine GRE composite exhibited ductile nature compared to EGCN with high clay content, so the crack propagation was slow and needed more energy for failure.

Jeyakumar et al. [33] reported that with the addition of Cloisite 93A into glass-epoxy, there was a conspicuous increase in fracture toughness of EGCN. For neat epoxy it was $0.9 \text{ MPa}\cdot\text{m}^{1/2}$, for glass-epoxy it was $1.1 \text{ MPa}\cdot\text{m}^{1/2}$. At 1, 3, and 5 wt% addition of nanoclay, the increase in fracture toughness of EGCN was about 36%, 63%, and 86% respectively compared to GRE. Beyond 5 wt% addition, there was a decreasing tendency (shown in **Figure 4c**). Therefore, it was concluded that the saturation limit is 5 wt% of nanoclay for the experimental conditions adopted by Jeyakumar et al. [33]. Senthil Kumar et al. [24] reported that with the addition of Cloisite 25A in EGCN, there was a considerable improvement in Mode-I fracture toughness of EGCN. At 2, 4, 6, and 8 wt% addition of nanoclay, there was about 118.85%, 9%, 56.55%, and 38.5% improvement in fracture toughness. Beyond 8 wt% addition, there was a decreasing trend (shown in **Figure 4d**). The increase in fracture toughness is attributed to the fiber bridging effect. At 10 wt% addition of nanoclay there was a decrease in the property, which is ascribed to the poor distribution of matrix between the fiber laminae.

2.4 Interlaminar shear strength (ILSS)

ILSS is a matrix dependent property, which means the strengthening of the matrix improves ILSS because the interface between the epoxy-clay matrix and the glass fiber becomes strong [57]. Therefore if the ILSS of the matrix is enhanced, then the ILSS of the composite also will get enhanced. The increase in ILSS of the composite is owing to the enhanced interfacial area between matrix and clay, the enhanced bond between resin and fiber, and the improved morphology of the matrix. The failure in ILSS mode is acknowledged as a critical mode of failure in FRP laminates. Thus there is a necessity to study the ILSS characteristics of the nanocomposites. It is proved that the shear strength of FRPs is remarkably enhanced with the incorporation of nanoclays [36]. EGCN with 1 and 2 wt% added Nanomer I.28E had shown 44% and 20% improvement in ILSS compared to GRE. The rough interface between the epoxy-fiber in fracture surface indicates a strong bond, whereas GRE and NE have shown a smooth interface which implies a weaker interface bond (shown **Figure 5a**) [26]. The increased ILSS of the composites with the addition of various surface modified nanoclays under different mixing conditions and making methods are given in **Table 1**. Bozkurt et al. [18] reported a decrease in ILSS of EGCN with the addition of MMT and OMMT. The ILSS of GRE is noted to be 32.7 MPa. But when the clay is added, it is observed that the laminate with the addition of clay reports a small decrease than when MMT is added; the decrease is high when OMMT is added. This decreasing trend is attributed to the creation of air voids in the interlaminar region while making the composite. The susceptibility to form voids in the interlaminar region is observed to be more when OMMT was added and further study is required to establish this phenomenon.

Figure 5.
Changes in ILSS of EGCN'S at various conditions.

The ILSS characteristics of GRE and EGCN with the addition of Cloisite 10A and Cloisite 30B were evaluated by Manfredi et al. [12]. There was a small increase of 7.5% in ILSS of EGCN with the addition of Cloisite 10A, but Cloisite 30B had no influence (shown **Figure 5b**). The trend of improvement with the addition of Cloisite 10A and decrease with the addition of Cloisite 30B was reported in the flexural properties section also. Laminates with Cloisite 10A have shown high flexural modulus and high σ_f . The morphologies of the composites indicated that the addition of Cloisite 30B had not provided strong adherence between matrix and fiber, but Cloisite 10A provided strong bonding between matrix and fiber. There is also a high attraction between Cloisite 10A and glass fiber surfaces since both are ceramic materials. The matrix without clay has shown a smooth and brittle surface at failure, whereas the matrix with nanoclay addition has shown a rough surface at failure which is also in line with the impact characteristics [12]. EGCN showed an 18.5% improvement in ILSS with the addition of 1 wt% of nanoclay by the magnetic stirring method. Above 1 wt%, there was a decreasing trend which is attributed to the aggregates of silicate tactoids and voids, whereas EGCN consists of a matrix processed by HSMT exhibited a 24% increase in ILSS, which might be attributed to the high shear force, which resulted in good dispersion of nanoclay platelets (shown **Figure 5c**) [19].

Jeyakumar et al. [33] reported that with the addition of Cloisite 93A, the ILSS of EGCN improved notably. At 1, 3, and 5 wt% addition of nanoclay in EGCN, there was about an 8%, 16%, and 38% increase in ILSS (shown **Figure 5d**). The presence of nanoclay brought about strong adhesion amongst nanoclay and epoxy matrix and in this manner enhanced the shear properties of the composites. Beyond 5 wt% the

ILSS started decreasing which might be due to the non-uniform scattering of nanoclay. Anni et al. [57] stated that with the addition of organically modified nanoclay into woven flax fiber reinforced epoxy, there was a rise in ILSS. Before reinforcing the fibers, some flax fibers were washed in distilled water, some treated with alkali solution, some with saline solution, and some others treated with nanoclay dispersed solution, to graft the nanoclay particles onto the flax fibers. The improvement in ILSS with the addition of these four kinds of treated fibers in ILSS was observed to be 8%, 10%, 17.9% compared to the composite reinforced only with water treated fibers.

Senthil Kumar et al. [24] reported that with the addition of Cloisite 25A into EGCN there was a significant increment in the ILSS property of EGCN. There was an increasing trend in the property up to 2 wt% addition of nanoclay, after that, it started decreasing. At 2 wt% of nanoclay addition, there was about a 70% increase in ILSS of EGCN (shown **Figure 5e**). ILSS mainly depends on matrix behavior if the matrix is tough, the ILSS is increased. The addition of nanoclay makes the matrix tough because the crack propagation is hindered by the clay platelets and the stress distributed to the fibers will be uniform as the interface becomes stronger. At 10 wt% addition of nanoclay, the ILSS decreased by 3% compared to GRE. Lim et al. [58] showed that the geometry of the interface between epoxy-nanoclay platelets may also influence ILSS.

2.5 Impact strength

The impact strength of the composite depends mainly on the strength of the matrix and the ability of the fiber matrix to withstand the impact loads. At 5 wt% addition of Cloisite 10A, the EGCN has exhibited a 23% improvement in impact strength; this improvement is attributed to the creation of a complex path for the fracture propagation, as the layered silicate platelets hinder the extension of microcracks created in the matrix (shown **Figure 6a**) [59]. The increase in the strength of the fiber-matrix interface has decreased the resistance to impact force. Manfredi et al. [12] stated that the failure strength of EGCN depends on two factors, one being the tortuous path formed by clay platelets, and another being the fiber-matrix interface strength. The well-dispersed nanoclay platelets hinder crack propagation by diverting the crack to a longer path or splitting it into sub cracks that require more energy, whereas a strong fiber-matrix interface reduces the impact resistance. The laminates were made with low fiber content hence the properties of the laminate are mainly dependent on the matrix behavior. An improvement in the impact characteristics of the nanocomposite with no glass fiber reinforcement was observed. The enhancement in the impact characteristics was observed for laminates with nanocomposite matrix irrespective of the clay type [12].

Shi and Kanny [19] carried out an Izod impact test at a high strain rate to study the impact characteristics of EGCN. When the matrix incorporated into the laminate was processed by magnetic stirring, the impact strength of the laminate was noticed to be decreasing with the addition of Cloisite 30B. A sudden decrease in impact strength of 27% is observed for the laminate at 1 wt% clay; further addition of clay did not affect impact strength (shown **Figure 6b**). The sudden decrease at 1 wt% clay is attributed to the agglomeration and air voids in the matrix, Siddiqui et al. [60] addressed the same finding, whereas 44.9% improvement in the impact strength.

At 1 wt% nanoclay was observed when the laminate prepared was incorporated with a matrix processed by HSMT [19]. The changes in the impact strength of the composites with the addition of various surface modified nanoclays under different mixing conditions and making methods are given in **Table 1**.

Figure 6.
Changes in impact strength of EGCN'S under various conditions.

Zulfli and Chow [27] reported that the impact strength of the laminates with Nanomer 1.28E incorporated in the matrix exhibited a higher value compared to GRE. This improvement in the impact characteristics was ascribed to strong adhesion between Nanomer 1.28E and epoxy which implies that the resin has wetted all layers of the nanoclay particles. This, therefore, enhances the energy required to debond the fiber and matrix due to the strong bond. Yasmin et al. [49] stated that the enhanced impact strength of the laminate is because of the complex path for cracks to propagate through the matrix. The OMMT and glass fiber provides a synergistic increment to the impact characteristics. OMMT at the fiber matrix interface acts as an interfacial modifier while the stress transfer from the matrix to fiber gets enhanced through clay particles; thus as the clay content at the fiber matrix interface increases, higher stress levels can be taken by the composite because of which better characteristics were attained [40]. But the content of clay that can be added to the epoxy is limited by the agglomeration and air voids that are formed while mixing the clay into the resin. Rafiq Ahmad et al. [41] added Nanomer I.30E into EGCN to evaluate its effect on the impact strength of EGCN. The laminates were stroked with low-speed impact forces ranging between 10 and 50 J. The optimum property was obtained at 1.5 wt% of nanoclay addition with 23% improvement in the maximum load required to damage the specimen and 11% improvement in stiffness. Also, a notable decrease in physical damage was observed for EGCN compared to GRE (shown **Figure 6c**).

Najafi et al. [20] studied the effect of the addition of pristine MMT into EGCN on impact strength. To study the effect of hygrothermal aging, some EGCN specimens were immersed in distilled water at 80°C for 10 weeks. At 3 wt% nanoclay addition there was about a 7% increase in impact strength for EGCN. At 5 wt%, the impact strength reduced nearly by 5% compared to the value obtained at 3 wt%, and this decrease was attributed to agglomerates. Also, the brittleness of EGCN increased with the addition of nanoclay, causing the energy absorption to decrease [59]. The 3 wt% and 5 wt% nanoclay added EGCN subjected to hygrothermal conditioning exhibited a 7.23% and 10.47% decrease in impact strength compared to the control specimen which

was dry GRE. The conditioned GRE exhibited about 13% decrease compared to dry GRE, whereas for 3 and 5 wt% added, conditioned EGCN exhibited about 14% and 8% increase compared to conditioned GRE (shown **Figure 6d**). In both dry and conditioned states, the 3 wt% added EGCN's exhibited good impact strength compared to the control specimen. Prabhakar et al. [11] stated that EGCN reinforced with acid treated glass fiber and MMT exhibited the highest impact strength out of all the composites made using neat glass fiber, silane treated glass fiber, and acid treated glass fiber, MMT, and Nanomer I.28E. Neat GRE exhibited the second highest impact strength value. The next highest impact strength was exhibited by EGCN with silane treated fiber and Nanomer I.28E. Compared to neat GRE the former one was 2% superior in property and the latter one is 2% inferior in the property. Prabhakar et al. [11] stated that a decrease in impact strength was compensated by an improvement in hardness of composites added with Nanomer I.28E and silane treated fiber, because the increase in hardness increases the brittleness, thereby reducing the energy absorption capability.

3. Conclusion

After reviewing the existing literature available on EGCNs reinforced with surface modified nanoclays, it is clear that the interfacial bond between reinforced fibers and the matrix is enhanced which resulted in enhancement in the mechanical properties of the composite. The enhanced fiber-matrix interface strength is due to good adhesion between clay platelets and epoxy allowing better stress transfer to all the fibers.

Conflict of interest

The authors have declared no conflict of interest.

Author details

Shanti Kiran Zhade¹, Syam Kumar Chokka^{2*}, V. Suresh Babu³ and K.V. Sai Srinadh³

¹ RGUKT, Basar, India

² Ellenki College of Engineering and Technology, India

³ NIT, Warangal, India

*Address all correspondence to: chokka.syamkumar@gmail.com

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References

- [1] Kaczmar JW, Pietrzak K, Wlonsinski W. The production and application of metal matrix composite materials. *Journal Material Processing Technology*. 2000;**106**:58-67. DOI: 10.1016/S0924-0136(00)00639-7
- [2] Miracle DB. Metal matrix composites—From science to technological significance. *Composites Science and Technology*. 2005;**65**:2526-2540. DOI: 10.1016/j.compscitech.2005.05.027
- [3] Mortensen A, Llorca J. Metal matrix composites. *Annual Review of Materials Research*. 2010;**40**:243-270. DOI: 10.1146/annurev-matsci-070909-104511
- [4] Mc Garry FJ. Polymer composites. *Annual Review of Materials Science*. 1994;**24**:63-82. DOI: 10.1146/annurev.ms.24.080194.000431
- [5] Saheb DN, Jog JP. Natural fiber polymer composites: A review. *Advances in Polymer Technology*. 1999;**18**: 351-363. DOI: 10.1002/(SICI)1098-2329(199924)18:4<351:AID-ADV6>3.0.CO;2-X
- [6] Matabola KP, Vries AR De, Moolman FS, Luyt AS. Single polymer composites: A review. *Journal of Materials Science* 2009;**44**:6213-6222. DOI: 10.1007/s10853-009-3792-1
- [7] Ku H, Wang H, Pattarachaiyakoo N, Trada M. A review on the tensile properties of natural fiber reinforced polymer composites. *Composites Part B: Engineering*. 2011;**42**:856-873. DOI: 10.1016/j.compositesb.2011.01.010
- [8] Dhingra AK. Metals Replacement by Composites. *The Journal of The Minerals, Metals & Materials Society*. 1986;**38**:17. DOI: 10.1007/BF03257887
- [9] Chakraverty AP. Some aspects of evaluation of GFRP composite [thesis]. Rourkela: National Institute of Technology; 2015
- [10] Roco MC. Nanoparticles and Nanotechnology Research. *Journal of Nanoparticle Research*. 1999;**1**:1-6. DOI: 10.1023/A:1010093308079
- [11] Prabhakar K, Debnath S, Anwar M, Palanikumar K. Experimental analysis on the effect of surface treatment of glass fibers & nanoclay on mechanical properties of glass fiber reinforced polymer nanocomposites. *Conf. Series: Materials Science and Engineering*. 2019;**495**:012091. DOI: 10.1088/1757-899X/495/1/012091
- [12] Manfredi LB, De Santis H, Vázquez A. Influence of the addition of montmorillonite to the matrix of unidirectional glass fibre/epoxy composites on their mechanical and water absorption properties. *Composites Part A: Applied Science and Manufacturing*. 2008;**39**:1726-1731. DOI: 10.1016/j.compositesa.2008.07.016
- [13] Lan T, Kaviratna PD, Pinnavaia TJ. Mechanism of clay tactoid exfoliation in epoxy-clay nanocomposites. *Chemistry of Materials*. 1995;**7**:2144-2215. DOI: 10.1021/cm00059a023
- [14] Wang Z, Pinnavaia TJ. Hybrid organic-inorganic nanocomposites: Exfoliation of magadiite nanolayers in an elastomeric epoxy polymer. *Chemistry of Materials*. 1998;**10**:1820-1826. DOI: 10.1021/cm970784o
- [15] Lagaly G. Interaction of alkylamines with different types of layered compounds. *Solid State Ionics*. 1986;**22**:43-51

- [16] Alexandre M, Dubois P. Polymer-layered silicate nanocomposites: preparation, properties and uses of a new class of materials. *Materials Science and Engineering*. 2000;**28**:1-63. DOI: 10.1016/S0927-796X(00)00012-7
- [17] Kornmann X, Rees M, Thomann Y, Necola A, Barbezat M, Thomann R. Epoxy-layered silicate nanocomposites as matrix in glass fibre-reinforced composites. *Composites Science and Technology*. 2005;**65**:2259-2268. DOI: 10.1016/j.compscitech.2005.02.006
- [18] Bozkurt E, Kaya E, Tanolu M. Mechanical and thermal behavior of non-crimp glass fiber reinforced layered clay/epoxy nanocomposites. *Composites Science and Technology*. 2007;**67**:3394-3403. DOI: 10.1016/j.compscitech.2007.03.021
- [19] Shi Y, Kanny K, Jawahar P. Hybrid nanocomposites: Processing and properties. *Advanced Composite Materials*. 2009;**18**:365-379. DOI: 10.1163/156855109X434757
- [20] Najafi M, Darvizeh A, Ansari R. Effect of nanoclay addition on the hygrothermal durability of glass/epoxy and fiber metal laminates. *Fibers and Polymers*. 2018;**19**:1956-1969. DOI: 10.1007/s12221-018-8235-7
- [21] Swaminathan G, Shivakumar K. Thermomechanical and fracture properties of exfoliated nanoclay nanocomposites. *Journal of Reinforced Plastics and Composites*. 2011;**30**:256-268. DOI: 10.1177/0731684410393052
- [22] Tsai J-L, Wu M-D. Organoclay effect on mechanical responses of glass/epoxy nanocomposites. *Journal of Composite Materials*. 2008;**42**:553-568. DOI: 10.1177/0021998307087514
- [23] Srikanth I, Kumar S, Singh V, Rangababu B. Effect of carbon nanofibre addition on the mechanical properties of different V_f carbon-epoxy composites. *Bulletin of Materials Science*. 2015;**38**:309-317
- [24] Senthil Kumar MS, Chithirai Pon Selvanb M, Sampathc PS, Raja K, Balasundaram K. Influence of nanoclay on interlaminar shear strength and fracture toughness of glass fiber reinforced nanocomposites Influence of nanoclay on interlaminar shear strength and fracture toughness of glass fiber reinforced nanocomposites. *IOP Conference Series: Materials Science and Engineering*. 2018;**346**:012081. DOI: 10.1088/1757-899X/346/1/012081
- [25] Steinmann W, Saelhoff AK. Essential properties of fibres for composite applications. Rana S, Figueiro R, editors. *Fibrous and Textile Materials for Composite Applications*. Textile Science and Clothing Technology. Singapore. Springer; 2016. p. 39-73. DOI: 10.1007/978-981-10-0234-2_2
- [26] Haque A, Shamsuzzoha M, Hussain F, Dean D. S2-glass/epoxy polymer nanocomposites: Manufacturing, structures, thermal and mechanical properties. *Journal of Composite Materials*. 2003;**37**:1821-1838. DOI: 10.1177/002199803035186
- [27] Zulfli M, Chow W. Mechanical and thermal behaviours of glass fiber reinforced epoxy hybrid composites containing organo-montmorillonite. *Malaysian Polymer Journal*. 2012;**7**:1-8
- [28] Kanny K, Mohan TP. Resin infusion analysis of nanoclay filled glass fiber laminates. *Composites Part B: Engineering*. 2014;**58**:328-334. DOI: 10.1016/j.compositesb.2013.10.025
- [29] Gurusideswar S, Velmurugan R. Strain rate sensitivity of glass/epoxy composites with nanofillers. *Materials*

and Design. 2014;**60**:468-478. DOI: 10.1016/j.matdes.2014.03.065

[30] Sharma B, Mahajan S, Chhibber R, Mehta R. Glass fiber reinforced polymer-clay nanocomposites: processing, structure and hygrothermal effects on mechanical properties. *Procedia Chemistry*. 2012;**4**:39-46. DOI: 10.1016/j.proche.2012.06.006

[31] Gurusideswar S, Velmurugan R. High Strain Rate Sensitivity of Glass/Epoxy/Clay Nanocomposites. Losboa. Portugal: Proceedings of 10th International Conference on Composite Science and Technology (ICCST '10); 2-4 September 2015. pp. 1-12

[32] Krushnamurthy K, Rasmitha D, Srikanth I, Ramji K, Subrahmanyam C. Effect of Volume Fraction of Fibre on the Mechanical Properties of Nanoclay Reinforced E-Glass-Epoxy Composites. *International Journal of Materials and Metallurgical Engineering*. 2016;**10**:98-101. DOI: scholar.waset.org/1999.2/10003722

[33] Jeyakumar R, Sampath PS, Ramamoorthi R, Ramakrishnan T. Structural, morphological and mechanical behaviour of glass fibre reinforced epoxy nanoclay composites. *International Journal of Advanced Manufacturing Technology*. 2017;**93**:527-535. DOI: 10.1007/s00170-017-0565-x

[34] Kini UA, Shettar M, Sathyashankara Sharma PH, GM C, Hegde A, Siddhartha D. Effect of hygrothermal aging on the mechanical properties of nanoclay- glass fiber-epoxy composite and optimization using full factorial design. *Materials Research Express*. 2019;**6**:1-13. DOI: 10.1088/2053-1591/ab0d68

[35] Jawahar P, Balasubramanian M. Influence of nanosize clay platelets on

the mechanical properties of glass fiber reinforced polyester composites. *Journal of Nanoscience and Nanotechnology*. 2006;**6**:3973-3976. DOI: 10.1166/jnn.2006.656

[36] Wang X, Zhao X, Wu Z, Zhu Z, Wang Z. Interlaminar shear behavior of basalt FRP and hybrid FRP laminates. *Journal of Composite Materials*. 2016;**50**:1073-1084. DOI: 10.1177/0021998315587132

[37] Lin JC, Chang LC, Nien MH, Ho HL. Mechanical behavior of various nanoparticle filled composites at low-velocity impact. *Composite Structures*. 2006;**74**:30-36. DOI: 10.1016/j.compstruct.2005.03.006

[38] Basara C, Yilmazer U, Bayram G. Synthesis and characterization of epoxy based nanocomposites. *Journal of Applied Polymer Science*. 2005;**98**:1081-1086. DOI: 10.1002/app.22242

[39] Taylor AC, Kinloch AJ. Mechanical and fracture properties of epoxy/inorganic micro-and nano-composites. *Journal of Materials Science Letters*. 2003;**22**:1439-1442. DOI: 10.1023/A

[40] Mishra S, Mohanty AK, Drzal LT, Misra M, Parija S, Nayak SK, et al. Studies on mechanical performance of biofibre/glass reinforced polyester hybrid composites. *Composites Science and Technology*. 2003;**63**:1377-1385. DOI: 10.1016/S0266-3538(03)00084-8

[41] Rafiq A, Merah N, Boukhili R, Al-qadhi M. Impact resistance of hybrid glass fiber reinforced epoxy/nanoclay composite. *Polymer Testing*. 2017;**57**: 1-11. DOI: 10.1016/j.polymertesting.2016.11.005

[42] Okoli O, Smith G. High strain rate characterization of a glass/epoxy composite. *Journal of Composites*

Technology and Research. 2000;**22**:3.
DOI: 10.1520/CTR10619J

[43] Fereshteh-Saniee F, Majzoobi GH, Bahrami M. An experimental study on the behavior of glass-epoxy composite at low strain rates. *Journal of Materials Processing Technology*. 2005;**162-163**:39-45. DOI: 10.1016/j.jmatprotec.2005.02.011

[44] Shokrieh MM, Omid MJ. Tension behavior of unidirectional glass/epoxy composites under different strain rates. *Composite Structures*. 2009;**88**:595-601. DOI: 10.1016/j.compstruct.2008.06.012

[45] Hussain F. Polymer-matrix nanocomposites, processing, manufacturing, and application: An overview. *Journal of Composite Materials*. 2006;**40**:1511-1575. DOI: 10.1177/0021998306067321

[46] Li X, Zhan Z, Peng G, Wang W. A new method for preparing completely exfoliated epoxy/clay nanocomposites: Nano-disassembling method. *Polymer Bulletin*. 2011;**67**:719-727. DOI 10.1007/s00289-011-0496-x

[47] Withers GJ, Yu Y, Khabashesku VN, Cercone L, Hadjiev VG, Souza JM, et al. Improved mechanical properties of an epoxy glass-fiber composite reinforced with surface organomodified nanoclays. *Composites Part B: Engineering*. 2015;**72**:175-182. DOI: 10.1016/j.compositesb.2014.12.008

[48] Brown KA, Brooks R, Warrior NA. The static and high strain rate behaviour of a commingled E-glass/polypropylene woven fabric composite. *Composites Science and Technology*. 2010;**70**:272-283. DOI: 10.1016/j.compscitech.2009.10.018

[49] Yasmin A, Luo JJ, Abot JL, Daniel IM. Mechanical and thermal behavior of clay/epoxy nanocomposites.

Composites Science and Technology. 2006;**66**:2415-2422. DOI: 10.1016/j.compscitech.2006.03.011

[50] Yasmin A, Abot JL, Daniel IM. Processing of clay/epoxy nanocomposites by shear mixing. *Scripta Materialia*. 2003;**49**:81-86. DOI: 10.1016/S1359-6462(03)00173-8

[51] Sinha Ray S, Okamoto M. Polymer/layered silicate nanocomposites: A review from preparation to processing. *Progress in Polymer Science*. 2003;**28**:1539-1641. DOI: 10.1016/j.progpolymsci.2003.08.002

[52] Wu CL, Zhang MQ, Rong MZ, Friedrich K. Tensile performance improvement of low nanoparticles filled-polypropylene composites. *Composites Science and Technology*. 2002;**62**:1327-1340. DOI: 10.1016/S0266-3538(02)00079-9

[53] Mittal V. Polymer layered silicate nanocomposites: A review. *Materials*. 2009;**2**:992-1057. DOI: 10.3390/ma2030992

[54] Karippal JJ, Murthy HNN, Rai KS, Sreejith M, Krishna M. Study of mechanical properties of epoxy/glass/nanoclay hybrid composites. *Journal of Composite Materials*. 2011;**45**:1893-1899. DOI: 10.1177/0021998310389087

[55] Khan SU, Munir A, Hussain R, Kim JK. Fatigue damage behaviors of carbon fiber-reinforced epoxy composites containing nanoclay. *Composites Science and Technology*. 2010;**70**:2077-2085. DOI: 10.1016/j.compscitech.2010.08.004

[56] Wichmann MHG, Sumfleth J, Gojny FH. Glass-fibre-reinforced composites with enhanced mechanical and electrical properties—Benefits and limitations of a nanoparticle modified

matrix. Vol. 732006. pp. 2346-2359.
DOI: 10.1016/j.engfracmech.2006.05.015

[57] Wang A, Xia D, Xian G, Li H. Effect of nanoclay grafting onto flax fibers on the interfacial shear strength and mechanical properties of flax/epoxy composites. *Polymer Composites*. 2019;**40**:1-11. DOI: 10.1002/pc.25210

[58] Lim JW, Hassan A, Rahmat AR, Wahit MU. Morphology, thermal and mechanical behavior of polypropylene nanocomposites toughened with poly (Ethylene-Co-Octene). *Polymer International*. 2006;**55**:204-215.
DOI: 10.1002/pi.1942

[59] Khan SU, Iqbal K, Munir A, Kim JK. Quasi-static and impact fracture behaviors of CFRPs with nanoclay-filled epoxy matrix. *Composites Part A: Applied Science and Manufacturing*. 2011;**42**:253-264. DOI: 10.1016/j.compositesa.2010.11.011

[60] Siddiqui NA, Woo RSC, Kim J, CCK L. Mode I interlaminar fracture behavior and mechanical properties of CFRPs with nanoclay-filled epoxy matrix. *Composites Part A: Applied Science and Manufacturing*. 2007;**38**:449-460. DOI: 10.1016/j.compositesa.2006.03.001