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TENSILE AND FLEXURAL BEHAVIOR OF NANOCLAY FILLED EPOXY MATRIX BASED FIBER REINFORCED COMPOSITE LAMINATES

M. Sc. THESIS

IN

MECHANICAL ENGINEERING

BY
MOHAMMED HUSSEIN MAHMOOD MAHMOOD
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Supervisor

Assist. Prof. Dr. Ömer Yavuz BOZKURT

by

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Mohammed Hussein Mahmood MAHMOOD

ABSTRACT

TENSILE AND FLEXURAL BEHAVIOR OF NANO-CLAY FILLED EPOXY MATRIX BASED FIBER REINFORCED COMPOSITE LAMINATES

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In this study, the effect of nanoclay filler on tensile and flexural behavior of epoxy matrix based glass fiber reinforced composite laminates $[G_{12}]$ and aramid/glass hybrid fiber reinforced composite laminates were investigated. The composite laminates with different nanoclay contents (0.5 wt.%, 1 wt.%, 2 wt.%, 3 wt.% and 5 wt.%) were fabricated using hand lay-up followed by hot press. The nano-structured hybrid fiber reinforced composite laminates were prepared with a variety of stacking configurations ($[K_1G_4]_S$, $[K_2G_3]_S$,$[K_3G_2]_S$ and $[K_4G_1]_S$). The tensile and flexural tests were conducted by following ASTM 3039 and D638-10 for uniaxial tensile and ASTM D790-10 for three-point bending.

The results showed that the increase in tensile strength for composites $[G_{12}]$ with nanoclay is 8%, 4% and 1% for 1 wt.%, 2 wt.% and 3 wt.% nanoclay filled epoxy based glass fiber reinforced composites, respectively. The reductions from 327 MPa to 280 MPa and 15 GPa to 13 GPa were determined for both flexural strength and modulus, respectively. It was shown that the enhancement in tensile strength is more significant at lower nanoclay contents and the highest tensile strength was determined for 1 wt.% clay content. The maximum tensile strength of hybrid composites was obtained for the configuration $[K_1G_4]_S$ using 2 wt.% of nanoclay and the maximum flexural strength was observed for 1 wt.% nanoclay inclusion.

Keywords: Nanocomposite, Hybrid composite, Flexural strength, Tensile, Nanoclay, Glass fiber

ÖZET

NANOKİL KATKILI EPOKSİ MATRİS TABANLI ELYAF TAKVİYELİ KOMPOZİT LAMİNATLARIN ÇEKME VE EĞME DAVRANIŞLARI

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Bu çalışmada, nanokil katkısının epoksi esaslı cam elyaf takviyeli kompozit laminatların $[G_{12}]$ ve aramid/cam hibrit elyaf takviyeli kompozit laminatların çekme ve eğilme davranışlarına etkisi araştırılmıştır. Farklı nanokil içeriklerine (ağırlıkça % 0.5, % 1, % 2, % 3 ve % 5) sahip kompozit laminatlar, el yatırması ve bunu takiben sıcak pres kullanılarak imal edilmiştir. Nano yapılı hibrid elyaf takviyeli kompozit laminatlar çeşitli istif yapılandırmalarıyla hazırlanmıştır ($[K_1G_4]_S$, $[K_2G_3]_S$, $[K_3G_2]_S$ ve $[K_4G_1]_S$). Çekme ve eğilme testleri, tek eksenli çekme için ASTM 3039 ve D638-10 ve üç noktalı eğilme için ASTM D790-10 standartları takip edilerek gerçekleştirilmiştir.

Sonuçlar, nano kil katkılı kompozitler için $[G_{12}]$ çekme mukavemetindeki artışın % 1, % 2 ve % 3 nanokil katkılı epoksi esaslı cam elyaf takviyeli kompozitler için sırasıyla % 8, % 4 ve % 1 olduğunu ortaya koymuştur. Eğilme mukavemeti ve modülü için sırasıyla 327 MPa'dan 280 MPa'ya ve 15 GPa'dan 13 GPa'ya düşüşler tespit edilmiştir. Çekme mukavemetindeki artışın, daha düşük nanokil içeriklerinde daha belirgin olduğu ve en yüksek çekme mukavemetin ağırlıkça % 1 kil içeriğinde belirlenmiştir. Hibrit kompozitlerin maksimum gerilme mukavemeti, ağırlıkça % 2 nanokil kullanan $[K_1G_4]_S$ konfigürasyonu için elde edilmiş ve maksimum eğilme mukavemeti, ağırlıkça % 1 nanokil katkısı için gözlenmiştir.

Anahtar Kelimeler: Nanokompozit, Hibrit kompozit, Eğilme mukavemeti, Çekme, Nanokil, Cam elyafı

Dedication

To whom Allah said in them "and goodness to your parents" ……… (My father and my mother)

To my partner ……………. (my beloved wife)

To my dear children , whose name is associated with my name ………… (Khatab , Manar and Mustafa)

To those who I proud to belong to them, and draw strength from them ……… (my brothers and sisters)

To whom that the life not Pleasant without them …… (My relatives and sincere friends)

Mohammed Hussein Mahmood
MAHMOOD

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LIST OF SYMBOLS

FRP	Fiber Reinforced Polymer
FRPs	Fiber Reinforced Polymer Composites
CFRPs	Carbon Fiber-Reinforced Composites
GFRP	Glass Fiber Reinforced Polymeric composite
CFRP	Carbon Fiber Reinforced Polymeric Composite
BFRP	Bamboo Fiber-Reinforced Plastic
CF	Fiber Carbon
FG	Fiber Glass
FK	Fiber Kevlar
PP	PolyPropylene
HDPE	High Density Poly Ethylene
Phc	Per hundred compounds
BSCC	Basalt Skin-Carbon Core
CNT	Carbon Nano Tube
CNTs	Carbon Nano Tubes
UV	UltraViolet
KFRE	Kenaf Fiber Reinforced Epoxy
HP-PE	High-Performance Poly Ethylene

LCP	Liquid Crystalline Polymer
OMMT	Organo - Montmorillonite
VARTM	Vacuum-Assisted Resin Transfer Molding
CPC	Cork Powder and Coconut
CNC	Computer Numerical Control
σt	Tensile Strength
σf	Flexural Strength
Ef	Flexural Modulus
$[K_1G_4]_S$	One Layer Kevlar and Eight Layer Glass and One Layer Kevlar = K1G8K1
$[K_2G_3]_S$	Two Layer Kevlar and Six layer Glass and Two Layer Kevlar = K2G6K2
$[K_3G_2]_S$	Three Layer Kevlar and Four Layer Glass and Three Layer Kevlar = K3G4K3
$[K_4G_1]_S$	Four Layer Kevlar and Two Layer Glass and Four Layer Kevlar = K4G2K4
wt. %	Weight Percentage
EC	Electric Cutter
ASTM	American Society for Testing and Materials

CHAPTER 1

INTRODUCTION

1.1 General Introduction

In recent years, due to their higher stiffness-to-weight and strength-to-weight, better corrosion resistance and good fatigue performance, composite materials are usage in numerous applications ranging from household articles to highly sophisticated engineering applications [1]. Especially the fiber reinforced composite polymeric materials have become a popular alternative to metallic components and find place in numerous engineering applications like sporting goods, household appliances, marine, automotive, aerospace, and defense industries. With the increasing use of fiber reinforced polymeric composites, the determination and performance enhancement of fiber reinforced polymeric composites under varied loading conditions like axial, flexural, torsional and impact loading turn into a crucial challenge for the engineering applications and becomes a popular research topic among the engineers and scientists.

Fiber hybridization is a general procedure to get composite laminates with enhanced characteristics compared to neat fiber reinforced composites. Dealing with polymer composites, hybridization may result in a compromise between mechanical characteristics and cost to meet specified design requirements, as one of the reinforcement is commonly cheaper than the other one [2]. The use of hybrid fiber reinforced composite materials has extensively increment in structural applications, because of their enhanced and better characteristics. Hybrid fiber reinforced composites provide the incorporation of varied fiber materials in a structure with utilization of advantageous material characteristics. A typical desired material property combination of a hybrid structure is good mechanical characteristics combined with lower weight [3].

Hybrid fiber reinforced composites are of great research interest as a convenient way to achieving tailored material characteristics [4]. The mechanical characteristics of a hybrid composite can be vary by altering the volume fraction and stacking sequence of layers of composite laminates. Carbon fibers are vastly usage in many aerospace applications because of their high specific modulus. Nevertheless, the impact strength of composites made of carbon fibers is generally lower than conventional steel alloys or glass reinforced composites. An influence procedure of enhancing the ultimate strain and impact characteristics of high modulus fiber composites is the hybridization of high modulus fibers with lower modulus fibers like E-glass or Kevlar [5].

One of the recently developed procedures to enhance the mechanical characteristics of fiber reinforced composite materials is the addition of particle into matrix as a second reinforcement phase. The use of particle fillers, especially nanoparticles, in a polymer matrix is a recent improvement in the field of polymer composite industry [6]. The influence of this strategy depends on dispersion of the filler, characteristics of the nano-scale filler and interaction between the filler and the matrix. The types of nano-particles usage in polymer composites are extremely varied like nano-particles of ceramics, clays, silica, graphene, iron [7,8], gold [9], zeolite [10], boron [11] and carbon nanotubes [12]. The benefits of nanoclay-filled composites are generally demonstrated using the enhancements in mechanical characteristics like quasi-static tensile and flexural characteristics, fracture resistance [13].

The unique characteristics of fiber reinforced polymer nanocomposites are achieved mostly due to increment interfacial surface areas, enhanced bond properties and intercalated/exfoliated morphology of the epoxy-clay nanocomposites [14]. During the past two decades, the technologies of composite materials have got up rapidly and are now become very commonplace around the world. Fiber reinforced polymer composites also exhibit better damping characteristics, good fatigue resistance and high resistance to corrosion [15].

Despite the huge number of publications of polymer-clay, polymer-silica nanocomposites, there is very few literature about the influences of adding nano-clay to polymer on tensile and flexural glass/aramid hybrid fiber and glass fiber reinforced polymer composites. Therefore, the aim at this work is to analyze the variation on tensile and flexural behavior of glass/Kevlar hybrid fiber and glass fiber reinforced nano-clay based epoxy matrix composite with respect to the nano-clay content. A group of glass/Kevlar hybrid fibers and glass fiber reinforced nano-clay based epoxy matrix composites with clay concentration up to 5 wt.% and glass/Kevlar hybrid fiber composite laminates with various stacking sequence have been prepared using hand lay-up method.

1.2 Research Objectives and Tasks

In this study, the main objective is to investigate the influences of nano-clay additive on tensile and flexural behavior of glass fiber and aramid/glass hybrid fiber reinforced composite laminates. The research tasks can be summarized as follows:

I. Prepare of glass fiber reinforced composite laminates with varied amount of nano-clay inclusions.
II. Production of glass/Kevlar hybrid fiber reinforced composite laminates using various stacking sequence and various nano-clay contents.
III. Conduction of the tensile and flexural tests for the fabricated laminates.
IV. Discussion about the influences of the nanoparticles on the tensile and flexural behaviors using the results of the tests.

1.3 Layout of Thesis

The study has classified into five chapters.

- In Chapter 1, a short introduction about the composite materials in terms of fiber reinforced composites and nanoparticle added fiber reinforced composites is presented.
- A comprehensive literature review about the fiber-reinforced composites is given in Chapter 2. The literature review is presented in five subsections: introduction, studies about the fiber reinforced composite materials, studies related with hybrid fiber reinforced composite materials, studies about fiber reinforced composite laminates with nano fillers, and conclusion on literature survey.
- Information about the materials (epoxy, nanoparticles and fibers), preparation of the composite laminates and the physical characteristics of the fabricated composite laminates are given in Chapter 3.
- The results and discussions of tensile and the three-point bending tests are introduced in Chapter 4.

- General conclusions about the results are inclined in Chapter 5.

CHAPTER 2

LITERATURE SURVEY

2.1 Introduction

A review of available literature is done to put in front the background information on the issues to be considered in this study and to highlight the important of the deliver study. The literature review focuses on varied sides of hybrid composite materials. Tensile and flexural characteristics are investigated by many researchers because of increasing importance of composite materials in engineering applications. This literature review has been classified in four parts:

- In part 2.2 studies about the fiber reinforced composite material.
- In part 2.3 studies related with hybrid fiber reinforced composite material.
- In part 2.4 studies about fiber reinforced composite laminates with nano fillers.
- In part 2.5 conclusion on literature review.

2.2 Studies About the Fiber Reinforced Composite Material

The influence of the interface between the plies of glass fiber on the mechanical characteristics of the laminates has been studied by Queck et al. [16] This study showed that the type of sizing has a strong influence on the mechanical characteristics of the UD laminates this as the tensile strength and shear strength. The best fiber/matrix interface leads to best fatigue performance.

According to Bahadur et al. [17] the increase in volume fraction of glass fiber within thermosetting polyester enhances the hardness and the flexural modulus of the composites. This fact was considered as a result of the study of mechanical and tribological behavior of the reinforcement of short glass fiber.

The result of the research that was performed by Aktaş and Karakuzu [18] indicated that the tensile strength and modulus of elasticity of glass/epoxy composites decrease rapidly after 60 and 80 °C respectively. The shear modulus of unidirectional glass/epoxy composite laminates is fairly influenced with increasing temperature.

The influence of temperature on the mechanical characteristics of SiC fiber reinforced glass-matrix composite system was investigated by Prewo and Brennan [19] It was found that good material characteristics can be achieved, and excellent fracture toughness and flexural strength were observed over the temperature from 22 to 700°C.

Zhong et al. [20] examined the impact behavior and damage properties of hydrothermally conditioned carbon epoxy composite laminates. It was indicated that the interface between matrix and fiber, was reduced when exposed to subsequent aging and water immersion.

A comparison between the characteristics of different fiber types was carried out by Lopresto [21]. It was shown that the elastic modulus of basalt fiber composite laminates were 35-42 % higher than E-glass fiber reinforced laminates. Also, basalt fiber composite laminates have better compressive flexural and strength behavior. On the other hand, E-glass fiber reinforced laminates have higher tensile strength than basalt fiber reinforced ones.

In basalt fiber type, a study was carried out by Bozkurt et al. [22] to show the influence of fiber orientation on damping and vibration characteristics of basalt epoxy composite laminates. The results indicate that the fiber angle orientation affects the natural frequency of the laminate. The increase in angle of fiber orientation from 0˚ to 45˚ resulted in a decrease in natural frequency.

Composite materials are a combination of many entities such as matrix and fiber. The bonding strength between the entities play a significant role in mechanical characteristics of the laminate. Ku et al. [23] found that the tensile characteristics are highly effected by the strength of bonding between constituents.

Cheng et al. [24] conducted a research to clarify the influence of fiber volume fraction on mechanical characteristics of poly (butylene succinate) (PBS) biocomposites reinforced with surface modified fiber of jute. It was found that modulus or mechanical strength are gradually increased with increasing volume fraction from 0-20%. It was also showed that with 30 % fiber content, the relevant properties show decrements or nearly remain constant.

The influence of corona discharge and ultraviolet (UV) treatment on the flexural characteristics of jute-fiber epoxy composites has been studied by Gassan and Gutowski [25]. With the optimum treatment conditions, 30% increment in flexural strength were achieved.

2.3 Studies Related to Hybrid Fiber Reinforced the Composite Material

The flexural behavior of hybrid composites reinforced with S-2 glass and T700S carbon fibers was studied by Dong et al. [26] in an intra-ply arrangement. An increase in flexural strength was shown with respect to span-to-depth ratio. The maximum flexural strength was indicated for the $[G/C_7]$ hybrid arrangement. The utilization of hybridization can enhance the flexural strength.

Peijs and Kok. [27] investigated the tensile and fatigue behavior of carbon-high-performance polyethylene/epoxy hybrid laminate structures and the influence of surface treatment of the high-performance polyethylene (HP-PE) fibers. The results showed that the tensile strength of hybrid composite well agreed with the strength predicted by the constant strain model. First failure strain of the carbon component enhanced in both fatigue and monotonic testing for the case of hybridization. The finite element result of the statistical influence and stress concentration well agree with experimental results.

The influence of surface treatment on flexural strength and interfacial adhesion strength was investigated by Wan et al. [28]. The result of this work indicated that after two-step surface treatment, the fiber hybridization showed significant enhancements. Moreover, the two-step surface treated carbon/aramid hybrid fiber reinforced composite led a positive hybrid influence on flexural strength.

One of the most important factors which influence the mechanical characteristics of the laminates is the stacking sequences of the laminates. Salman et al. [29] investigated the influence of stacking sequence on tensile characteristics of carbon/glass hybrid fiber reinforced composite materials. Tensile characteristics of carbon and glass hybrid fiber reinforced composites with a varied number of layers and stacking sequences were investigated in the work. It was showed that the best mechanical characteristics were achieved with three layers of carbon and two layers of glass.

Aramid plain fabric and glass/aramid hybrid fabric composite were tested by Leonardo et al. [30] to evaluate the mechanical properties. The result showed that good mechanical characteristics like tensile, bending and impact energy is seen when aramid/glass hybrid structure was usage in the reinforcing fabric.

Dong et al. [4] used unidirectional S-2 glass and T700S carbon fiber reinforced epoxy hybrid composites with varied stacking sequence to develop an approach to the robust design.

Mechanical characteristics of glass/carbon hybrid fiber reinforced composites were investigated under low-frequency cyclic loading by Poyyathappan et al. [31] Moreover, the tensile characteristics were studied and the breaking load was measured. The tensile strength of the hybrid composites was a combination between CFRP and GFRP. Under this type of loading, hybrid composites have better flexural characteristics than the GFRP.

The flexural and impact behavior of carbon/basalt fiber reinforced hybrid laminates were investigated by Dorigato and Pegoretti [32] Charpy impact tests were performed to find the impact characteristics of the composites. The results showed that the introduction of basalt fibers into carbon fiber reinforced laminates could promote an increment in the absorbed energy of impact, with an improvement of the fracture propagation.

The influence of fiber hybridization on flexural strength of the unidirectional hybrid epoxy composites reinforced by S-2 glass and T700S carbon fibers was investigated by Dong and Davies [33] It was shown that the maximum flexural strength was obtained at [G_2/C_6] hybrid arrangement. Compared to those of the neat glass and neat carbon arrangements, the strength increment were 16.6% and 42.58%, respectively.

The influence of fiber type reinforcing polymers on the flexural strength was investigated by Dong and Davies [34]. E glass and T700S carbon fibers were used for this purpose in bidirectional hybrid epoxy composites. The replacement of carbon layers with glass layers had no significant effect on the flexural strength as the experiments showed. Nevertheless, in simulation part, the results showed that hybridization can potentially enhance the flexural strength.

Hybrid composite laminates reinforced with carbon/glass woven fabrics for lightweight load bearing structures was examined by Jin Zhang et al. [35] It was shown that the reinforcement of glass fiber composite laminates by adding 50% carbon at the exterior and by adding a varied type of fiber resulted with an improvement on the tensile, flexural and compressive properties.

Rathnakar et al. [36] experimentally studied the stiffness and flexural strength of glass/graphite fiber reinforced composites. The main concern of this research is to determine the flexural parameters of glass/graphite fiber reinforced epoxy composites under static flexural loading.

Valenca et al. [37] investigated the variations on mechanical properties of Kevlar/epoxy composite laminates with the hybridization of glass fiber. The plates were prepared using hand lay-up technic and the tensile, bending and impact tests were performed to determine the mechanical characteristics. It was shown that Kevlar/glass/epoxy provided better mechanical characteristics than Kevlar/epoxy.

Kitano et al. [38] presented the variation of mechanical characteristics with respect to fiber content, mixing ratio and length. The mechanical characteristics like the tensile, bending, Izod impact and maximum rate impact strength were examined. Long and short fibers glass (FG) and varied types of organic fibers, Kevlar-49 (KF) and liquid crystalline polymer (LCP) were used in hybrid composites.

The mechanical characteristics like impact, compression after impact, and tensile stiffness of carbon-aramid fiber combined sandwich composites were studied by Gustin et al. [39] It was shown that a combination of Kevlar and carbon fiber of the sandwich laminate enhance the maximum absorbed energy. A carbon fiber on the bottom face of the sandwich and Kevlar fiber on the top of the laminate was used in the sandwich structure. The reductions on the longitudinal and transverse Young modulus of the sandwich laminate were noted in the results of the study.

Pandya et al. [5] studied in-plane mechanical characteristics of carbon/glass hybrid fiber reinforced composites. It was shown that there was a loss of 17.2% for tensile strength of hybrid composite H1 compared with that of 8H satin weave T300 carbon/epoxy composite. On the other hand, there was an increase of 90.4 % for supreme tensile strain of hybrid composite H1 compared with that of 8H satin weave T300 carbon/epoxy composite. The amount loss of tensile strength was significantly lower than gain in supreme tensile strain for hybrid composite. At fiber volume fraction of 0.52, there was a gain up to 42% of tensile strength for hybrid composite compared to that gained using rule-of-mixtures.

The influence of basalt fiber hybridization on lower velocity impact behavior of glass/epoxy composites was searched by Sarasini et al. [40] It was shown that presence of intercalated arrangement exhibited within hybrid laminates has higher impact absorbed energy capacity than glass laminates, and improved damage tolerance capability. The laminates with symmetrical sandwich-like arrangement (E-glass fiber fabrics as core and basalt fiber fabrics as skins) provided the most favorable flexural behavior.

Fiore et al. [41] studied the mechanical properties of glass-basalt/epoxy hybrid composites. The results showed that adding two external layers of basalt enhance the mechanical characteristics compared to those of GFRP laminates.

The influence of stacking sequence on the flexural characteristics of hybrid composites reinforced with carbon and basalt fibers were investigated by Subagiaet al. [42] The results showed that the staking sequence play an important role on the modulus and flexural strength of hybrid composite laminates. It was also presented that the Carbon fiber at the compression side gives higher flexural strength than basalt fiber.

The stack of carbon or basalt within the laminate also influence on the mechanical characteristics of the laminate and the dominant type of damage. Kim et al. [43] searched the influence of stacking sequence on fracture and flexural characteristics of carbon/basalt/epoxy hybrid composites. Results of the study showed that when the carbon skin-basalt core composites were used instead of the basalt skin-carbon core (BSCC) composites, an increase of ~245% and ~32% for flexural modulus and flexural strength were determined, respectively. It was noted that fiber breakage and matrix cracking were the dominant fracture mechanisms for the carbon skin-basalt core composites. The debonding between fibers and the matrix was presented as the dominant fracture mechanism for the BSCC composites.

Flexural and impact characteristics of hybrid composites based on Kevlar and basalt woven fabrics were examined by Sarasini et al. [44]. The outcome of this research indicated that absorbed impact energy capability and damage tolerance with respect to the all-aramid laminates can be enhanced by using hybrid laminates with intercalated arrangement (alternating sequence of aramid and basalt fabrics). It was also shown that the best flexural conduct can be present by using basalt and hybrid laminates with sandwich-like arrangement (7 basalt fabric layers at the center of the laminate as core and 3 aramid fabric layers for each side of the composite as skins).

The vibration and damping properties of basalt/epoxy and aramid/epoxy composites have been investigated by Bulut et al. [3]. They used the two fibers to produce basalt-aramid/epoxy hybrid composite laminates with improved damping properties. The presence of aramid fibers in composite laminates enhances vibration characteristics like the damping characteristics of laminates, but reduces the tensile strength values.

The influence of combination of carbon fiber and Kevlar fiber in a common epoxy matrix on fracture toughness of composites has been studied by Yadav et al. [45]. It was shown that the fracture toughness increased twice in all laminates. The improvement in fracture toughness was considerable in interleaved laminate than Kevlar one because of huge absorbed energy capabilities of interleaf.

Shan et al. [46] studied the fatigue behavior of carbon/glass hybrid fiber reinforced composite laminates. It was indicated that the combination of carbon and glass fiber within one laminate enhance the life prediction and environmental fatigue behavior of unidirectional composites.

Naik et al. [47] investigated the effect of arrangement of carbon and glass fiber on impact behavior and post impact compressive properties. This was investigated by Naik et al. [47] The results showed that the hybrid composites were less notch sensitive compared to neat glass or neat carbon composites. It was also shown that it is better to cover the glass fiber lamina with a carbon fiber lamina to get lower notch sensitivity.

Ramesh et al. [48] examined the mechanical properties of jute-sisal hybrid fiber reinforced composites. The results showed that the hybridization of sisal and jute can enhance tensile, impact and flexural strength over neat sisal and neat jute fiber reinforced composites. It was also revealed that sisal-jute-glass hybrid composites can be used as an alternative to glass fiber reinforced polymer composites.

Ahmed et al. [49] examined the fiber volume fraction on mechanical characteristics of jute-glass fiber reinforced polyester composite laminates. The results showed that the flexural characteristics enhanced with the increase of fiber content from 0 to 40% but there was no clear influence beyond that content.

Ho and Lau [50] studied the effect of fiber type on mechanical characteristics of composite laminates using short silk fibers and the woven glass fiber. It was pointed that hybridization of short silk fiber and the woven glass fiber formed a new hybrid composite and led better Young’s modulus and impact resistance compared to composites of neat short silk fiber and woven glass fiber.

Fonseca et al. [51] investigated mechanical characteristics of high density polyethylene based hybrid composites resulted from the combination of agave and pine fibers. The results displayed that addition of agave fibers enhanced impact, flexural and tensile strength, while water uptake led a decrement with an increment in the amount of pine fibers.

The influence of the flax-carbon hybrid fiber combination on damping modulus was studied by Guen et al. [52]. The mechanical tests indicated that the damping coefficient of composites reinforced with flax fiber was found to be 4 times higher than composites reinforced with carbon fiber alone.

The thermal and mechanical characteristics of pine cone fiber/clay hybrid composites were studied by Arrakhiz et al. [53]. It was indicated that the improvement in Young’s modulus for the whole system reached a gain of 80%, while the tensile strength remained stable with the use of both charges An increment in the torsional resistance was noted with the clay additive and a decrease in hardness characteristics was marked for high clay loading.

The influence of adding banana fiber to jute fiber-epoxy composites was studied by Boopalan et al. [54]. The results showed that hybrid composites had enhanced mechanical characteristics with lower moisture absorption.

2.4 Studies about Fiber Reinforced Composite Laminates with Nano Fillers

Chowdhury et al. [55] studied flexural and thermo mechanical characteristics of nanoclay reinforced composited. It was shown that maximum enhancements in flexural strength and modulus were found as 14% and 9% for 2 wt% nano-clay reinforced composites, respectively. It was also reported that nano-clay promotes good adhesion of fiber and matrix.

Naeli et al. [56] investigated the influence nanoclay filler on mechanical characteristics of polypropylene-made cellulose composites. It was reported that adding up to the level 2 phc of nano-clay increased the tensile, flexural strengths and modulus of composites. On the other hand, decrements for strengths were reduced by increasing the amount of nano-clay to the level 4 phc.

The influence of thermal conditions on the tensile characteristics of basalt fiber reinforced polypropylene-clay nanocomposites was studied by Farsani et al. [57]. In this study, the influence of nano-clay content also was studied. It was noted that presence of nano-clay particles (up to 5 wt.%) can increase the tensile mechanical characteristics.

Zulfli and Shyang [58] examined the morphological and flexural characteristics of epoxy/GF/silane treated organo- montmorillonite (OMMT) composites. It was shown that the flexural modulus enhanced significantly as the loading of silane-treated OMMT increased. In addition, the flexural modulus of E/GF/Si-15/OMMT was enhanced by13% and reached 4.98GPa.

Siddiqui et al. [59] examined fracture and mechanical characteristics of nanoclay modified CFRPs. The results showed that flexural modulus enhanced 26% with the addition 3 wt.% nanoclay and the flexural strength gradually decreased with the increase of clay content.

Khan et al. [13] presented the influence of nano-clay content on impact fracture and quasi-static conducts of CFRPs. It was shown that the impact fracture toughness of clay-epoxy nanocomposite and clay-CFRP hybrid composites were enhanced to a maximum at 3 wt.% nanoclay. Moreover, adding more clay led to decrease the fracture toughness.

The influence of nano-clay on mechanical characteristics of polyester and S-glass fiber was examined by Chowdary and Kumar [60]. Excellent result was gained by adding 5 wt.% nano-clay. The average value of impact energy for 5 wt.% of nano-clay was presented as 10.75 J/m.

Preparation and characterization of a specific type of composite of layered silicate with fiber glass/epoxy hybrid nanocomposites via vacuum-assisted resin transfer molding (VARTM) was investigated by Lin et al. [61]. It was indicated that the mechanical and thermal characteristics of this type of composite can be enhanced by adding a small amount of organoclay to the glass fiber/epoxy composites.

Helmy et al. [62] investigated the influence of nano-clay on tensile fatigue behavior of glass fiber reinforced epoxy composites. It was shown that there was an enhancement of the modulus and static tensile strength of tapered glass/epoxy composites by the addition of nano-clay. The presence of nano-clay in the matrix improved the supreme strength and decreased the strain to failure.

The effect of carbon nanotube-epoxy nanocomposite coating on tensile strength of glass fibers was studied by Siddiqui et al. [63] It was shown that the application of carbon nanotube nanocomposite coatings on the surface of glass fiber is an effective way to enhance the tensile strength of glass fibers.

Boroujeniet al. [64] analyzed the mechanical characteristics of carbon nanotube-carbon fiber hybrid composites. The results showed that on-axis tensile strength and ductility of the hybrid FRPs were enhanced by 11% and 35%, respectively. This arrangement also exhibited 16% enhancement in the off-axis stiffness.

The size scale effect on the post-impact residual strength of hybrid carbon/glass/epoxy nano-composites was studied by Kavitha et al. [65]. The results showed that tensile strength decreases with an increment in thickness of the specimen and with the addition of nanoclay.

An assessment about the effect of nanoclay content on flexural characteristics of fiber glass reinforced waterborne epoxy laminates was performed by Altan [66]. This assessment included the influence of nano clay on the enhancements in interlaminar shear strength, flexural stiffness and flexural strength. It was found that adding 0.5

wt.%. nano-clay increased the interlaminar shear strength, flexural stiffness and flexural strength by 5, 8 and 12%, respectively.

Hossain [67] examined the flexural behavior of surface modified fiber of jute reinforced biopol nanophased green composites. The improvement in flexural modulus and flexural strength was 9 % and 12 %, respectively, when nano clay was introduced into jute fiber reinforced polymer. The composites with 4 wt.% nano clay filler showed better dynamic mechanical characteristics, and flexural characteristics.

Fernandes et al. [68] showed the effect of adding short fiber to cork-HDPE composites. Composites were made from high-density polyethylene (HDPE) filled with cork powder and coconut (CPC) short fibers. It was shown that this type of addition increased the tensile strength and elastic modulus of HDPE by 98% and 33%, respectively. The presence of 2 wt. % of coupling agent based on maleic anhydride resulted in an improvement in flexural and tensile characteristics of the composites.

A comparison between the characteristics of pure recycled polypropylene (PP) composites and hybrid composites made from waste materials was performed by Ashori [69]. It was shown that the flexural and tensile modulus of the composites were significantly improved with the addition of fibers in both types (fiber and flour), as compared with neat polypropylene. On the other hand, the content of wood flour led to reduce the tensile and flexural modulus.

2.5 Conclusion on Literature Review

The following conclusions can be derived from the literature review:

1. Fiber reinforced epoxy composites are becoming essential structural materials in numerous engineering applications where high specific strength and specific stiffness are required.
2. Also, it is seen from the literature another procedure to enhance the mechanical properties of fiber reinforced polymer composites is the addition of low weight content of nanoparticles like nanoclay into the matrix of composites.

3. To the best of found knowledge, researchers in literature did not inspect the effect of nano-clay content on flexural and tensile properties of hybrid/epoxy composite**.**

4. In this work, tensile and flexural, properties of glass and hybrid composite were examined with the incorporation of nano-clay particles.

CHAPTER 3

EXPERIMENTAL STUDIES

3.1 Introduction

This chapter deals with the definitions of materials, equipments used in preparation of laminates, and experimental procedure of tensile and flexural tests. Some common informations about the constituents of the prepared composites like glass fiber, Kevlar fiber, epoxy resin system, nanoclay are revealed and the fabrication technique, hand layup technique, is shortly described.

3.2 Materials

3.2.1 Glass Fiber

Glass is an amorphous material, with virtually no crystalline structure, mainly composed by silicon oxides and other metallic oxides that, according to the proportion in which they are present, these give to the glass a few certain characteristics. In a general way, fiberglass presents good tensile and impact resistance, galvanic or chemical corrosion resistance, lower cost than other composite materials and electrical characteristics [70]. The glass fiber used in this thesis was supplied by DOST Chemical Industrial Raw Materials Industry, Turkey. It is a plain weave E-glass fabric (03G200.080) with an areal density of (200 g/m2). Figure 3.1 shows glass fiber.

Figure 3.1 Fiber glass

3.2.2 Kevlar (aramid)

Kevlar is DuPont’s name for aramid fibers. Kevlar fibers have a high resistance to impact damage, they are strong, light weight and tough, offering the best characteristics in damage tolerance of all fibers available. However, Kevlar fibers present some disadvantages like susceptibility to degradation by UV radiation and huge absorption of moisture which means weight increment of the order of 7-8%. [70]. Twill aramid fabric (03A173K) with an areal density of (173 g/m^2) supplied by DOST Chemical Industrial Raw Materials Industry, Turkey is used in this thesis. The Kevlar fabric used in this study is shown in Figure 3.2.

Figure 3.2 Twill Kevlar fabric

3.2.3 Matrix Material

In composite materials, the constituent, which is continuous and introduce in big quantity is named matrix. The main functions of the matrix are to hold or bind the fiber with each other, distribute the load evenly between the fibers and protect the fiber from the environmental and mechanical damage. The matrix material can be polymeric, metallic or can even be ceramic. The more usually used matrix material is polymer. It has benefits such lower cost, best chemical and corrosion resistance, lower specific gravity, easy process ability, top specific characteristics, manufacturing, chemical stability and flexibility [71, 72].

Epoxies are polymerizable thermosetting resins being available from liquid to solid. Their characteristics depend on the basic resin, the curing agent, the added modifiers and the polymerization conditions. [70]

The main reasons that make epoxy the most used polymer matrix material are:

- Higher strength
- Lower viscosity and lower flow rates, which allow better wetting of fibers and avoid misalignment of fibers during processing
- Lower volatility during cure

- Lower shrink rates, which decrease the tendency of gaining huge shear stresses of the bond between epoxy and its reinforcement
- Available in more than 20 grades to meet specific property and processing requirements. [73].

Figure 3.3 shows the epoxy used to produce composite laminates in this study and Table 3.1 presents the properties of epoxy.

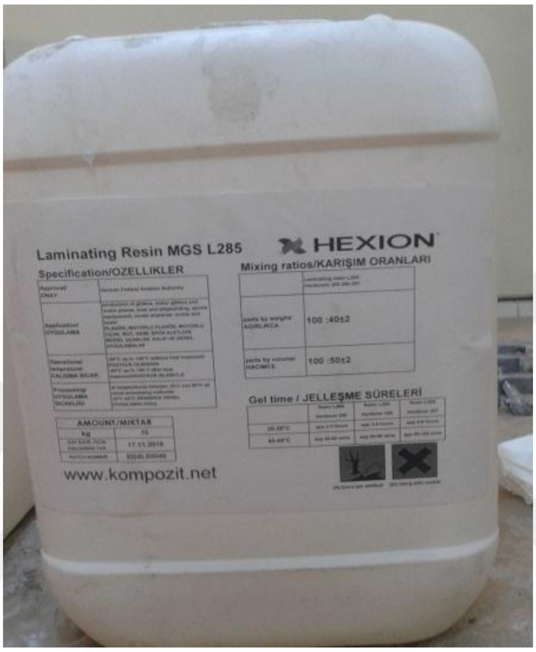


Figure 3.3 Epoxy

Table 3.1 Characteristics of Typical Epoxy

Properties	Resin (MGS L285) specification
Density (g/cm³)	1.18 – 1.23
Viscosity (mPas)	600 – 900
Epoxy equivalent (gr/equivalent)	155 –170
Epoxy value (eq /100gr)	0.59 – 0.65
Refractory index	1.525 –1.530

The second component of resin is a curing agent called hardener. Hardener is a substance blend with paint or other protective covering to make the finish harder or more stable. Figure 3.4 shows hardener Hexion MGS H285 and Table 3.2 presents the properties of hardener.

Figure 3.4 Hardener

Table 3.2 Hardener characteristics

Properties	**Hardener (H285) specification**
Density (gr/ cm^3)	0.94 –0,97
Viscosity (mPas)	50 – 100
Amine Value (mgr KOH/gr)	480 –550
Refractory index	1.5020 – 1.5500

3.2.4 Nanoclay

Nanoclay is one of the widely used nano fillers for composites. Clay minerals appear in varied structural forms but most usually, usage grades in nanocomposite product belong to the family of layered aluminium silicates. They consist of silicate platelets where SiO_4 tetrahedrons and AlO_6 octahedrons are organized in varied combinations. [74]. Nano-clay has received much attention as strengthening materials for polymer because of its potentially high aspect ratio and unique intercalation properties. The small quantity of nano-clay addition into polymer matrix displays unexpected properties included decreasing gas permeability, enhanced solvent resistance, being superior in thermal stability and mechanical characteristics, and improve flame retardant characteristics [60]. Figure 3.5 shows nano-clay sample that used this study.

Table 3.3 The physical characteristics of nano-clay

Constituent	**Density** (kg/m3**)**	**Thickness** (nm)
Nano-clay	200 – 500	1 – 10

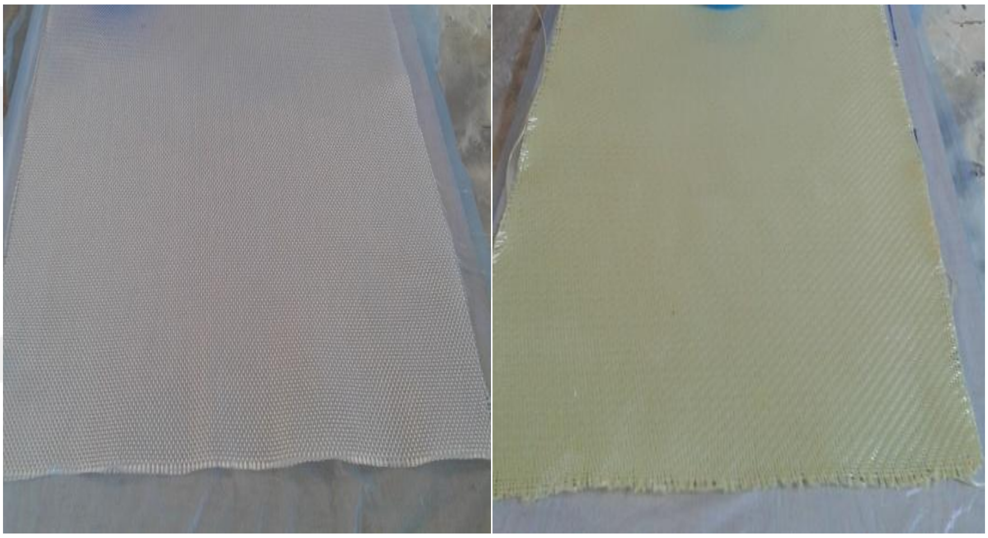
Figure 3.5 Nano-clay

3.2.5 Composite materials

In this research, various composite materials like fiber glass reinforced composite laminates, nano-clay modified glass fiber reinforced composite laminates, and nano-clay filled glass/aramid hybrid fiber reinforced composite laminates are fabricated by using varied combinations of glass fiber, aramid fiber, nano-clay particle.

3.2.6 Laminate

A lamina (also named a ply or layer) is a single flat layer of unidirectional fibers or woven fibers arranged in a matrix [73]. The Figure 3.6 shows glass fabric and aramid fabric reinforcements.



(a) **(b)**

Figure 3.6 (a) Glass fabric (b) Kevlar fabric

While the laminate consists of stack of fabric layers. Each layer can be laid at varied orientations and can be made up of varied material systems [73]. Figure 3.7 shows the laminated composite that are fabricated in this study.

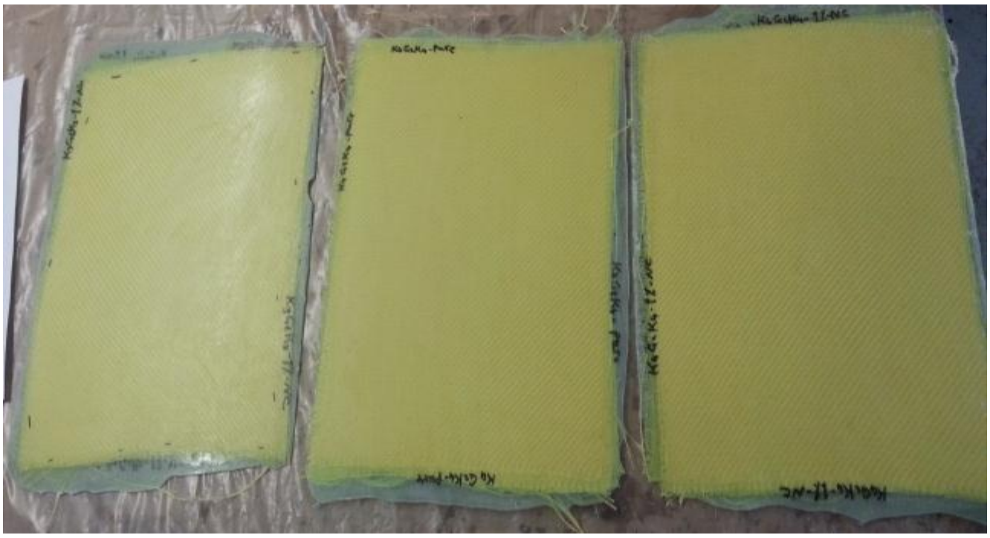
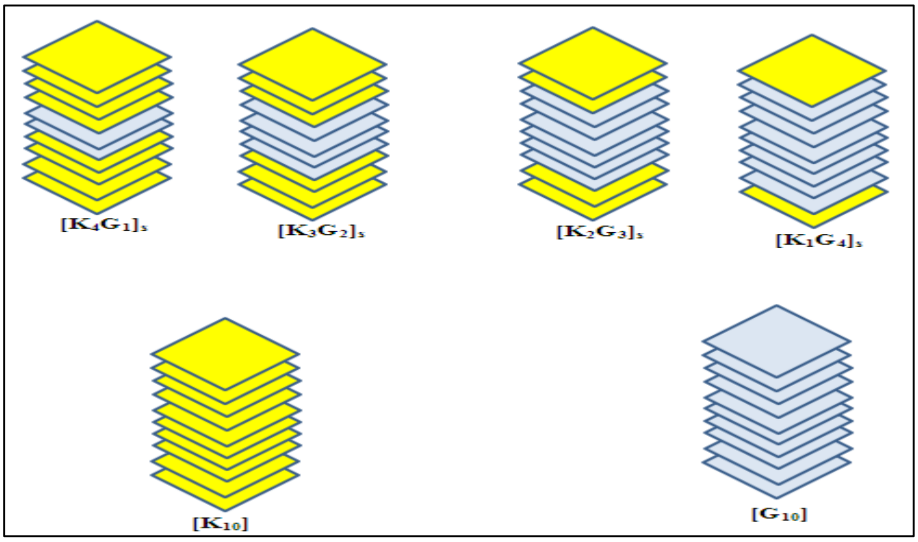


Figure 3.7 Various laminates

3.2.7 Hybrid composites

The hybrid fiber reinforced composites were fabricated by stacking glass fabrics and aramid fabrics with various arrangements. It is well-known that the characteristics of hybrid fiber reinforced laminates depend on fiber orientation, individual fiber content and fiber length [75]. In this research, plain woven glass fabric and twill aramid fabric were used as the fiber reinforcement as shown in Figure 3.8.

(a)



(b)

Figure 8. (a) Hybrid composites (b) Varied stacking sequences of Kevlar (K) and glass (G) fiber plies

3.2.8 Preparation of Nonoclay/Epoxy Mixture

Nano-clay, epoxy and hardener were mixed in a plastic cup. Firstly nano-clay was mixed with epoxy well by a mechanical stirrer with a constant speed (750 rpm). This process takes about 15-20 minutes. Then the hardener is added to nano-clay and epoxy mixture and mixed well to get homogenous mixture it takes about 1-3 minutes. Figure 3.9 shows mixing process of epoxy resin and nano-clay.

Figure 3.9 Mixing process of epoxy resin and nano-clay

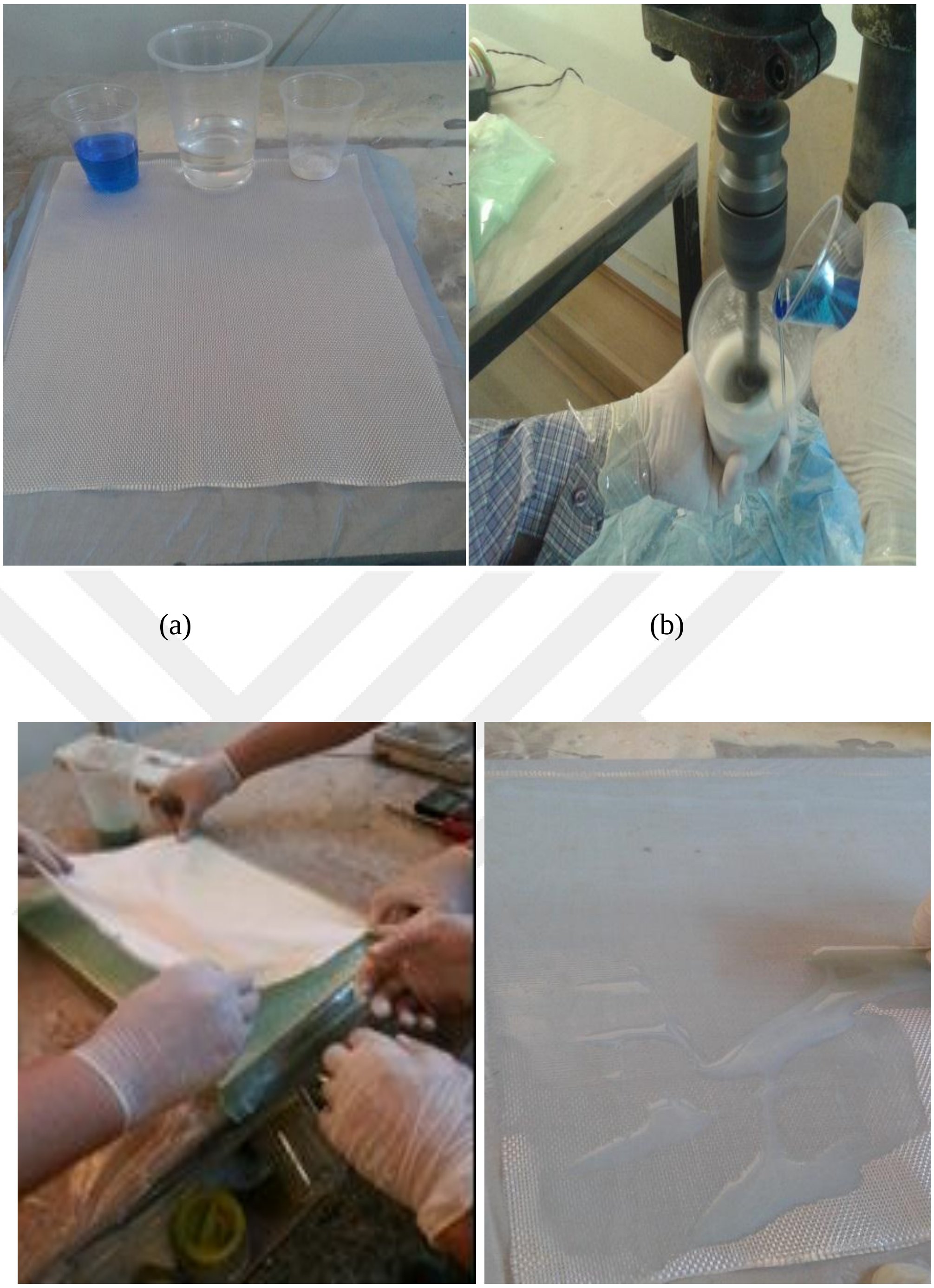
3.3 Fabrication of Composite Laminates (Hand Lay-up Technique)

Fabrics were cut into 270 mm × 300 mm by using electric cutter as shown in Figure 3.10. The required amount of epoxy, hardener and nanoclay are weighted and are mixed together. Composite laminates were prepared by hand lay-up process. The first layer of woven fabric was laid and resin was spread uniformly over the cloth by means of brush, the same process was repeated for the other layers.

(a) (b)

Figure. 3.10 Cutting fibers by electric cutter (a) E-glass (b) Kevlar

After second layer, to improve impregnation and wetting, a teethed steel roller was used to roll over the fabric before applying resin as shown in Figure 3.11. Also, resin was tapped and dabbed with spatula before pervasion it over fabric layer. This procedure was repeated till all 10 layers were stacked. After applying resin, the laminates have been placed in the hot press as shown in Figure 3.12.



(a) (b)

(c) (d)

Figure 3.11 Fabrication of Composite Laminates (Hand Lay-up Technique)

Figure 3.12 Hot press. (1) Combination of heat pressure and vacuum (2) Hydraulic unit (3) Vacuum pump

The wetted fiber reinforcement was cured in the production unit for 1 hour at a temperature and pressure of 80 °C and 0.4 MPa, respectively. Then, the composite laminates were cooled to room temperature under pressure for three hours at least. Finally, the product laminate was removed from the mold to get a fine finished composite plate as shown Figure 3.13. This process was repeated to prepare all of the hybrid laminates. The examples of fabricated [G_{12}] laminates with various nanoclay content were shown in Figure 3.14.

Figure 3.13 Production unit

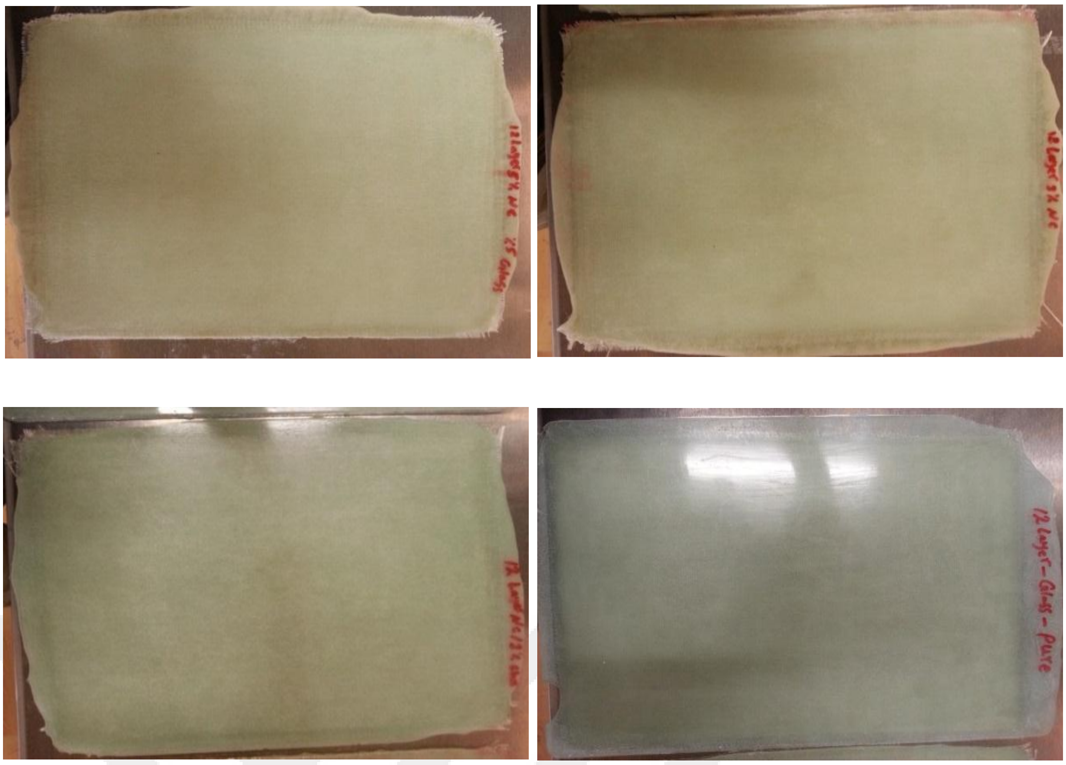


Figure 3.14 Composite laminates consisted of (12) layers of glass fiber

In a similar manner, some examples of fabricated glass/Kevlar hybrid fiber reinforced composite laminates with various nanoclay content and stacking sequences were presented in Figure 3.15.

Figure 3.15 Various arrangement of hybrid composite laminates

3.4 CNC machine

A 3-axis CNC router device was used for cutting plates and getting the required specimens used in tensile and flexural tests. The dimensions of the produced specimens were prepared according ASTM standards. CNC router and cutting specimens are shown in the Figure 3.16.

Figure 3.16 Cutting the specimens

3.5 Determination of the Mechanical Properties

In this section, uniaxial tensile and flexural tests were performed to determine mechanical characteristics. Five specimens were used for the test each laminate configuration and averages were presented. The main determined properties of laminated composite plates are flexural strength (σ_f), tensile strength (σ_t) and flexural modulus (E_f). These mechanical characteristics were determined according to the American Society for Testing and Materials (ASTM) standards.

3.5.1 Determination of Tensile Properties

Tensile characteristics of samples were determined according to the ASTM D638-10 standard test procedure [76] for 10 layered glass, Kevlar and glass/Kevlar hybrid laminates, and ASTM-D3039 standard test procedure [77] for 12 layered glass laminate. Suitable dimensions for this standard are given in the Figure 3.17 and Figure 3.18 considering specimen dimensions as:

- $width\ of\ narrow\ section\ (W)\ =\ 13\ mm,$
- $overall\ width\ (Wo)\ =\ 19\ mm$
- $overall\ length\ (Lo)\ =\ 165\ mm$
- $gage\ length\ (G)\ =\ 50\ mm$
- $distance\ between\ grips\ (L)\ =\ 115\ mm$
- $radius\ of\ fillet\ (R)\ =\ 76\ mm.$

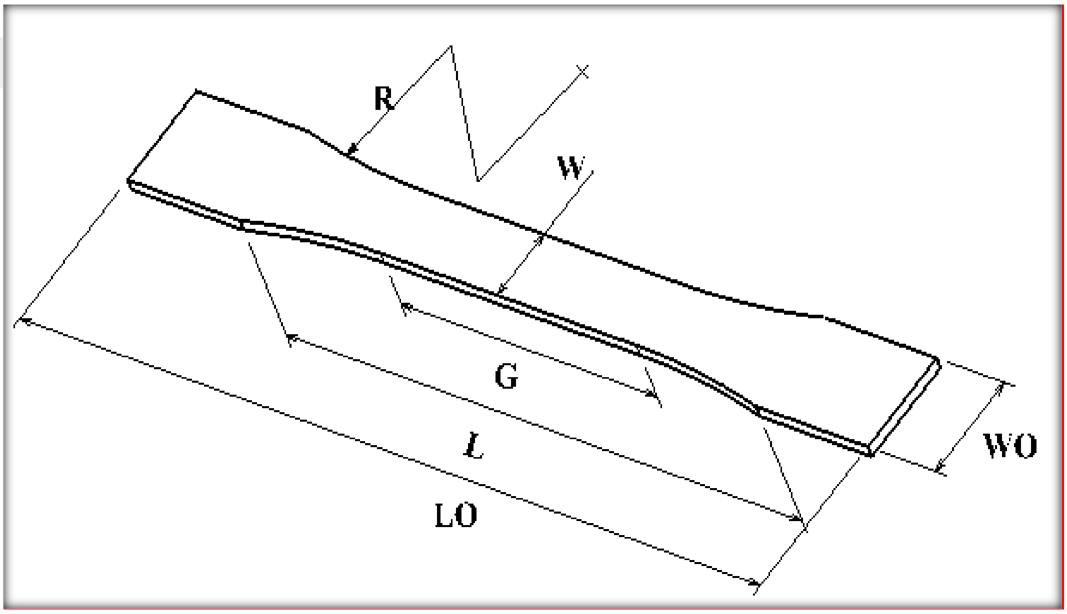


Figure 3.17 The dimensions of tensile specimens according to ASTM 638-10

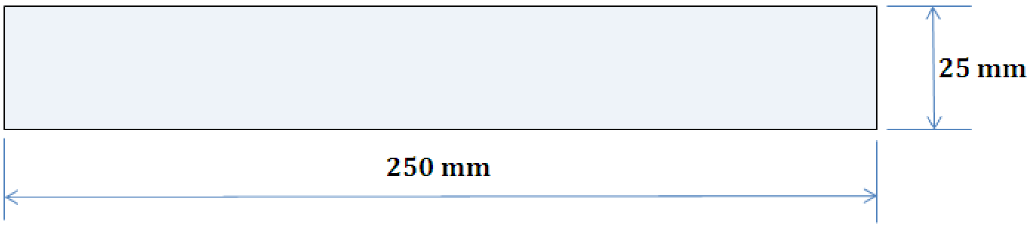


Figure 3.18 The dimensions of tensile samples according to ASTM-D 3039

Tests were conducted at standard humidity and room temperature conditions. Mechanical characteristics of samples were gained using a 300 kN Shimadzu AG-X series universal testing machine shown in Figure 3.19. To determine tension characteristics, samples were loaded in tension direction with the 2 mm/min cross head speed up to failure. Then tensile strength, (σ_t), were determined using the stress and strain data's gained from the testing machine [78]. Produced tensile test samples are shown in Figure 3.20.

Figure 3.19 Test set-up Shimadzu AG-X series testing machine (tensile test)

Figure 3.20 Samples of tensile test specimens

3.5.2 Determination of Flexural Properties

Three-point bending test can be defined as the deformation occurring in the sample when force is applied in the middle of a test sample which is rectangular cross-section that placed freely on the two supports. The flexural strength represents the higher stress experienced within the material at its moment of rupture. It is measured in terms of stress. The main purpose of the bending test is to determine the ability to endure the cold state cracking of the material. The specimens were prepared using span-to-depth ratio as 32:1 [78,79].

Flexural characteristics of samples were determined according to ASTM D790-00 standard test procedure. A suitable samples of rectangular cross section (L=200mm, w=12.7 mm and t=thickness of the laminate) rests on two supports and was loaded by means of a loading nose middle between the supports shown in Figure 3.21.

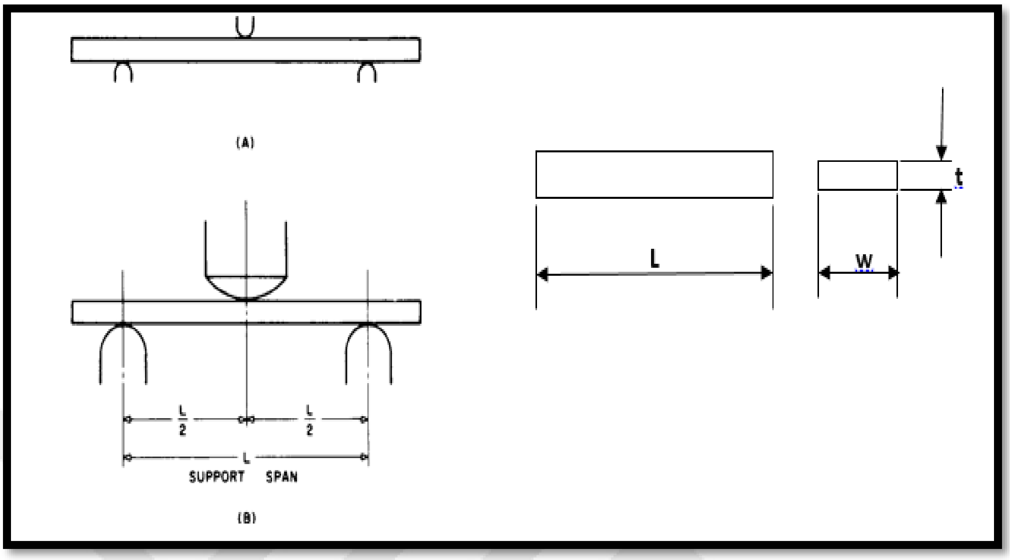


Figure 3.21 The dimensions of flexural specimens according to ASTM D 790-00

The flexural strength and modulus of the samples were evaluated using the following equations.

$$\sigma_f = \frac{3PL}{2bd^2} \tag{1}$$

$$E_f = \frac{L^3 m}{4bd^3} \tag{2}$$

where:

σ_f = flexural strength, MPa,

E_f = modulus of elasticity in bending, MPa,

P = load at a given point on the load-deflection curve, N,
L = support span, mm,

b = width of beam tested, mm,

d = depth of beam tested, mm,

m = slope of the tangent to initial straight-line portion of load-deflection curve

Because the loading nose is wider than the test specimen's width, the center load is uniformly distributed along the width of the samples, and the load is unidirectional [80].

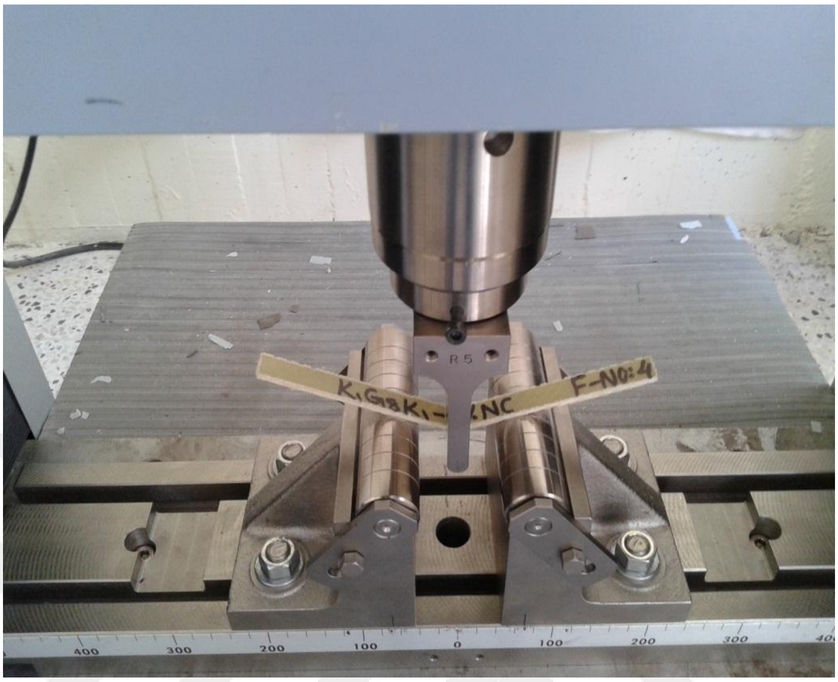


Figure 3.22 Test set-up Shimadzu AG-X series testing machine (flexural test)

Figure 3.23 samples of flexural test specimens

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Introduction

This chapter presents the results obtained from the uniaxial tensile and three-point bending tests of prepared composites.

4.2 Tensile Test Results of Glass/Epoxy with Nano-clay Composite Laminates [G_{12}]

The tensile strengths of the prepared composite samples were determined by conducting uniaxial tensile test. The test specimen had been prepared according to ASTM-D-3039 standard. The variation of tensile strength values against nano-clay contents is presented in Figure 4.1.

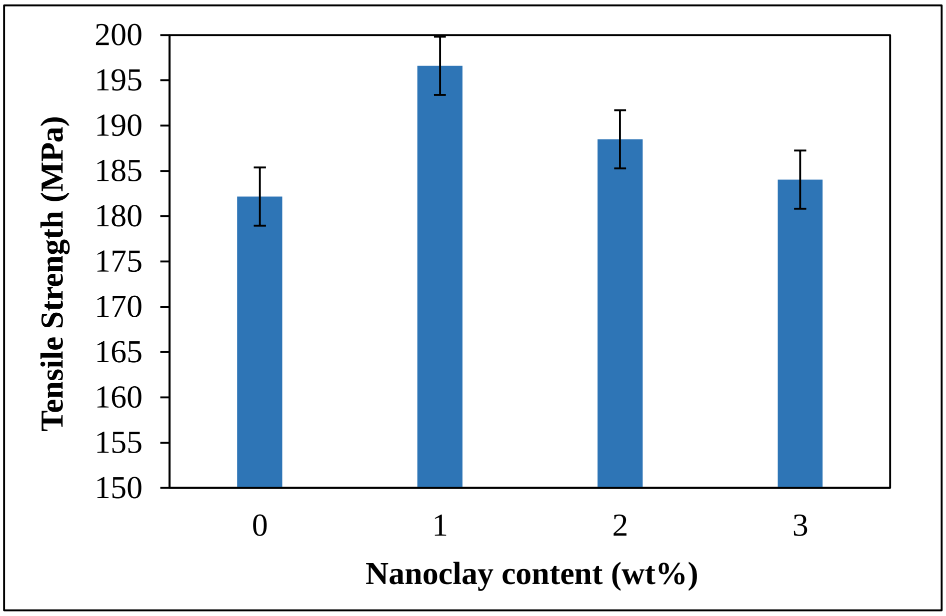


Figure 4.1. Variation of tensile strength for [G_{12}] laminates according to nano-clay contents

Compared to tensile strength of neat (without nano-clay content) [G_{12}] composite laminate, the increase in tensile strength were 8%, 4% and 1% for 1 wt.%, 2 wt.% and 3 wt.% nano-clay filled ones, respectively. As it can be shown in Figure 4.1, the enhancement of tensile strength at lower nano-clay contents was more significant and at 1 wt.% clay content yielded the highest tensile strength. At higher content, the introduction of nano-clay was not so effective in enhancement of tensile strength. Probably, it can be attributed to the agglomeration of nano-clay particles which resulted with poor adhesion.

Tensile modulus of nano-clay filled [G_{12}] were plotted against nano-clay contents as shown in Figure 4.2. Nano-clay modifed composites showed higher tensile modulus compared to the composites without nano-clay content. The addition 1 wt.%, 2 wt.% of nano-clay into glass fiber reinforced epoxy composites resulted an increase in tensile modulus from 15.79 GPa to 17.14 GPa and 18.80 GPa, respectively. The introduction of nano-clay was so effective in enhancement of tensile modulus. While the addition of 3 wt.% of nano-clay showed a decrease in tensile modulus from 15.79 GPa to 14.80 GPa. The declines in tensile modulus with addition of nano-clay can be seemed as a result of agglomeration or poor dispersion. The agglomeration or poor dispersion caused weak bonding between epoxy and clay particles.

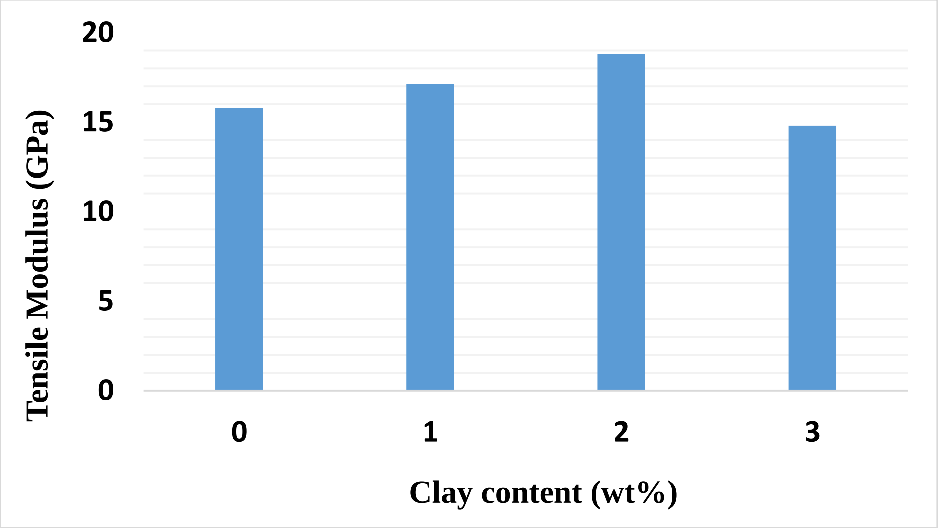


Figure 4.2 Variation of tensile modulus for [G_{12}] laminates according to nano-clay contents

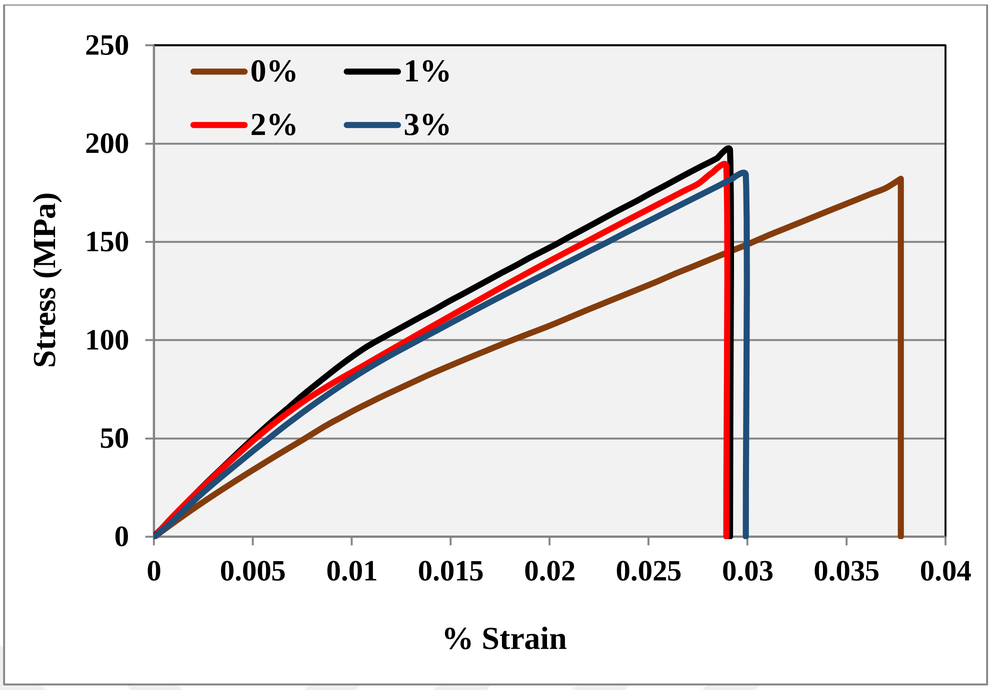


Figure 4.3 Tensile stress–strain curves for G12.

From Figure 4.3, the neat [G_{12}] specimens have higher strains and less strength than the nanoclay filled ones. The laminates with 1 wt.% nanoclay inclusion have the highest tensile strength. The laminates with 1 wt.% and 2 wt.% nanoclay content have nearly the same rupture strain which are less than the rupture strain of neat [G_{12}] laminates. The variation in tensile strength and strain can be attributed to change in the toughness characteristics of the specimens.

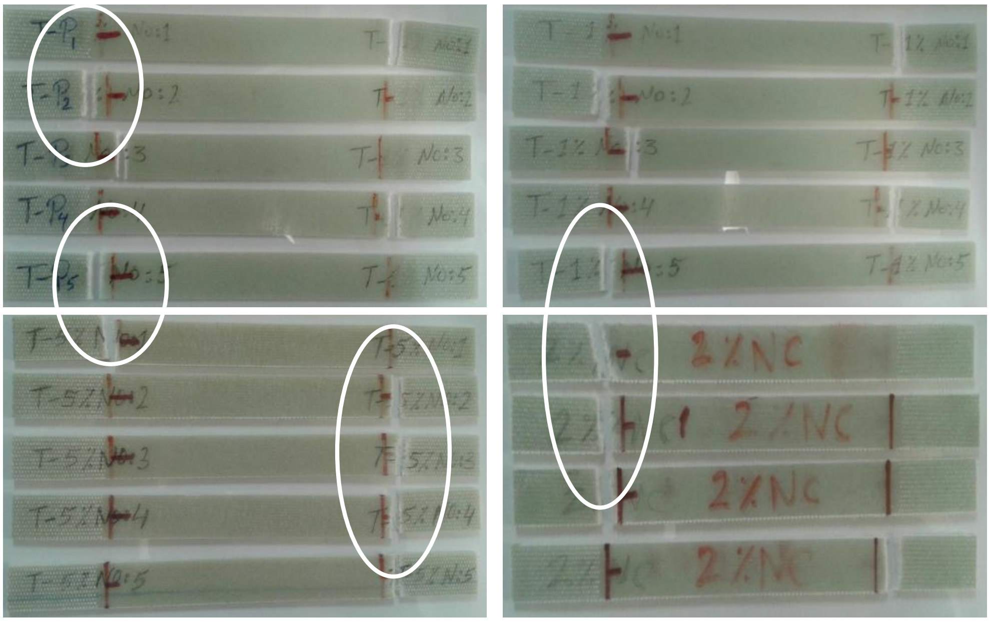


Fig 4.4 Specimens after tensile test

All the specimens showed the failure characteristics as shown in Figure 4.4. The matrix cracking and fiber breakages are source of failures. It is shown that there is no fiber pull-out found on failed specimens.

4.3 Flexural Test Results (12 Layers Glass Fiber) with Nano-clay

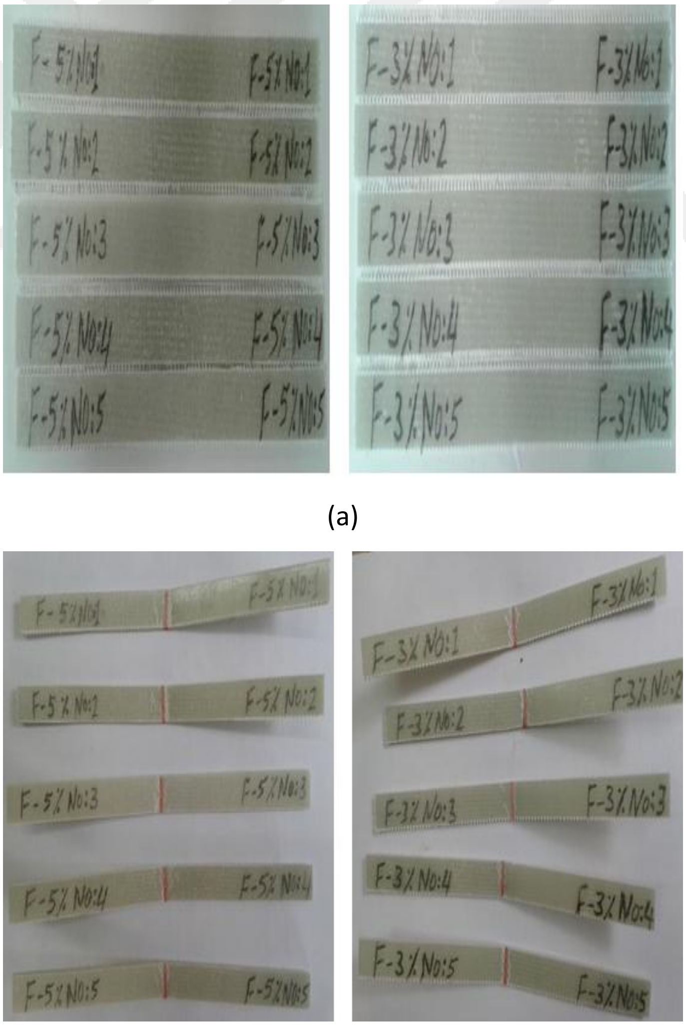
Flexural strength and modulus values are recorded in Table 4.1 and 4.2, respectively. As seen in tables, all nano-clay modified composite samples showed lower flexural strength and modulus compared to the composites without nano-clay inclusion. The addition of nano-clay into glass fiber reinforced epoxy composites resulted with decreases in both flexural strength and modulus from 327 MPa to 280 MPa and 15 GPa to 13 GPa, respectively. The declines in modulus and flexural strength with addition of nano-clay can be explained considering the characteristics of bending. It is well known that one of neutral axis shows tensile and other shows compression behavior during the bending. The decreases can be attributed to poor response of nano-clay to compression and shear formed during bending. Also, the presence of multiple micro-sized voids due to excess stretching fibers can be considered as a source of decreases. The increase in the rate of decline with respect to increase in nano-clay content can be attributed to agglomeration of nano-clay particles [81]. To follow the deformation characteristics of the laminates, the specimens before and after the flexural tests are presented in Figure 4.5.

Table. 4.1. Values of flexural strength according to nano-clay content for G_{12}

Flexural Strength (MPa)				
Nanoclay content (wt.%)				
Specimen	0	1	2	3
1	304.2	278.61	286.75	283.09
2	324.88	277.21	285.65	281.09
3	337.17	295.3	280.54	276.4
4	339.27	295.1	281.47	278.1
5	328.88	290.09	283.69	282.22
Average	326.88	287.262	283.62	280.18

Table.4.2. Values of flexural modulus according to nano-clay content for G_{12}

Flexural Modulus (GPa)				
Nanoclay %				
Specimen	0	1	2	3
1	15.3	11.5	13.75	12.65
2	14.8	13.5	13.86	12.4
3	15.28	11.7	14.5	11.55
4	14.92	13.27	14.76	12.94
5	15.2	12.28	14.58	13.4
AV	15.1	12.45	14.29	12.59



(a)

(b)

Figure 4.5 (a) Specimens before flexural tests (b) Specimens after flexural tests

4.4 Tensile Test Results (10 Layers Glass, Kevlar and Hybrid) with Nanoclay

The tensile strengths of the prepared G_{10}, K_{10} and glass/Kevlar hybrid composite samples were determined by conducting uniaxial tensile test. The results of the tests were illustrated in the Table 4.3. The averages of five specimens for each composite configurations were presented in the table. The variations of tensile strengths and modulus for G_{10}, K_{10}, and glass/Kevlar hybrid laminates with 0 wt.% and 1 wt.% nancolay content were illustrated in Figure 4.6 and Figure 4.7, respectively. $[K_3G_2]_S$ hybrid configuration with pure epoxy has the highest tensile strength and modulus. However, $[K_1G_4]_S$ hybrid configuration has the highest tensile strength with 1 wt.% nanoclay addition. Also, it is noticed that the highest improvement in tensile strength was recorded for $[K_4G_1]_S$ arrangement with 1 wt.% nanoclay inclusion. The introduction of nano-clay was so effective in enhancement of tensile strength. Compared to pure ones, the variations in tensile strengths with 1 wt.% nanoclay inclusions are 4.09%, 6.75%, -23.94%, 2.13%, 10.15% and 5.87% for G_{10}, $[K_1G_4]_S$, $[K_2G_3]_S$, $[K_3G_2]_S$, $[K_4G_1]_S$, and K_{10}, respectively. The pictorial view of failed specimens are presented in Figure 4.8.

Table 4.3 Tensile strength values of G_{10}, K_{10} and glass/Kevlar hybrid composites

Specimens	**Pure (MPa)**	**1% Nanoclay (MPa)**	**Percentage increase, according neat laminates**
G_{10}	257.63	268.17	4.09
$[K_1G_4]_S$	316.82	327.56	6.746
$[K_2G_3]_S$	377.28	286.95	-23.94
$[K_3G_2]_S$	392.63	400.98	2.13
$[K_4G_1]_S$	375.42	413.55	10.15
K_{10}	453.78	393.60	5.87

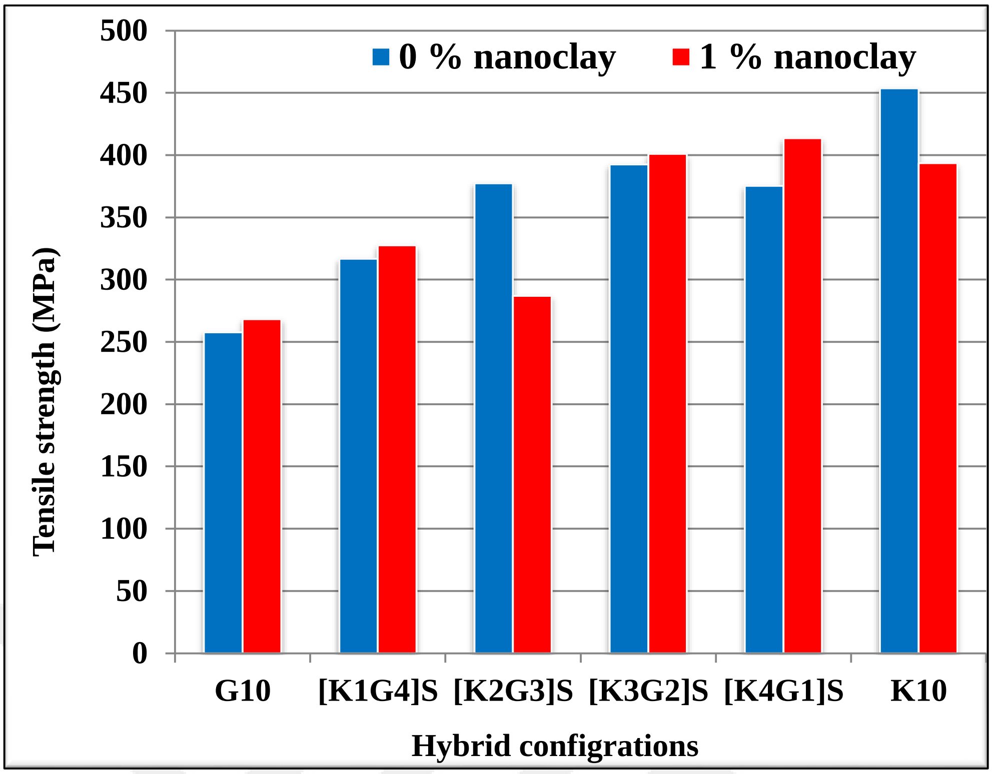


Figure 4.6 Variation of tensile strength according to hybrid arrangements

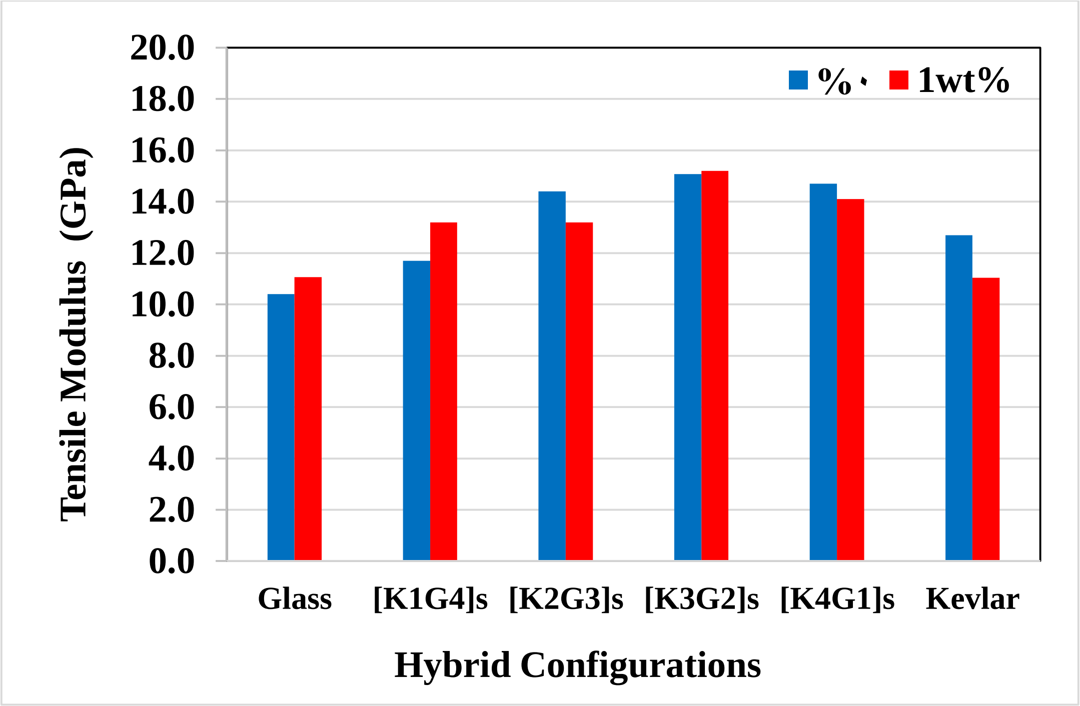


Figure 4.7 Variation of tensile modulus according to hybrid arrangements.

Fig 4.8 Specimens after tensile test

4.5 Flexural Test Results (10 Layers Glass, Kevlar And Hybrid) with Nano-clay Flexural Results:

The results of flexural tests for G_{10}, K_{10} and glass/Kevlar hybrid composites were presented in Table 4.2. The variation of flexural strength and modulus for G_{10}, K_{10} and glass/Kevlar hybrid composites were illustrated in Figure 4.9 and Figure 4.10, respectively. For the pure laminate samples, $[K_3G_2]_S$ laminate has the highest flexural strength and $[K_2G_3]_S$ has the highest flexural modulus. After the inclusion of 1 wt.% nanoclay, the highest flexural strength was recorded for $[K_2G_3]_S$ laminate sample and highest flexural was recorded for $[K_1G_4]_S$ laminate sample. The declines in flexural strength and modulus with the addition of nano-clay can be seemed as a result of weak bonding between nano-clay and epoxy, poor dispersion of nanoclay particles, the presence of multiple micro-sized voids due to excess stretching fibers and poor response of nanoclay modified epoxy to compression. The pictorial view of failed specimens are presented in Figure 4.11.

Table 4.4 Flexural strength values of hybridization of glass fibers with Kevlar fibers by adding1 wt.% of nano-clay

Specimens	**Pure (MPa)**	**1% Nanoclay (MPa)**	**Percentage increase, according neat laminates**
G_{10}	212.75	190.36	-10.45
$[K_1G_4]_S$	220.9	232.74	5.36
$[K_2G_3]_S$	227.60	250.77	10.18
$[K_3G_2]_S$	234.57	190.74	-18.69
$[K_4G_1]_S$	210.64	212.22	0.75
K_{10}	204.12	185.49	-9.13

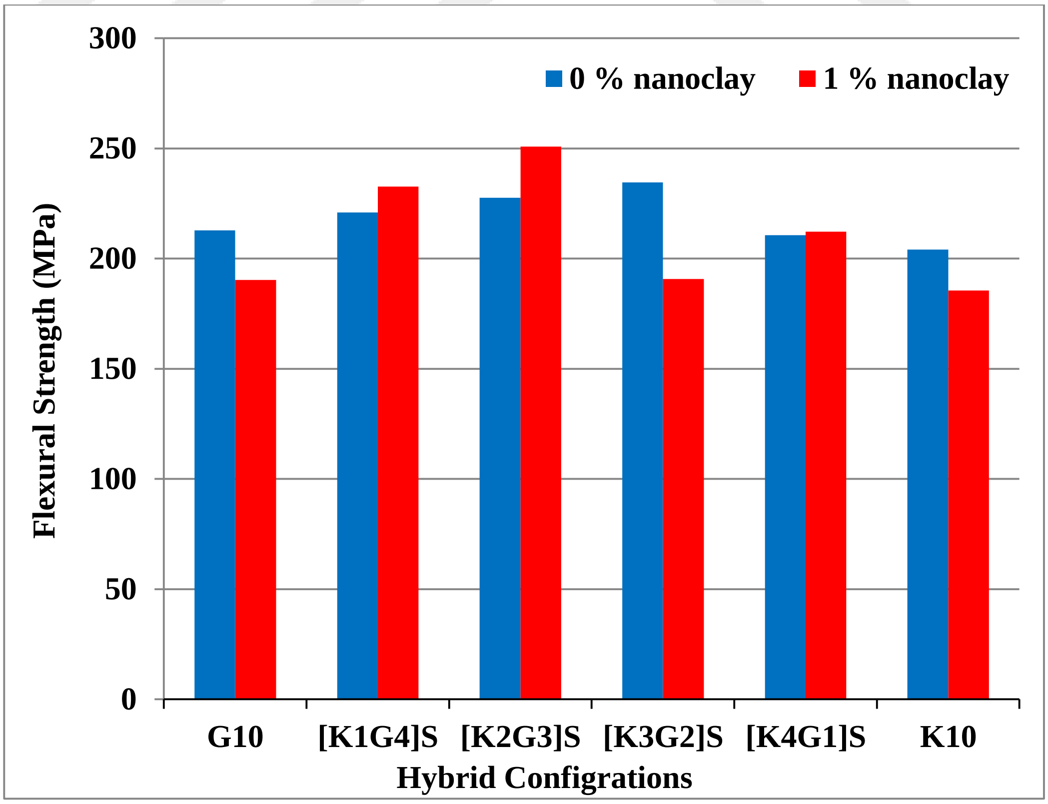


Figure 4.9 Variation of flexural strength according to hybrid arrangements

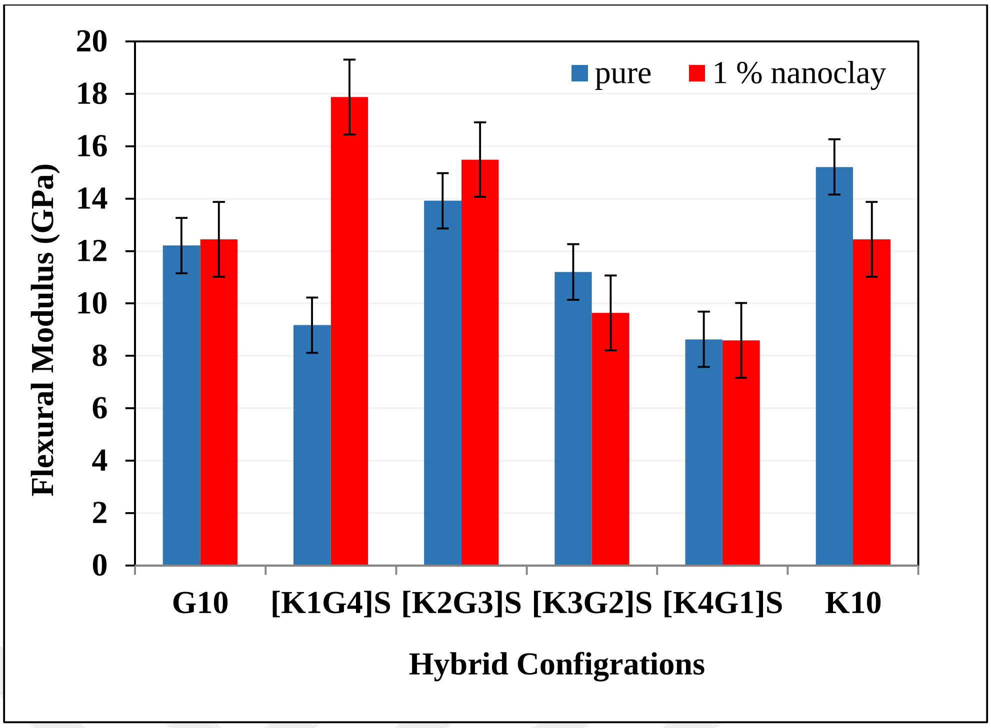
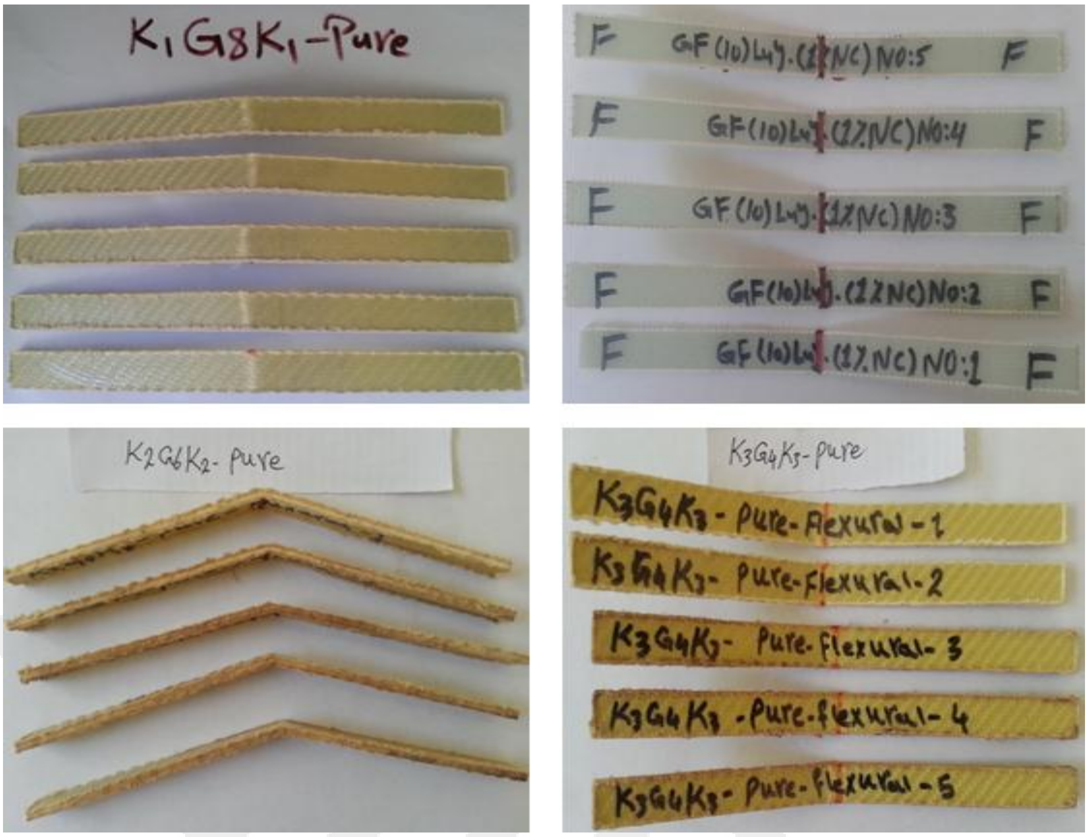


Figure 4.10 Variation of flexural modulus according to hybrid arrangements

(a)



(b)

Figure 4.11 (a) Specimens before flexural test, (b) failed specimens during flexural tests

4.6 Tensile Test Results 10 Layers Hybrid Glass and Kevlar $[K_1G_4]_S$ with Nanoclay

The tensile test results of nanoclay modified $[K_1G_4]_S$ hybrid composite laminate arrangement were presented in Table 4.5. The variation of tensile load according to nano-clay content for $[K_1G_4]$ hybrid laminate is presented in Figure 4.12

Table 4.5 Tensile strength average of hybridization of glass fibers with Kevlar fibers for $[K_1G_4]_S$ arrangement by adding varied rates of nano-clay.

Nanoclay (wt.%)	**0.00**	**0.50**	**1.00**	**2.00**	**3.00**	**5.00**
Average (MPa)	316.83	326.93	327.56	338.2	327.74	326.53
Increase (%)	0	3.18	3.39	**6.74**	3.44	3.06

The results of the tensile tests showed that there is an enhancement for tensile strength by the addition of nano-clay, and the percentage increments were determined as 3.18, 3.39, 6.74, 3.44, 3.06, for 0 wt.%, 0.50 wt.%, 1 wt.%, 2 wt.%, 3 wt.%, 5 wt.% respectively. From Figure 4.13, it was noticed that the highest value of tensile strengths was recorded for 2 wt.% nano-clay inclusion. This indicated that the chemical compatibility and adhesion strength between nano-clay particles and epoxy/glass-Kevlar fibers was optimum at this content. While tensile strength decreased with 3 wt.% and 5 wt.% nano-clay as compared with 2 wt.% nano-clay content. It can be attributed to beginning of nanoclay agglomeration and formation of stress concentration which are resulted with crack initiation and weak bonding [83].

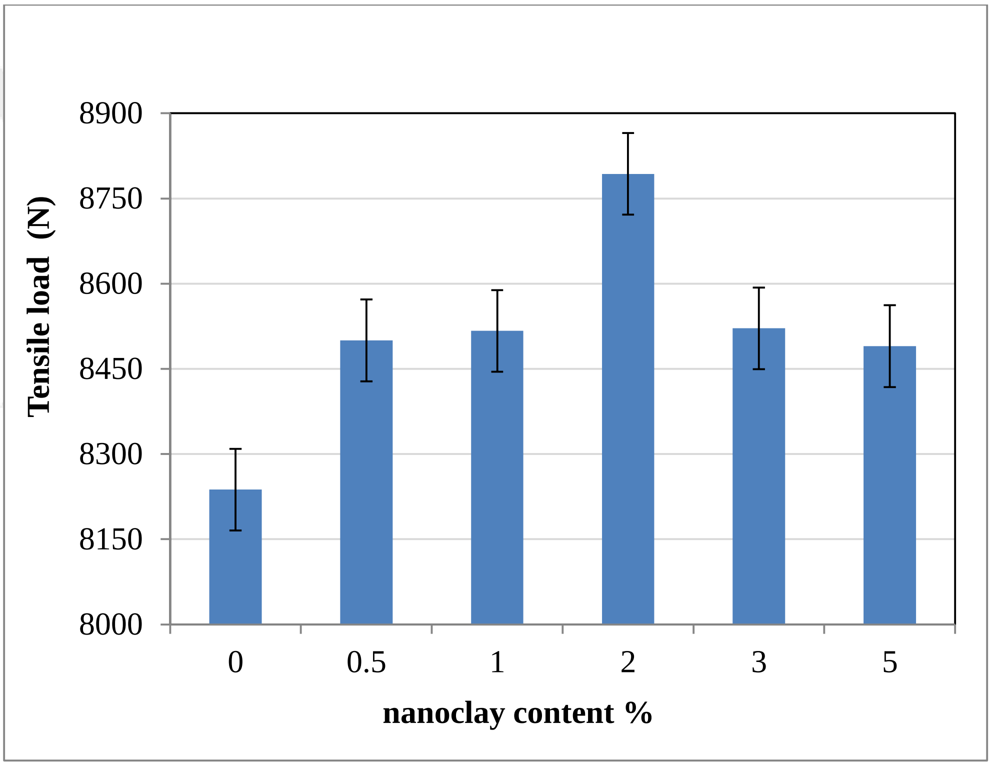


Figure 4.12 Variation of tensile load according to nano-clay content for $[K_1G_4]_S$

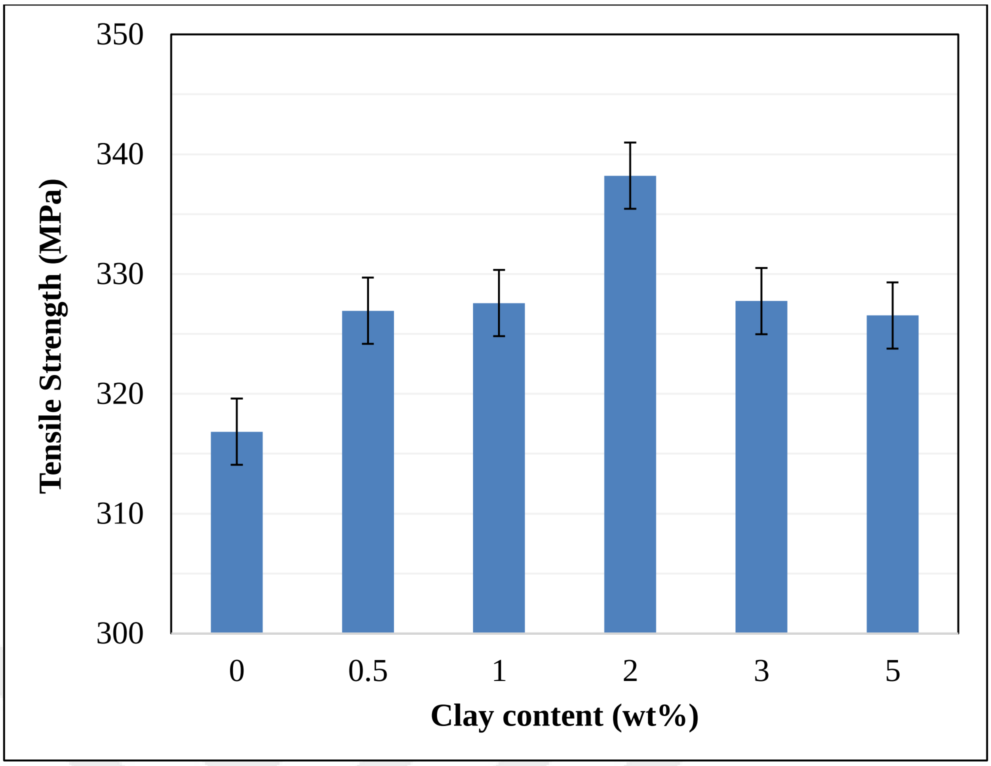


Figure 4.13 Variation of tensile strength according to nano-clay content for $[K_1G_4]_S$

Figure 4.14 Specimens after tensile test

The pictorial view of failed specimens are presented in Figure 4.14. It is shown that the fiber pull-out for 2 wt.% nanoclay content is less than pure specimen. It can be attributed to the interfacial adhesion between nanoclay and matrix. In addition, the laminates showed fiber pull-out, fiber breakage and matrix cracks at the same time for 5 wt.% nanoclay inclusion. It can be explained with the agglomeration of nanoclay [81].

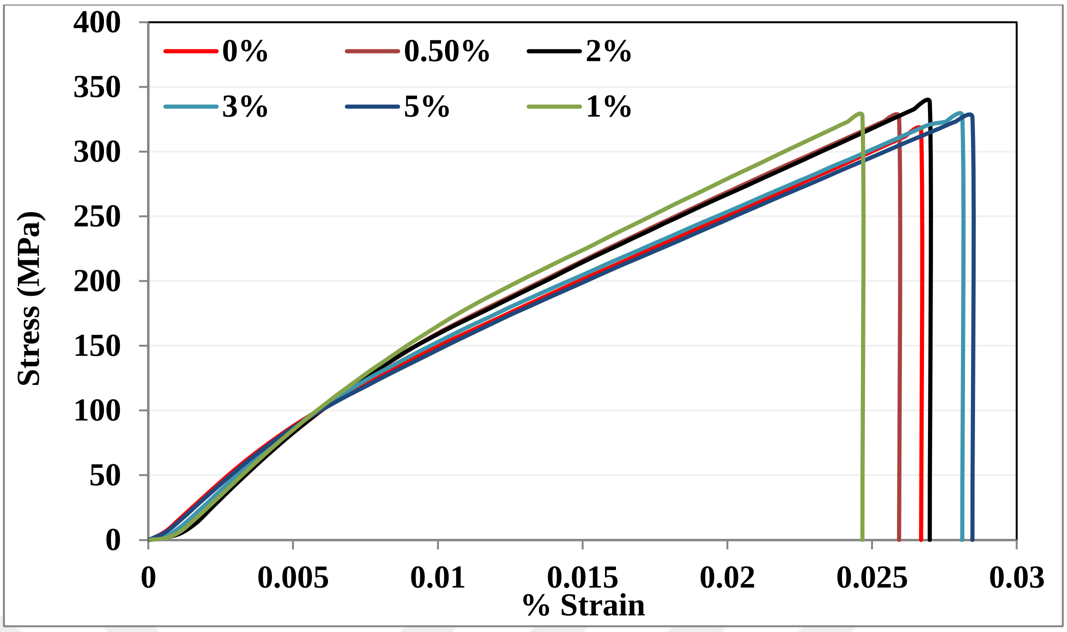


Figure 4. 15 Tensile stress–strain curves for $[K_1G_4]_s$

The stress-strain diagrams for $[K_1G_4]_S$ laminate with 0 wt.%, 0.5 wt.%, 1 wt.%, 2 wt.%, 3 wt.% and 5 wt.% nanoclay inclusion are presented in Figure 4.15. It was shown that the highest tensile strength was recorded for 2 wt.% nanoclay inclusion. Up to 2 wt.%, nanoclay addition make the laminates stiffer [84.

4.7 Flexural Test Results (10 Layers Hybrid Glass and Kevlar $[K_1G_4]_S$ with Nanoclay

The flexural strength values against nanoclay content for $[K_1G_4]_S$ arrangement were presented in Table 4.6. The results showed that the highest increase on flexural strength was obtained as 14.52% for 1 wt.% nano-clay addition. From Figure 4.16, it was shown that 0.5 wt.%, 2 wt.%, 3 wt.% and 5 wt.% nanoclay added laminates showed reductions on flexural strength compared to 0 wt.% nanoclay inclusion of same arrangement. Probably, it can be attributed to poor response of nanoclay modified epoxy to compression, debonding of nano-clay and epoxy, poor dispersion and the presence of multiple micro-sized voids due to excess stretching fibers. The relationship between flexural modulus and nano-clay content for $[K_1G_4]_S$ shown in Figure 4.17. The specimens before and after flexural tests are shown in Figure 4.18

Table 4.6. Flexural strength values of hybridization of glass fibers with Kevlar fibers for $[K_1G_4]_S$ arrangement by adding varied rates of nano-clay.

Specimen No.	$[K_1G_4]_S$	0.5% NC	1% NC	2% NC	3% NC	5% NC
1	216.82	208.76	245.62	216.72	202.8	206.76
2	215.05	230.17	241.60	214.05	202.60	202.79
3	201.23	201.37	240.65	202.94	221.49	190.07
4	215.77	190.11	244.71	211.95	202.24	200.60
5	214.71	190.73	245.60	199.75	190.83	204.47
Average	212.71	204.22	243.60	209.08	203.99	200.90
Increase %	0	-3.99	**14.52**	-1.708	-4.10	-5.52

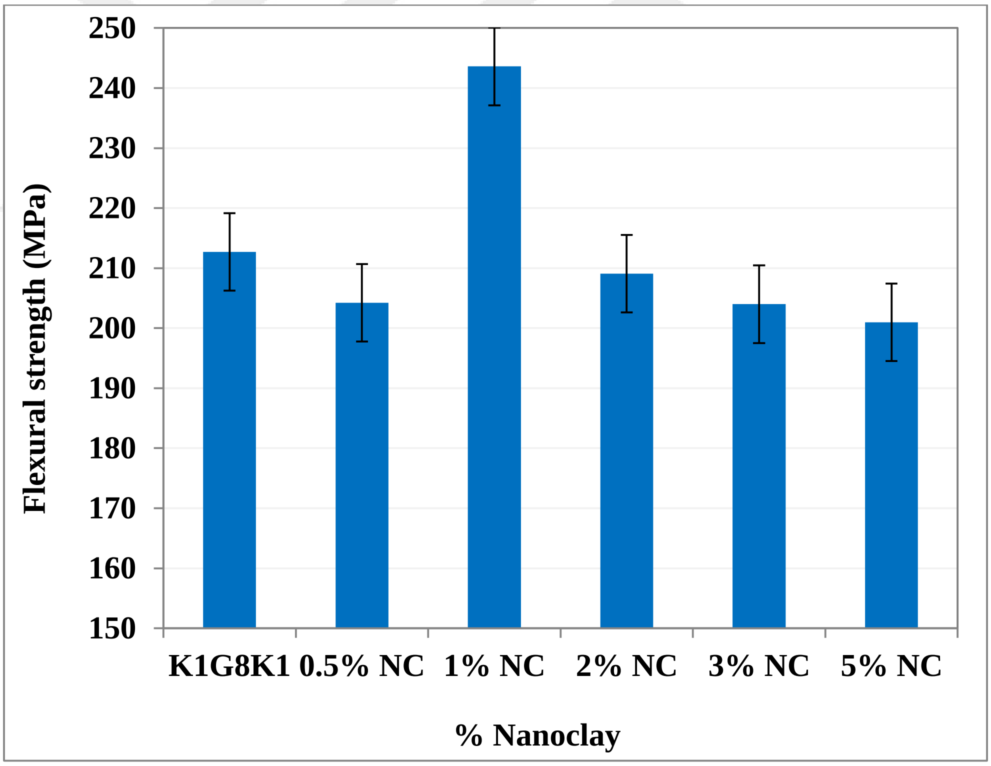


Figure 4.16 Variation of flexural strength according to nano-clay content for $[K_1G_4]_S$

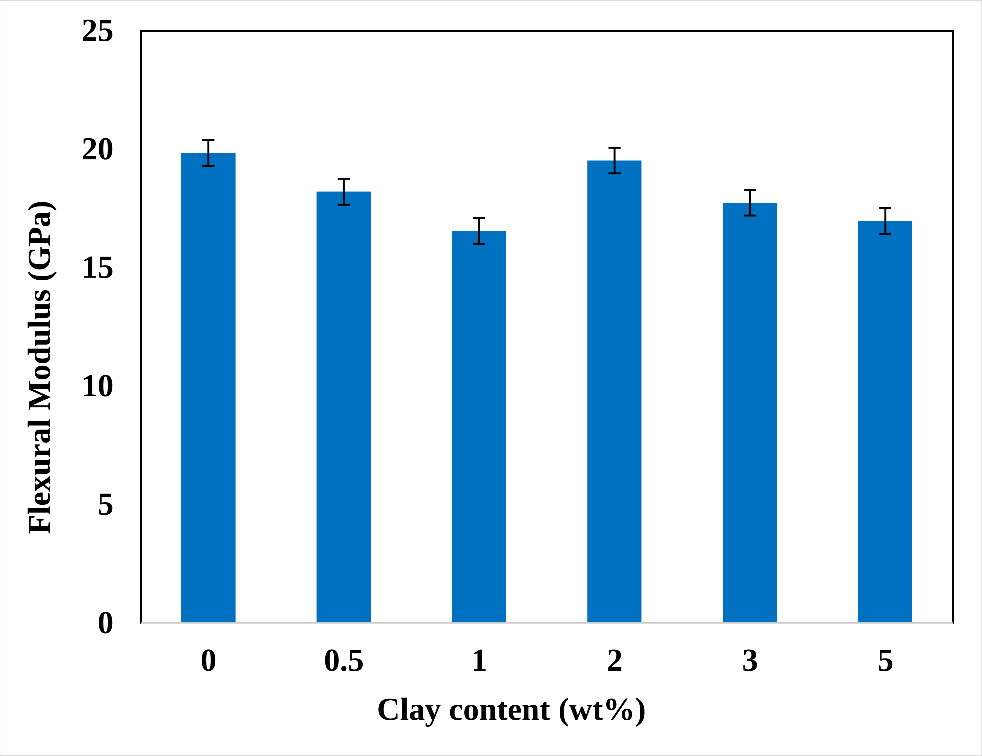
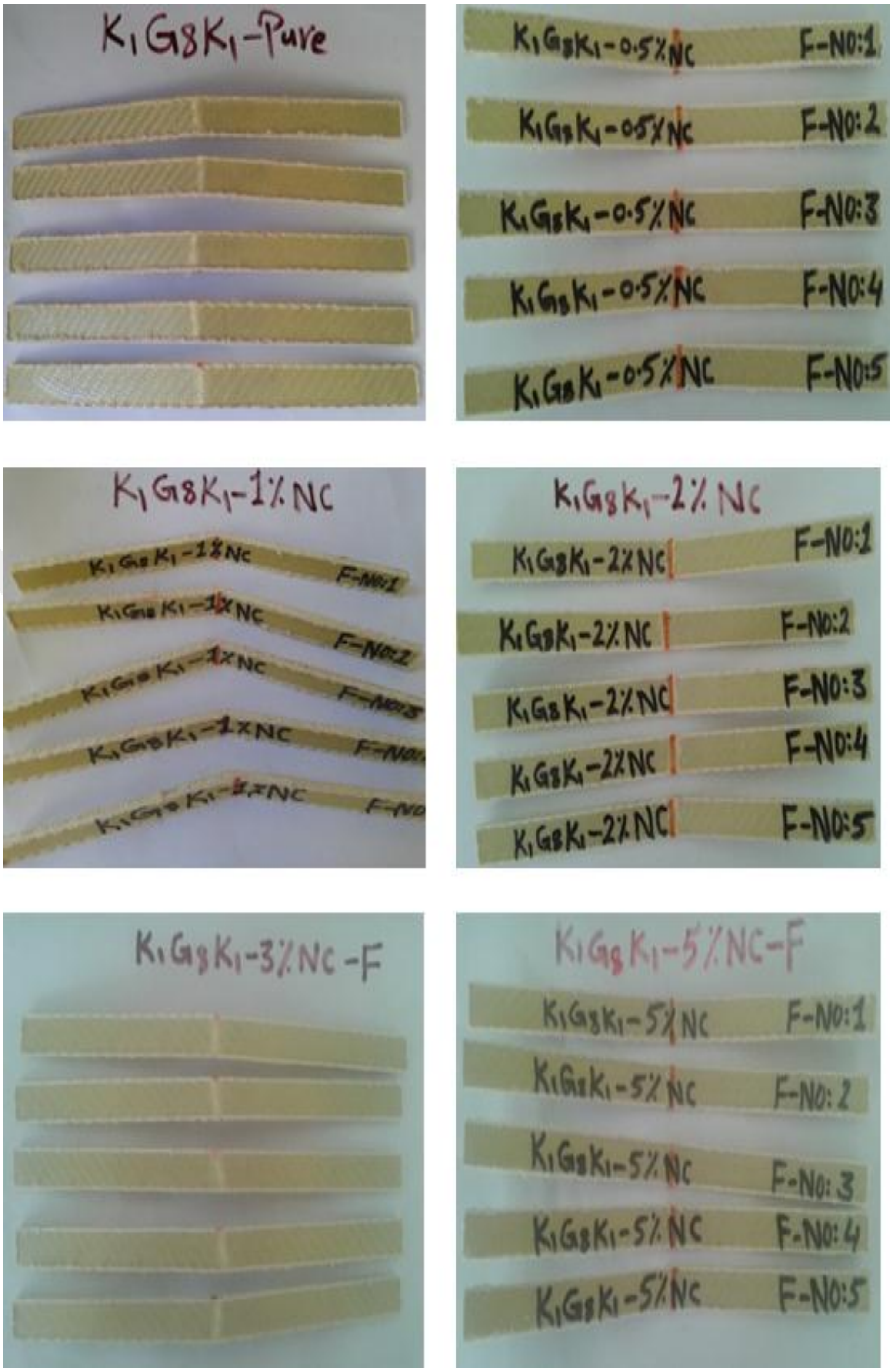


Figure 4.17 Variation of flexural modulus according to nano-clay content for $[K_1G_4]_S$


(1)K+(8)G+(1)K-Pure F-1
(1)K+(8)G+(1)K-Pure F-2
(1)K+(8)G+(1)K-Pure F-3
(1)K+(8)G+(1)K-Pure F-4
(1)K+(8)G+(1)K-Pure F-5
K1G8K1-0.5%NC F-NO:1
K1G8K1-0.5%NC F-NO:2
K1G8K1-0.5%NC F-NO:3
K1G8K1-0.5%NC F-NO:4
K1G8K1-0.5%NC F-NO:5
K1G8K1-1%NC F-NO:1
K1G8K1-1%NC F-NO:2
K1G8K1-1%NC F-NO:3
K1G8K1-1%NC F-NO:4
K1G8K1-1%NC F-NO:5
K1G8K1-2%NC F-NO:1
K1G8K1-2%NC F-NO:2
K1G8K1-2%NC F-NO:3
K1G8K1-2%NC F-NO:4
K1G8K1-2%NC F-NO:5
K1G8K1 (3%NC) F-NO:1
K1G8K1-3%NC F-NO:2
K1G8K1-3%NC F-NO:3
K1G8K1-3%NC F-NO:4
K1G8K1-3%NC F-NO:5
K1G8K1-5%NC F-NO:1
K1G8K1-5%NC F-NO:2
K1G8K1-5%NC F-NO:3
K1G8K1-5%NC F-NO:4
K1G8K1-5%NC F-NO:5

(a)



(b)

Figure 4.18 Specimens (a) before the flexural test, (b) after the flexural test

CHAPTER 5

CONCLUSIONS

In this study, the influence of nano-clay on the mechanical characteristics of hybrid and non-hybrid composite materials was investigated. Glass fiber, Kevlar fiber and glass/Kevlar hybrid fiber reinforced epoxy composite laminates with various stacking arrangements were used for this purpose. In the light of the experimental results, the following results can be drawn:

- The addition 1 wt.% nanoclay resulted with enhancement in tensile strength about 8% higher than pure laminate of G_{12}.

- The addition of nano-clay with various ratios such as 1 wt.%, 2 wt.%, and 3 wt.% into G_{12} composite laminate resulted in lessening the flexural strength.

- For glass/Kevlar hybrid fiber reinforced composite laminates with arrangements of $[K_1G_4]_S$, $[K_2G_3]_S$, $[K_3G_2]_S$ and $[K_4G_1]_S$, the results showed that the arrangement of $[K_4G_1]_S$ laminate without nano-clay had the maximum tensile strength and the inclusion of 1 wt.% of nano-clay within this arrangement resulted the highest enhancement for tensile strength.

- For glass/Kevlar hybrid fiber reinforced composite laminates with arrangements of $[K_1G_4]_S$, $[K_2G_3]_S$, $[K_3G_2]_S$ and $[K_4G_1]_S$, the results showed that the arrangement of $[K_3G_2]_S$ laminate without nano-clay had the maximum flexural strength. Nevertheless, the inclusion of 1 wt.% of nano-clay within $[K_2G_3]_S$ arrangement has increment the flexural strength by about 10%.

- The addition of nano-clay into $[K_1G_4]_S$ composite had a positive influence on the tensile strength and the highest enhancement was determined for 2 wt.% nano-clay inclusion which was 6.74% higher than that of un-particulate one.
- Nano-clay had a considerable influence on the flexural strength of $[K_1G_4]_S$ composite and the addition of 1 wt.% nano-clay resulted in an increase of flexural strength by 14.52% higher than that of un-particulate one.

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