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M. Sc. in Mechanical Engineering

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IMPACT BEHAVIOR OF NANO-CLAY AND NANO-SiO_{15} FILLED EPOXY MATRIX BASED FIBER REINFORCED COMPOSITE LAMINATES

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Supervisor

Assist. Prof. Dr. Ömer Yavuz BOZKURT

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Atban Rafea Abdo ABDO

ABSTRACT

IMPACT BEHAVIOR OF NANO-CLAY AND NANO-SiO_{15} FILLED EPOXY MATRIX BASED FIBER REINFORCED COMPOSITE LAMINATES

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M. Sc. in Mechanical Engineering

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In this study, the impact behavior of nanoclay and nanosilica filled epoxy matrix based glass fiber reinforced composite laminates ([G_{12}] and [G_{10}]) and aramid/glass hybrid fiber reinforced composite laminates were investigated by Charpy impact test. The composite laminates were fabricated by hand lay-up process. The Charpy impact test of fabricated composite laminates was conducted following ISO 179/92 standard by Köger 3/70 Charpy impact test machine. The results showed an increase in absorbing impact energy of the edgewise specimens of glass fiber reinforced composites were 19.44 % for 2 wt.% nanoclay addition and 38.02 % for 1.5 wt.% nanosilica addition. The increase in absorbed impact energy for flatwise test specimens of [G_{12}] and [G_{10}] was 11.38 % and 32.83 % for 2 wt.% nanoclay and 1.5 wt.% nanosilica, respectively. It was also shown that the highest impact energy absorption on hybrid fiber reinforced composites was obtained for both flatwise and edgewise test of $[K_1G_4]_S$ stacking configuration with 1 wt.% nanoclay additive.

Key Words: Nanoclay, Nanosilica, Charpy, Hybrid fiber composite, Glass fiber

ÖZET

NANOKiL VE NANO-SiO_{15} KATKILI EPOKSİ MATRİS ESASLI ELYAF TAKVİYELİ KOMPOZİT LAMİNATLARIN DARBE DAVRANIŞI

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Bu çalışmada, nanokil ve nanosilika katkılı epoksi esaslı cam elyaf takviyeli kompozit laminatların ([G_{12}] ve [G_{10}]) ve aramit/cam hibrit elyaf takviyeli kompozit laminatların darbe davranışı Charpy darbe testi kullanılarak araştırılmıştır. Kompozit laminatlar el yatırma işlemi ile imal edilmişlerdir. Üretilen kompozit laminatların Charpy darbe testi, ISO 179/92 standardı uyarınca Charpy darbe test makinesi ile gerçekleştirilmiştir. Sonuçlar, cam elyaf takviyeli kompozit laminatların yanlamasına numuneleri için emilen darbe enerjisinde, ağırlıkça % 2 nanokil katkısı için % 19,44 ve ağırlıkça % 1,5 nanosilika katkısı için % 38,02 artış olduğunu göstermiştir. [G_{12}] ve [G_{10}]'un diklemesine numuneleri için emilen darbe enerjisinde, ağırlıkça % 2 nanokil katkısı için % 11,38 ve ağırlıkça % 1,5 nanosilika katkısı için % 32,83 artış olmuştur. Hibrit elyaf takviyeli kompozitler üzerindeki en yüksek darbe enerji emiliminin, ağırlıkça % 1 nanokil katkılı [K_1G_4]$_S$ dizin konfigürasyonunun hem yanlamasına hem de diklemesine yönelik test numuneleri için elde edildiği görülmüştür.

Anahtar Kelimeler: Nanokil, Nanosilika, Charpy, Hibrit elyaf kompozit, Cam elyafı

Dedication

This Thesis Is Dedicated To ….

My Country (IRAQ)

My family especially my father and my mother, my brothers and their families, my sisters and their families, my wife, my sons, my daughters, and My Friends, For Their Support and Encouragement….

To All The People Who Want To Take Advantage From This Research…..

With Great Love

ATBAN AL-ANI

2017

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LIST OF SYMBOLS

FRP	Fiber Reinforced Polymer
CFRP	Carbon Fiber Reinforced Polymer
CNTs	Carbon Nanotubes
TiO2	Titanium Dioxide
$[K_1G_4]_S$	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
K	Kevlar /Aramid fiber
G	Glass fiber
N	Notch specimen
N1,2,3,..	Notch specimen number 1,2,3,…
P	Pure specimen
P1,2,3,…	Pure specimen number 1,2,3,…
ch	Charpy test
AFRP	Aramid Fiber Reinforced Polymer
wt.%	Weight percentage
CTBN	Carboxyl-Terminated Butadiene acrylonitrile copolymer
Si-O-Al	Silicate – Aluminum
DTMA	Dynamic Thermal Mechanical Analysis

CHAPTER 1

INTRODUCTION

1.1 General Introduction

Fiber reinforced polymer composite materials have attracted significant interest in the past few decades due to their outstanding performance-to-weight ratio in relation to conventional engineering materials [1]. Fiber reinforced polymer composites also exhibit better damping characteristics, good fatigue resistance and high resistance to corrosion [2]. With these outstanding properties, fiber reinforced polymer composites have become promising materials for the application of aerospace, defense, automotive [3], and marine industries [4]. However, fiber reinforced polymer composites are susceptible to out-of-plane impact damage resistance which can cause significant reductions in strength and, in turn, leads to heavier designs to meet safety requirements [2]. One of the method to enhance the impact damage resistance of fiber reinforced polymer composites is the addition of nanoparticles into the matrix of composites [5].

The introduction of nanoparticles into the resin constituting the composite matrix is a comparatively new advancement in the field of polymer composites. Over the last two decades, more researchers have reported that the addition of small amounts of nanoparticles, like carbon nanotubes, nanometal oxides, graphene, nanosilica and nanoclays, lead to remarkable improvements in mechanical, thermal, morphological, electrical and optical characteristics of polymer composite materials without compromising on toughness, density and manufacturing process [6,7-10]. Among different types of nanoparticles, nanoclays have received significant attention due to its simple availability and inexpensive. Numerous researchers have investigated the various properties and characteristics of nanoclay reinforced polymer composites [6]. The range of properties in which the introduction to nanoclay yield improvements to neat polymers used composite materials is much more than the expected.

The advantages of nanoclay filled composites are generally demonstrated for the improvements in mechanical and thermal properties like quasi-static tensile and flexural properties [5, 11-13], fracture resistance [14-17], thermal degradation resistance [18, 19]. However, the mechanical characteristics of nanoparticle reinforced polymer composite are very low compared to fiber reinforced polymer composites [20].

In a few years ago, there has been maximizing interesting in applying hybrid composite materials for constructional applications due to their enhanced and better characteristics than their individual mineral constituent [21]. Hybrid composite is manufactured by combining two or many antithetical reinforcement materials in a shared matrix. By doing so, a new material is manufactured with new and additional characteristics [22]. One way to enhance the weakness for some fiber reinforced plastic composite is exchanging few fiber fabric layers with the fabric layers that possess desired properties. This is named as fiber hybridization, which can guide to benefits of cost and improvement of mechanical and physical properties, thus creating new type of material. The mechanical properties of hybrid composite almost depended on the reinforcing fiber placement [23].

Hybrid composites are generally utilized when a group of characteristics of various kinds of fibers requires to be done, or when the longitudinal as well as the sidelong mechanical performance are needed [24]. Many investigations arrive at reported that the mechanical characteristics of interlaminar shear strength, fracture toughness, elastic modulus and flexural strength [25-27], were enhanced by the influence of nanoclay on the polymer systems. The improvement in mechanical properties was moderately attributed to the constraint on the polymer chains by their activities with the nanoclay surfaces [28, 29].

There is a developmental demand to utilize a high- accomplishment and low-weight composites to exchange the conventional utilized metals in several applications [30, 31]. Among the several composites, glass fiber reinforced epoxy composites are overmuch for use in civil usage such as strengthening of walls, bodies of automobile, bridges, ship shells and slabs to new building frames. In defense applications glass-epoxy composites are utilized as armor tiles for safeguard different vehicles [32-34]. There is a require to improve mechanical properties and impact on glass epoxy composites as it will become strong realizing sprightly weight structures of defense and civilian applications [35]. One of the possible action is to increment the interface compatibility of the glass fiber and epoxy [36, 37].

Composites of glass fiber are advanced engineering materials that deliver high strength-weight ratios, high modulus-weight and are excessively utilized in the sporting goods, military, automobile and aerospace manufactures. Epoxy resins are engineering type of polymer matrix that are used for their high stiffness and strength, thermal stability, high resistance to temperature, good adhesion, little creep, and very good process capability. However, cured epoxy resins have a small toughness with largely brittle behavior when affected to impact so to be capable to arise the resin without giving in to its existing properties different methods have been assumed, such as additive of toughening agents [38] and introduction of various type of nanoscaled materials into the resin system. There are various studies about the improvement of fracture toughness of epoxy resins using nanoparticles [39] and it has been shown that nanoparticles such as nanoclay, nanosilica, and nanotubes can improve epoxy fracture toughness [40, 41].

Artificial fiber reinforced composite materials have become significant in the years and compared to other traditional metallic materials, their applications become very wide due to its lighter weight, excellent mechanical properties, corrosion resistant, unique flexibility, ease of fabrication [42]. Among the artificial fibers, the poly aramid fiber known as Aramid fiber owns a lot unparalleled properties. It can also be watched as nylon with excess benzene rings in the polymer chain for enhancing its stiffness [43]. It is mainly common to its rising applications of manufacturing and advanced technologies like helicopter blades, ballistic armor, sporting goods, pneumatic reinforcement, etc. Compared to other artificial fibers, it occupancy importantly lowers fiber elongation and higher modulus and tensile strength [44-48]. It also exhibits very good high temperature properties of a polymeric material [49].

As well the composites in use for structures of aircraft have to resistance suddenly impact loading, which happens to the form of the projectile, debris or tool drop, bird striking. Generally, this type of impact will be in the intermediate velocity range (40-250 m/s) [50-52].

Damage because of low-velocity impact on fiber reinforced composites is deemed to be potentially unsafe chiefly because the damage is hard to discover by eyes. This kind of damage is normally named as scarcely visible impact damaged [53].

Different approaches have been successfully employed to improve the impact damage resistance of composite laminates. Such as inclusion of high strain to failure fibers into the fiber reinforced composites to enhance the impact damage resistance [54-56] and addition of nanoparticles into matrix.

Despite the huge number of publications of polymer-clay, silica nanocomposites, there is very little literature about the effects of adding nanoclay and nanosilica to polymer on Charpy impact behavior of glass/aramid hybrid fiber and glass fiber reinforced polymer composites. Therefore, the aim of this work is to analyze the impact behavior of nanoclay modified glass/aramid hybrid fiber, and nanoclay and nanosilica modified glass fiber reinforced epoxy matrix composites. A group of glass/aramid hybrid fiber reinforced composites with nanoclay concentration up to 5 wt.% and glass fiber reinforced composites with nanosilica concentration up to 3 wt.% have been prepared using hand lay-up technique.

1.2 The Objectives of Research and Tasks

In this study, the main aim is to investigate the effects of nanoclay and nanosilica on Charpy impact behavior of glass fiber reinforced and glass/aramid hybrid fiber composite laminates. The research tasks can be summarized as follows;

I. Fabrication of glass fiber reinforced composite laminates with different amount of nanoclay and nanosilica inclusions.

II. Production of glass/aramid hybrid fiber reinforced composite laminates using different stacking sequence and different nanoclay contents.

III. Production of glass fiber reinforced composite laminates using different nanosilica contents.

IV. Conduction of the Charpy impact tests for all of the prepared laminates.

V. Discussion about the effects of the nanoparticles on the Charpy impact behavior of composite using the obtained results from the tests.

1.3 Layout of Thesis

The study has been divided into five chapters.

- A general introduction, research objectives and tasks of the study are given in Chapter 1.
- A comprehensive literature survey is presented in Chapter 2. Literature survey has been grouped in five parts; introduction, studies about the fiber reinforced composite material, studies of hybrid fiber reinforced composite material, studies related to fiber reinforced composite material with nanoparticle filler, and conclusion on literature review.
- In Chapter 3, information about the materials (fibers, nanoparticles, epoxy) and fabrication method used in this study are provided.
- The results and discussions of Charpy impact experiments are presented in Chapter 4.
- General conclusions about the results are given in Chapter 5.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

In the literature, there are many researches on composite materials. A brief literature review related to the impact behavior of fiber reinforced composite materials and nano-particle inclusion fiber reinforced composite materials are presented in this chapter. A literature review has been classified into four parts; studies on impact behavior of neat fiber reinforced and hybrid fiber reinforced composite laminates are reviewed in Section 2.2 and Section 2.3, respectively. The studies on impact behavior of nano-particle filled fiber reinforced composite materials are given in Section 2.4, The conclusions of the literature review are presented in Section 2.5.

2.2 Literature Review on Impact Behavior of Neat Fiber Reinforced Composite Materials

Due to their superior characteristics like high strength- and stiffness-to-weight, better damping, corrosion resistance and good fatigue in relation to conventional engineering materials, fiber reinforced polymer composite materials have attracted important interest in the past few decades. However, fiber reinforced polymeric composites are susceptible to out-of-plane impact damage resistance which can cause important reductions in strength and, in turn, leads to heavier designs to meet safety requirements.

The impact behavior of glass fiber reinforced composite laminates at various temperatures using notched Izod impact test specimens were investigated by Badawy [57]. The result showed that more impact damaged area was produced in specimens impacted at lower temperatures than those at higher temperatures.

Generally, the failure characteristics altered from fiber pull-out to fiber breakage with rising the exposure temperature. An increment in fiber volume fraction led in an increment in impact strength of cross-ply laminated composites. However, the impact strength reduced by rising the exposure temperature for 0^0 cross-ply and unidirectional laminated composites.

Yucheng Zhong, [1] studied the resistance of impact of carbon fiber reinforced epoxy polymer (CFRP) composites. It was revealed that the load oscillation through low-velocity impact lead to the first significant damage and these damages were in the form of fiber debonding or multiple matrix cracking or fiber breakage. And observed that moisture importantly alleviated impact induced damage in the CFRP unidirectional laminates also leads to enhanced impact reaction of CFRP laminates.

Mili and Necib [58] ascertained experimentally the impact behavior of various E-glass/epoxy laminated composite. The drop weight impact tests were performed for three different cross-ply laminate configurations $[0_2/90_6/0_2]$, $[0_3/90_4/0_3]$ and $[0_4/90_2/0_4]$. It was presented that the change in the stacking sequence of the laminate resulted with a significant change in impact behavior and the configuration $[0_4/90_2/0_4]$ was found higher impact resistance.

Wong et al. [59] studied the behavior of impact of continuous and short fiber of E-glass, oil palm, coir as well as E-glass/coir and E-glass/oil palm hybrid fiber-reinforced polyester composites. It was shown that impact strength enhanced with fiber length and fiber content. In addition, longitudinal fiber exhibited best impact toughness likened to transverse fiber. Impact strength was bettered with the increasing number of layers, but worse by the increasing space between fibers.

2.3 Literature Review on Impact Behavior of Hybrid Fiber Reinforced Composite Materials

The use of two or more kind of fibers in a matrix is called as fiber hybridization. Fiber hybridization is an efficient technique to develop new composite materials with advanced characteristics over the neat fiber kind embedded composites. [21]. The impact behavior of hybrid composites depends on a great number of design parameters like laminate thickness, surface treatment, and stacking sequence.

Naik et al. [60] investigated impact conduct and post impact compressive properties of glass-carbon hybrid composites with alternative arrangement sequences. They resulted that hybrid composites have lower notch sensitive as likened to only carbon or only glass composites. Also, carbon-outside/glass-inside clustered hybrid arrangement led lower notch sensitivity likened to the other hybrid arrangement.

Enfedaque et al. [61] looked into the influence of glass fiber hybridization on the conduct under the impact of woven carbon fiber/epoxy laminates. The results presented improvements in impact conduct of carbon fiber/epoxy composites and it was attributed to the higher strain-to-fracture of the S2-glass fiber layer. Also, the presence of S2-glass fibers assisted to sustain higher deformations before laminate fracture by the percolation of a through-thickness crack, importantly betterment the energy dissipated under impact.

Martin et al. [62] examined the impact behaviour of hybrid glass/carbon epoxy composites. It was shown that hybrid composites were more capable of absorbed energy than carbon fiber composites. The place of the glass fiber plies was more important than the amount of hybridization when laminates were subjected to high strain rates. The glass fibers near to the non-impacted surface of the samples were led to better impact performance.

Dorigato and Pegoretti [63] researched flexural and impact the behaviour of E-glass and basalt fiber fabrics merged with carbon fiber. The results assured that the Charpy impact tests confirmed the synergistic influances on the upper limit strength of basalt and glass fiber hybridization.

Tirillo et al. [64] studied high velocity impact behavior of hybrid basalt-carbon/epoxy composites. The results demonstrated that all arrangements containing basalt fibers have higher ballistic limit velocity likened to only carbon laminates. It was also found that stacking sequence affected the ballistic limit with the intercalated BCBI ($[(B_2/C_2)_3/B_2/C]_S$) (14 carbon laminae and 16 basalt laminae) arrangements which displayed the highest amounts (in terms of impact and static flexural strength) among all hybrids.

Bozkurt et al. [65] investigated the hybridization influences on Charpy impact conduct of basalt/aramid fiber reinforced hybrid composite laminates. This study demonstrated that the replacement of aramid layers with basalt layers decreased the deformation and enhanced the impact energy of hybrid composite laminates through the delamination between layers of basalt. The delamination between basalt layers was obviously appeared as the main mechanism in the impact absorbed energy of hybrid composites specially at the impacted surface of the aramid layer. This can be attributed to the rigid structure of basalt and relatively frail bonding between basalt layers. The results showed that the impact energy of epoxy/aramid composites could be enhanced by the hybridization with inexpensivet naturalist basalt fiber.

Bozkurt [66] studied influence of hybridization on bending and tensile chracteristics of basalt/aramid fiber reinforced neat epoxy composites. The results appeared that the mechanical characteristics (flexural and tensile) of hybrid composite laminates can be tailored by the employment of basalt fibers for partial alteration of aramid ones, and large betterment in mechanical characteristics (liken to those of AFRP composite laminate) can be acquired with the suitable design of hybrid composite laminates.

Park et al. [67] investigated the impact conduct of four-layer composites through the analysis of the delamination area of glass fiber/aramid fiber hybrid composites. It was noticed that the delamination area and impact energy of the hybrid composites counted on the locating of aramid layer. Whenever aramid layer was at back surface, the composite showed the delamination area and higher impact energy.

Petrucci et al. [68] looked into mechanical description of hybrid composite laminates based on basalt fibers in collection with hemp, glass and flax fibers fabricated by vacuum molding. The results showed that mechanical characteristics of each the hybrid laminates are superior to neat flax and hemp fiber reinforced laminates and inferior to basalt fiber laminates. Among the hybrid, better characteristics were provided by those acquired by adding flax and glass to basalt fiber reinforced laminates.

Sarasini et al. [69] researched the influence of hybridization of basalt fibers on low velocity impact response, damage tolerance capability and damage resistance of aramid textiles reinforced epoxy composites. It was pointed that hybrid laminates with added form (alternating sequence of aramid and basalt textiles) have more best enhanced damage tolerance and impact absorbed energy capability with respect to the total aramid laminates, whilst hybrid laminates and basalt with sandwich-like form (three aramid textiles layers for each side of the composite as skins and seven basalt textiles layers at the middle of the laminate as core) provide the best flexural behaviour.

Silvio et al. [70] studied mechanical behaviour of epoxy composite reinforced with Kevlar plain textile and Kevlar/glass hybrid textile. The mechanical characteristics of composites were identified by impact, tensile, and bending test. It was noted that composites with glass/Kevlar hybrid structure of the reinforcement textile observed the best results with respect to specific mechanical strength, as well as impact energy and bending.

Subagia et al. [23] studied the influences of several arranging sequences of basalt and carbon fibers on the flexural characteristics of hybrid composite laminates. The results observed that the modulus and flexural strength of hybrid composite laminates were strongly dependent on the sequence of fiber reinforcement. Also sequences displayed a positive hybridization influence. The interply hybrid composite with carbon fiber at the compressive side exhibited high modulus and flexural strength than when basalt fiber was arranged at the compressive side.

The flexural and impact behavior of carbon/basalt fiber strengthened hybrid laminates has been investigated by Dorigato and Pegoretti [71]. Charpy impact tests have been conducted to determine the impact characteristics of composite. The results showed that the introduction of basalt fiber into carbon fiber laminates could promote an increment in the absorbed energy of impact, with an improvement of the fracture propagation component.

Ghasemnejad et al. [72] studied the influences of hybrid composite beams containing various delaminated region and locations. Charpy impact tests were conducted to see energy absorption ability of composite beams having delamination. Hybrid composite beams were manufactured by combining Carbon/Epoxy and Glass/Epoxy. The results showed that composite beams containing delaminated region near to impacted surface were absorbed higher energy than other locations.

2.4 Literature Review on Impact Behavior of Fiber Reinforced Composite Materials with Nanoparticle Filler

Anbusagar [73] investigated the influence of nanoclay content on the impact characteristic of glass fibre reinforced polyester sandwich composite laminates. The polyester was modified with 2 wt.%, 4 wt.%, 6 wt.% and 8 wt.% of nanoclay. The impact characteristics of composites were determined using Charpy impact test. The results showed that the nanoclay inclusion led 37% improvement in impact strength for 8 wt.% of nanoclay.

Shafi et al. [74] investigated the Charpy impact fracture behavior of nanoclay modified carbon fiber-reinforced composites (CFRP). The nanocomposite was fabricated using 0 wt.% to 5 wt.% nanoclay addition. The results showed that the highest improvement on impact and quasi-static fracture toughness values were obtained for 3 wt.% nanoclay addition. The clay inclusion resulted with significant improvement in critical stress intensity factor over the whole range of clay content for both clay-epoxy nanocomposite and clay-CFRP hybrid composite.

Thiagarajan et al. [75] tested the effectiveness of 3 wt.% nanoclay inclusion on the impact characteristics of glass fiber reinforced polymer composites. The results showed that inclusion of nanoclay in E-glass-epoxy composite led an enhancement on maximum load and energy absorption capability of both chopped strand mat (CSM) and woven roving mat (WRM) systems. Post-perforation photograph presented that inclusion of nanoclay improved the impact damage resistance under low velocity impact loading.

Alomari et al. [76] examined the influence of nanoclay additives on low impact conduct of Kevlar fiber reinforced composite laminates by adding different nanoclay amounts 4.3 wt.%, and 9.4 wt.%. The test results showed that the different ratio of nanoclay percentage usually leads to various properties of the resulting composite, and an increment in apsorbed energy by high percentage of fillers may accompany tendency to delamination. The nanoclay with low percentage 4.3 wt.% resulted with the better results in delamination resistance.

Sivasaravanan et al. [77] researched the effect nanoclay content on Charpy impact characteristics of glass fiber/epoxy hybrid composite laminates. The content of nanoclay inclusion was changed from 1 wt.% to 5 wt.%. It was shown that inclusion of nanoclay using sonication system led to improvements in impact values. The inclusion of 5 wt.% of nano clay provided excellent results compared to other percent of nano clay contents. The mean value of absorbed impact energy was 10.75 J/m for 5 wt.% of nano clay content.

Iqbal et al. [78] investigated the effect of 0 wt.%, 3 wt.% and 5 wt.% nanoclay inclusion on the resistance of impact damage of carbon fibers reinforced epoxy composites. The compression properties after impact were also evaluated. It was shown that the addition of nanoclay with different ratios up to 3 wt.% in the epoxy reduced the resistance of impact damage in comparison with that of laminates of pure epoxy. Up to 3 wt.% of nanoclay in the epoxy, both the tolerance and resistance of damage of the composite laminates were enhanced in terms of high and threshold energy of impact. Additive of nanoclay also enhanced the epoxy shear stiffness.

Reis et al. [79] studied the effect of 1.5 wt.% nanoclay inclusion on the response of an epoxy/Kevlar composite under low velocity impact. It was concluded that the fillers provided enhancement on impact damage resistance and maximum impact load compared to the control model. As well as increases the residual strength.

Khan et al. [38] examined the behavior of impact fracture and quasi-static fracture resistance of carbon fiber reinforced polymers (CFRPs) with the addition of nanoclay into epoxy. It was pointed that the modulus and flexural strength of epoxy were remarkably improved by the inclusion of nanoclay. Both the quasi-static fracture toughness and impact fracture amounts of CFRP-clay hybrid composites were higher than those of epoxy–clay nano-composites in any case of nanoclay weight content.

Dolati et al. [80] researched the effect of nanoclay amount on the resistance of glass-fiber/epoxy composites to impact damage by using high velocity repeated ice impact tests. The results showed that laminates, without nanoclay fiilers, having an angle of 45º for the orientations of ply resulted with improvement in impact damage. Adding a small amount of nanoclay particles led improvement in impact resistance.

Siddiqui et al. [81] investigated the mechanical characteristics and fracture conduct of organoclay modified carbon fiber reinforced epoxy composites. It was shown that the organoclay achieved an important development in flexural modulus. Compared to unmodified carbon fiber reinforced epoxy composite, the flexural modulus was improved nearly 26% for the additive of 3 wt.% clay. The fracture toughness under quasi-static load enhanced by 60% with the inclusion of 3 wt.% clay The flexural strength stepwise minimized by maximizing in clay content ratio. Depending on the rate of loading, there was a reverse or direct relation between the clay concentration and fracture toughness.

Haque et al. [82] investigated the influence of nanoclay molecules like montmorillonite on thermal and mechanical characteristics of the matrix of fiber reinforced polymer composites. The outcomes showed that the interlaminar shear and flexural strength of S2-glass/epoxy-nanoclay composites were increased nearly 44% and 24%, respectively by adding 1 wt.% of clay into the system. Also, similar improvements was observed for the fracture toughness.

Balaganesan et al. [83] studied ballistic limit and impact energy absorption of glass fiber reinforced nanocomposite laminates. The result showed that the absorbed energy by bending was 70% for whole events of the composite laminates at ballistic limits. An increasing in absorped energy was noticed with addition of clay up to 5 wt.% wt for the laminates.

Mohanty et al. [84] examined the effect of alumina nanomolecules on the improvement in impact and flexural characteristics of the carbon/glass fiber reinforced epoxy laminates. It was noticed that the incorporation of alumina nanomolecules into epoxy led to the enhancement in thermal stabile of the alumina/epoxy composites.

Seshanandan et al. [85] researched mechanical characteristics of nano titanium oxide (TiO_2) particles of hybrid jute-glass FRP composites. The mechanical examination results demonstrated that shear strength, flexural strength and tensile strength of the hybrid fiber reinforced plastics better with the add-on of nano TiO_2 filler particles.

Sua et al. [86] investigated the tribological conduct on hybrid composites of polytetrafluoroethylene/glass fabric filled by nano-TiO2 filler with a phenolic resin binder. Results pointed that the additive of sufficient content of nano-TiO2 importantly enhanced the load carrying amplitude and wear impedance of the hybrid of polytetrafluoroethylene/glass fabric under dry slipping condition. Furthermore, it also improves the friction-reduction capabilities of the hybrid composites under dry sliding condition and higher loads.

Kavitha et al. [87] studied the influences of the size scale on post-impact residual strength of hybrid carbon/glass/epoxy nano-composites. The results showed that the tensile strength was decreased with addition of nano-clay. The residual tensile strength was detected by handling tensile test of the impacted samples. The decrease in residual strength was much in nano-composite samples compared to the plain-composite material. The damage improved on the ply-level scaled samples was much compared to sub-laminate level scaled specimens.

Siegfried et al. [88] examined the characteristics of residual compressive strength after impact and impact on epoxy/carbon fiber composites modified with CNTs. Depending on the experiments results, it can be concluded that the CNT network had a positive influence on the characteristics of the composites.

Aymerich et al. [89] investigated absorbed energy capable of nanomodified epoxy/glass laminates. The results shown that nanomodified laminates had a better impact energy absorption capability up to 30% increments in energy dissipation compared to the unmodified laminates, likewise in combination with a decrement of the height impact force 10 to 15%.

Daud et al. [90] studied the role of layered silicates in nanocomposite matrix for modifying the properties of fiber reinforced composites. The production of glass fiber reinforced polymer (GFRP) with various weight ratios of layered silicates was perfect when layered silicates were added into the matrix by less than 5 % wt. The enhancement due to the high stiffness and high aspect ratio of the layered silicates was clarified through the controlled matrix features of the GFRP. It was observed that the addition of 5 wt.% layered silicates into GFRP composites produced the highest improving in both compressive and flexural strength by about 30% at high temperatures.

Manjunathaet et al. [91] verified the fatigue behaviour of a silica nanoparticle-modified glass fiber reinforced epoxy (GFRP) composite under tensile loads.The fatigue life of 10 wt.% silica (infusion under flexible tooling technique (RIFT)) nanoparticle-reinforced GFRP was higher than that of GFRP with neat epoxy by about three to four times.

Jacob et el. [92] studied the mechanical properties and compounding characteristics of the composites of nanosilica reinforcement on polypropylene–nylon fiber composite. It was concluded that the inclusion of nanosilica and modified nanosilica enhanced the mechanical characteristics of PP–nylon fiber composites. The inclusion of 1 wt.% of modified nanosilica within PP–10 wt.% nylon fiber composite appeared high impact strength.

Junjie Yuan et al. [93] examined the influence of molecule size of nanosilica on the silica/epoxy composites performance. The results appeared that the Si-O-Al bond was shaped at nanocomposite coating/substrate interface, introducing nanosilica importantly improved the agglutinant strength, abrasion resistance, scratches impedance and abrasion impedance of coats, but several sizes of nanosilica molecules had different impact on these characteristics , which appeared to be returned to the silica surface structure.

Zamanian et al. [94] investigated the role of nanosilica molecules in modifying epoxy fracture toughness. The dynamic thermal mechanical analysis (DTMA) and tensile tests illustrated that Young's modulus increased with gthe addition of nanosilica. Also, the fracture energy increment is about 620 J/m^2 for the epoxy with 3.17 vol. % of 12-nm diameter nanomolecules.

Shi Ai Xu et al. [95] inspected the influence of hybridization of liquid rubber and nanosilica molecules on the mechanical characteristics, fracture toughness, and morphology of epoxy composites. It was shown that the tensile characteristics of the binary (liquid carboxyl-terminated butadiene–acrylonitrile copolymer (CTBN)) improved epoxy composites can be much enhanced by adding of nanosilica molecules. Furthermore, an apparent improving in the epoxy fracture toughness can be obtained by the hybridization of nanosilica molecules and liquid CTBN rubber. The tripartite (CTBN/nanosilica/epoxy) composites provided better balanced characteristics than the composites of binary epoxy/CTBN.

Jun Ma et al. [96] researched the influence of silica nanomolecules on the fracture toughness and mechanical property of two epoxy systems. It was noted that the 20-30 nm silica nanomolecules with powerful interface were equally dispersed in the epoxy matrix. These nanomolecules provided increments in tensile strengths and diminished the influence of defect on the mechanical performance of fragile epoxy. The rate of energy release was improved by 274 % for J230-cured epoxy and by 81 % for the other one.

Jumahat et el. [97] examined tensile characteristics of epoxy/nanosilica nanocomposites. It was found that the incorporation of a well-disperse nanosilica enhanced the tensile characteristics of the polymer. The additive of 25 wt.% nanosilica improved the strength and tensile modulus by approximately 24% and 38%, respectively, in comparison with the pure polymer.

2.5 Conclusion of 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 too high strength and specific stiffness are required. That is must be resistance to the sudden impact loading, which happens to composite structure and that is important condition.
2. Some of these studies are concentrated on new methods to improvement the impact behavior by hybridization on fiber reinforced composite materials due to their enhanced and better characteristics than their individual constituent
3. Also it is seen from the literature another procedure to enhance the impact conduct of fiber reinforced polymer composites that is addition low weight content of nanoparticles like nanoclay and nanosilica into the matrix of composites.
4. There are a little literature on hybridization influence on the mechanical properties of composite materials with nanoclay that let to investigate it.

5. To experimentally find the effects of hybridization on impact behavior of nanoclay and nanosilica filled epoxy matrix based fiber reinforced composite laminates, hybrid composites with various configurations were produced and Charpy impact tests were performed.

CHAPTER 3

EXPERIMENTAL STUDIES

MATERIALS, EQUIPMENTS, PRODUCTION OF HYBRID COMPOSITE LAMINATE AND DETERMINATION OF IMPACT TEST

3.1 Introduction

This chapter concerned with a brief presentation about the fabrication of composite laminates, preparation of specimens and experimental procedure of Charpy impact tests. Some common information about the constituents of the prepared composites such as glass fiber, Kevlar fiber, epoxy resin system, nanoclay and nanosilica are revealed and the fabrication technique, hand layup technique, is described.

3.2 Materials

3.2.1 Nanoclay

Nanoclay is the best model of normally happening nanomaterials and are usually used for a clay mineral having a thickness of approximately 1 nm and surfaces approximately (50–150 nm) in one dimension [98-100]. Nanoclay is thus the general term for the layered mineral silicates nanomolecules having higher aspect proportion. Count on the morphology of chemical composition and nanomolecules nanoclay are organized into several classes like halloysite, illite, kaolinite, bentonite, chlorite and montmorillonitehectorite [108]. Researchers explored that the nanoclay can be found from raw clay minerals through less steps [101], instead of the various general synthesis technicalities of nanomolecules [6]. Montmorillonite nanoclay with (35-45 wt.%) dimethyl dialkyl (C14-C18) amine was obtained from Grafen Chemical Industries, Turkey used in this thesis. Figure 3.1 showed nanoclay particles and Table 3.1 shows the physical properties of nanoclay.

Figure 3.1 Nanoclay.

Table 3.1 Physical properties of nanoclay

Constituent	Density (gr/m^3)	Particle size (nm)	Surface area (m^2/gr)
Nanoclay	200-500	1-10	157

3.2.2 Nanosilica

Nanosilica is an inorganic chemical material commonly known as silica, since the ultrafine nanometer size rang 1-100nm. Silica nanomolecules achieved a definite position in scientific research because they can be readily created. A sequential procedure was used firstly to create the monodispersed silica nanomolecules of uniform magnitude using ultrasonic sol-gel operation. Due to high surface area to volume ratio, nanoscale materials display enhanced characteristics in comparison to macro level materials. In the present scenario, there has been demanding and incremental benefit for nanoscale materials, chiefly in the domain of industrial enforcement. Silica nanomolecules are used as electronic substrates, thin films, thermal/electrical insulators, stabilizers, emulsifiers, etc. The goodness of these materials is sharply dependent on the magnitude and distribution of the silica molecules. Various and adjacent scales of metal contaminants and improved magnitude distribution of commercialized silica nanomolecules have appeared promotion in initiatives to produce purer molecules with narrow magnitude distribution [102]. Nanosilica was obtained from Grafen Chemical Industries, Turkey. With a high purity 99.5%, [103]. Figure 3.2 shows nanosilica particle and Table 3.2 shows the physical properties of nanosilica.

Figure 3.2 Nanosilica.

Table 3.2 Physical properties of nanosilica.

Constituent	Density (gr/m^3)	Particle size (nm)	Surface area (m^2/gr)
Nanosilica	0.05	15	300

3.2.3 Glass Fiber (G)

Fiber glass refers to a collection of products made from individual glass fibers into a collective kind of shapes. Glass fibers can be classified into two main groups related to their geometry: continuous fibers utilized in yarns and textiles, and the discontinuous (short) fibers used as blankets, batts, or boards for filtration and insulation. Fiber glass can be shaped into yarn more such as cotton or wool, and woven into fabric which is sometimes utilized for drapery. Fiber glass textiles are usually used as a strengthener material for mold and laminated plastics. Fiber glass wool, a thick, superfine material is made from discontinuous fibers, is used for absorbed sound and thermal insulation [104]. Plain weave E-glass fabric (03G200.080) with an areal density of (200 g/m^2) was supplied by DOST Chemical Industrial Raw Materials Industry, Turkey that is used in this thesis. Figure 3.3 shows glass fiber.

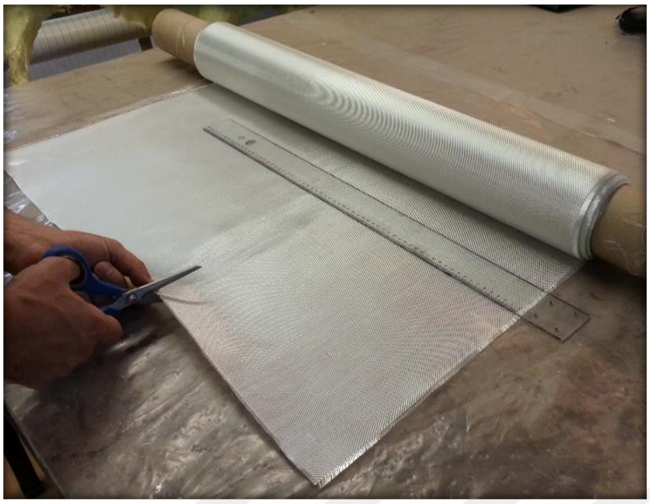


Figure 3.3 Glass fiber.

3.2.4 Kevlar or Aramid Fiber (K)

Kevlar is an organic in the aromatic polyamide family. The unparalleled properties and featured chemical composition of wholly aromatic polyamides (aramid) distinguished it from other commercial synthetic fibers. Kevlar, (trademark for DuPont) has an unparalleled combination of high modulus, high strength, thermal stability and toughness. It was advanced for demanding industrial and developed technology enforcement. Currently, many kinds of Kevlar are produced to meet a wide domain of end uses [105]. Twill aramid fabric (03A173K) with an areal density of 173 g/m^2 was supplied by DOST Chemical Industrial Raw Materials Industry, Turkey. Figure 3.4 shows Kevlar fabric used in this study.

Figure 3.4 Kevlar fiber.

3.2.5 Composites

In this study, several composite materials were produced with different ratios of nanoclay and nanosilica addition.

3.2.6 Hybrid Fiber Reinforced Composite

The hybrid fiber reinforced composites were prepared by combination of glass fiber and Kevlar fiber with different stacking sequences. Four hybrid configurations were produced as $[K_4G_1]_S$, $[K_3G_2]_S$, $[K_2G_3]_S$ and $[K_1G_4]_S$.

3.3 Matrix

The primary phase, having a continuous character, is named matrix. The matrix functions contains binding the fibers jointly, protecting the fibers from the surroundings, shielding from damage due to handling, and spreading the load to the fibers. Although matrices by themselves usually have little mechanical properties likened to those of fibers, the matrix affects much mechanical property of the composite. These properties contain strength transverse and modulus, strength and shear modulus, interlinear shear strength, compressive strength, thermal resistance, thermal expansion coefficient, fatigue strength, etc. Figure 3.5 shows a matrix and fiber [106].

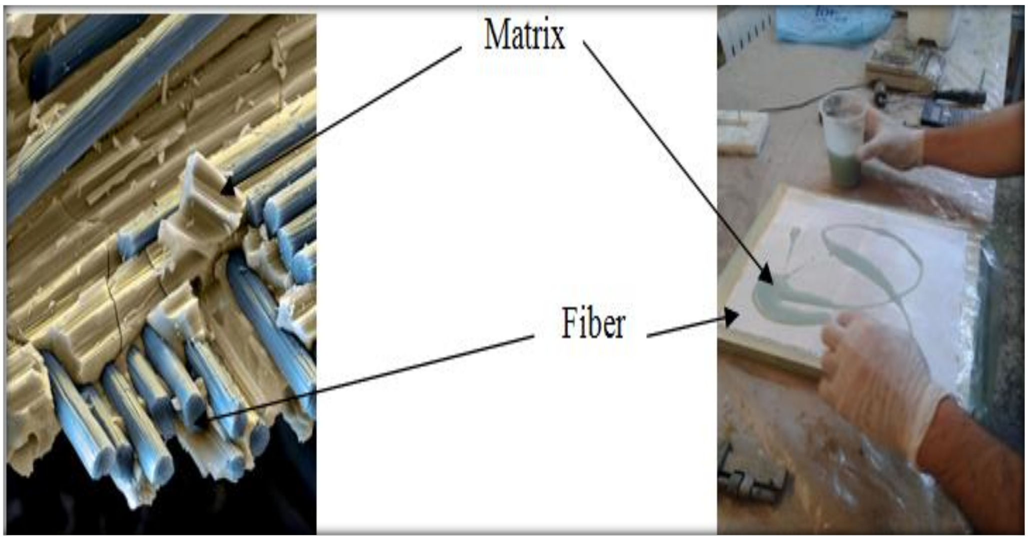


Figure 3.5 Matrix and fiber.

3.3.1 Epoxy Resin and Hardener

Epoxy resin is a flexible generally thermosetting resin produced by copolymerization of an epoxide with different compound having two hydroxyl groups and used mainly in adhesives and coatings and uses of the fiber reinforced polymer composites hardener is a substance mixed with paint or other protective covering to make the finish harder or more durable. It is a curing agent for epoxies or fiber glass. The hardener is usually classed as a corrosive, and as an irritant when in contact with the skin or by inhalation.

The important features of the epoxy matrix are;

- high strength,
- low flows rates and low viscosity, which allow best wetting of fibers, and inhibit misalignment of fibers during operating,
- low volatility during cure,
- low shrink rates, which decrease the tendency of gaining big shear stresses of the bond between the epoxy and its reinforcement,
- available in much than (20) grades to meet operating requirements and specific property.

There are large applications of epoxy in our life the Figure 3.6 shows that [107, 108].

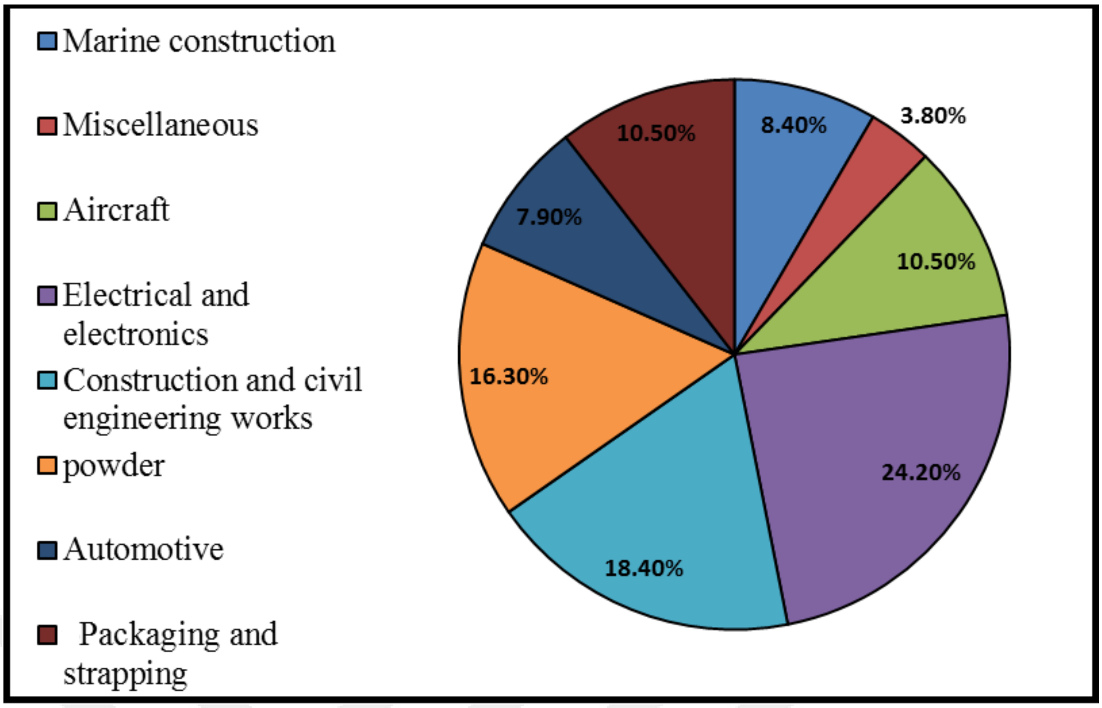


Figure 3.6 Application of epoxy in our life [107].

Epoxy resin (HEXION-MGS L285) and hardener (HEXION-MGS H285) used in this study were supplied by DOST Chemical Industrial Raw Materials Industry, Turkey. Figure 3.7 shows the sample of epoxy resin and hardener. The properties of epoxy and hardener shown in Table 3.3 and Table 3.4 respectively.

Table 3.3 Properties of 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

Table 3.4 Properties of hardener.

Properties	Hardener (H285) specification
Density [gr/ cm³]	0.94-0.97
Viscosity [mPas]	50-100
Amine Value [mgr KOH/gr]	480-550
Refractory index	1.5020-1.5500

Figure 3.7 Epoxy resins and hardener.

3.3.2 Laminate

Laminate is made of many layers, or plies, or sheets of unidirectional layers fabrics or mats, with proper orientations in each ply. The process were done by hand lay-up method. Laminate is shown in Figure 3.8.

Figure 3.8 Laminate.

3.3.3 Hand Lay-Up Method Followed by Hot Press

Hand lay-up is a method of composite laminate production. In first, a resin system (epoxy and hardener) were prepared with suitable and enough amount for the laminate by mixing epoxy and hardener by a mixer. The time of mixing nanoclay or nanosilica with epoxy approximately 20 minutes and the nanoparticle were added step by step to prevent agglomeration in particles and then hardener added and mixed for approximately 2 minutes to get a homogenous matrix as shown in Figure 3.9. First ply was placed over mold and resin mixture was applied with the help of a brush until it entirely wetted. Second ply was placed on the first one and resin mixture was applied until it became entirely wet. This operation was repeated until all plies be stacked. After completion of all plies, the laminate was transferred to the mold and whole assembly was placed in a hot press as shown in Figure 3.10. The laminate was cured at a temperature of 80°C and a pressure of 4 MPa for 3 hours. After the plate was cured, it was removed from the mold. Figure 3.11 shows hand lay-up method. This process was repeated to prepare all of the composite laminates.

Figure 3.9 Mixer.

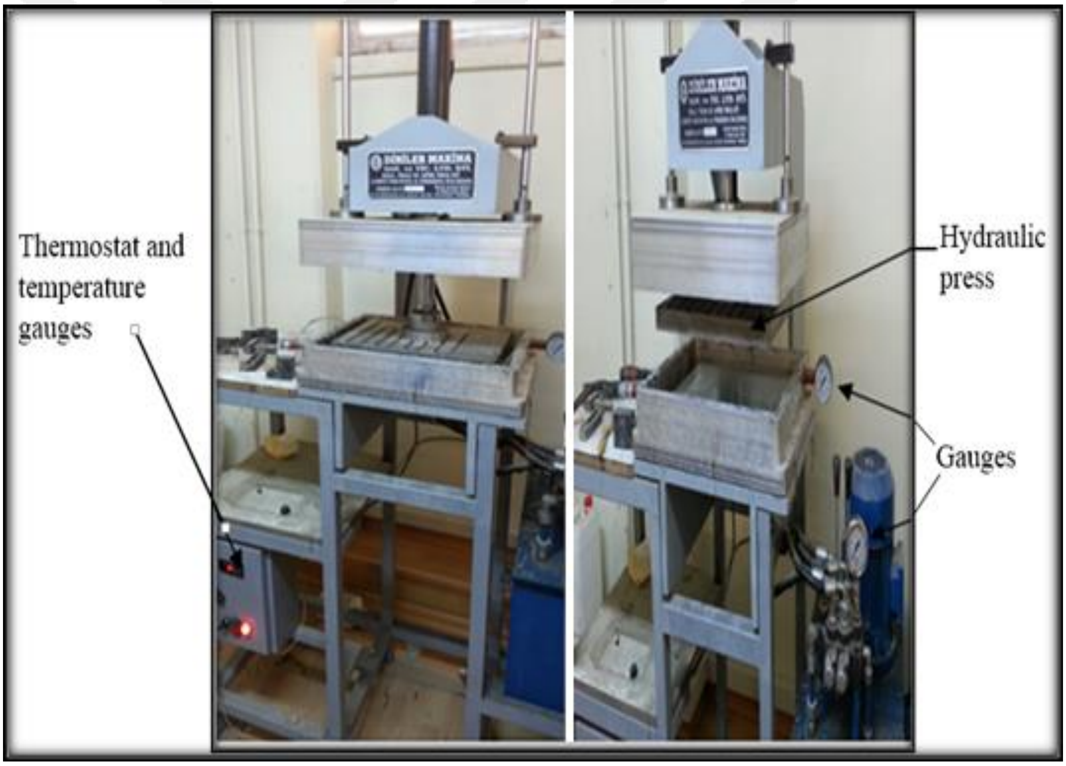


Figure 3.10 Hot press.

Figure 3.11 Hand lay-up method.

3.4 Epoxy Resin System Preparation

The epoxy and hardener prepared according to the stoichiometric ratio of 100:40 which is indicated on the containers. The amount of resin (epoxy and hardener mixture) was calculated by weighting the total pieces of fibers that it need to make a laminate and use that value of weight to estimate the total weight of resin for example the weight of 10 pieces of fiber glass equals 180 grams, thus the total weight of resin equals 180 grams and the weight of epoxy equal to:

$$weight\ of\ epoxy = 180 \times 71.43 = 128.57\ grams$$

$$weight\ of\ hardener = 180 \times 28.57 = 51.43\ grams$$

$$total\ amount\ of\ resin = 128.57 + 51.43 = 180\ grams$$

This calculation is for the case of pure resin, calculation for nano additive epoxy resin is different than pure one. Weight of nano particle is subtracted from the total weight of matrix and then same calculations use carried out for epoxy and hardener. For example 180 grams of mixture is needed for 10 layers of glass fiber production and 2 we. % nanoclay is required to add mixture, the calculations become:

$$weight\ of\ nanoclay = 180 \times 0.02 = 3.6\ gram$$

$$weight\ of\ total\ resin = 180 - 3.6\ = 176.4\ gram$$

$$weight\ of\ epoxy = 176.4 \times 71.43 = 126\ gram$$

$$weight\ of\ hardener = 176.4 \times 28.57 = 50.4\ gram$$

$$total\ amount\ of\ mixture\ = 126 + 50.4 + 3.6 = 180\ gram$$

3.5 Production of Composite Laminates

3.5.1 Production of Glass Laminates with 12 Layers

The preparation of nanoclay filled epoxy based glass fiber reinforced composites was carried out by hand lay-up method. Twelve plies of glass fabric were cut into $130\ mm \times 100\ mm$ dimensions that enough to prepare specimens for impact test. For this work prepared five composite laminates with various percentages of nanoclay (0 wt.%, 1 wt.%, 2 wt.%, 3 wt.%, 5 wt.%) as shown in Figure 3.12.

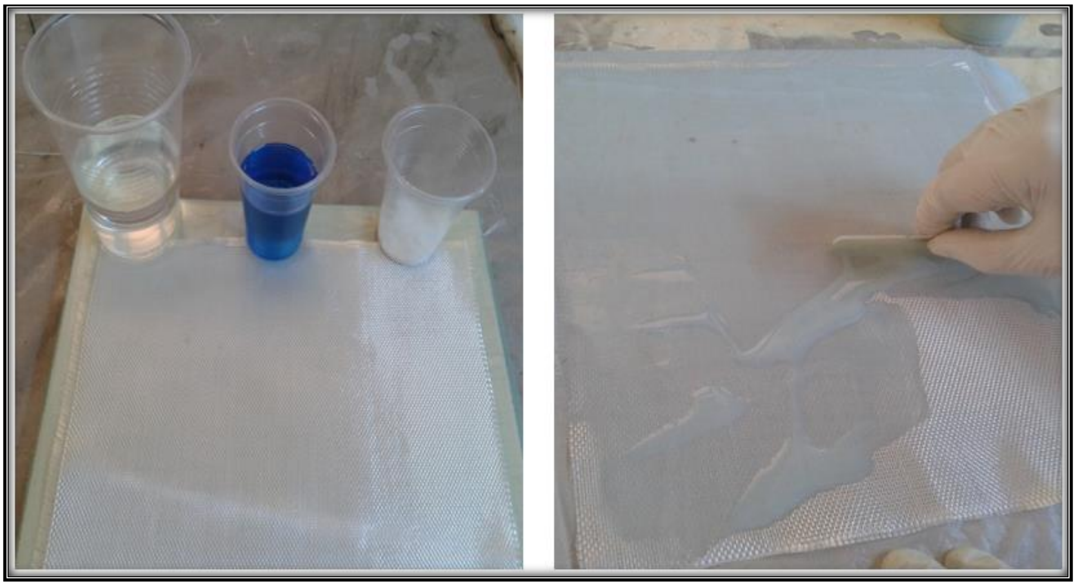
(a)

(b)

Figure 3.12 Glass laminates (G_{12}) with various percentages of nanoclay. (a) before fabrication (b) after fabrication

3.5.2 Production of Glass Laminate with 10 Layers

In this section, nanoclay modified glass fiber reinforced laminates were prepared using 0 wt.% and 1 wt.% nanoclay. The fabrication of laminates were done by stacking 10 plies of glass fabric and using hand lay-up technique. The fabrics were cut into 130 mm×100 mm dimensions to obtain enough number of specimens for Charpy impact test and to compare the results with hybrid configurations. As shown in Figure 3.13, five composite laminates were prepared using 0.5 wt.%, 1 wt.%, 1.5 wt.%, 2 wt.% and 3wt.% of nanosilica additive to conduct Charpy impact test



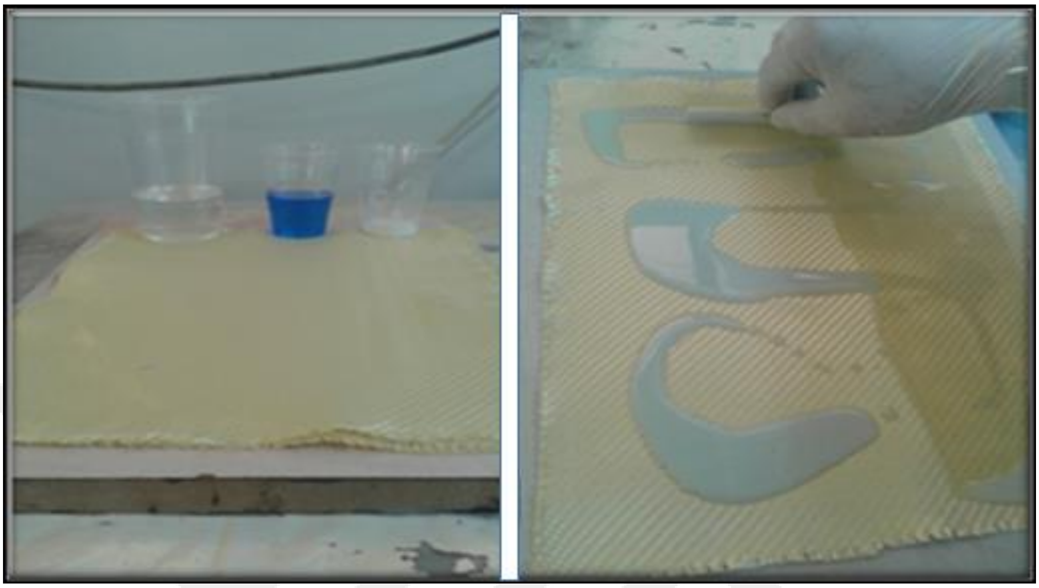
(a)

(b)

Figure 3.13 Glass laminate (G_{10}). (a) before fabrication (b) after fabrication

3.5.3 Production of Kevlar Laminate with 10 Layers

The preparation of nanoclay filled epoxy based Kevlar fiber reinforced composites was carried out by hand lay-up method. 10 plies of Kevlar fabric were cut into 130 mm × 100 mm dimensions that enough to prepare specimens for impact test. Two composite laminates were produced with percentage of nanoclay 0 wt.%, 1 wt.% to get 5 flatwise specimen pure, 5 edgewise specimen pure, 5 flatwise specimen with 1 wt.% nanoclay and 5 edgewise specimens with 1 wt.% nanoclay to make impact test to compare it with a hybrid composite. As shown in Figure 3.14.



(a)

(b)

Figure 3.14 Kevlar laminate. (a) before fabrication (b) after fabrication

3.5.4 Preparation of Hybrid Laminate

The preparation of nanoclay filled epoxy based hybrid composites was carried out by hand lay-up method. 10 plies of hybrid composite fabric were cut into 130 mm × 100 mm dimensions that enough to prepare specimens for impact test. Four hybrid composite configurations were produced as $[K_1G_4]_s$, $[K_2G_3]s$, $[K_3G_2]s$, $[K_4G_1]s$. Five different nanoclay weight ratios 0.5 wt.%, 1wt.%, 2 wt.%, 3 wt.%, 5 wt.% were investigated for $[K_1G_4]s$ hybrid configurations to see the effect of nanoclay ratios on hybrid configurations. After that other hybrid configurations were investigated for 1 wt.% nanoclay addition to see the effect of hybridization on nanocomposites. To do that flatwise and edgewise spacemen were prepared for impact tests. Also pure glass and Kevlar composites were tested. Hybrid configuration are shown in Figure 3.15.

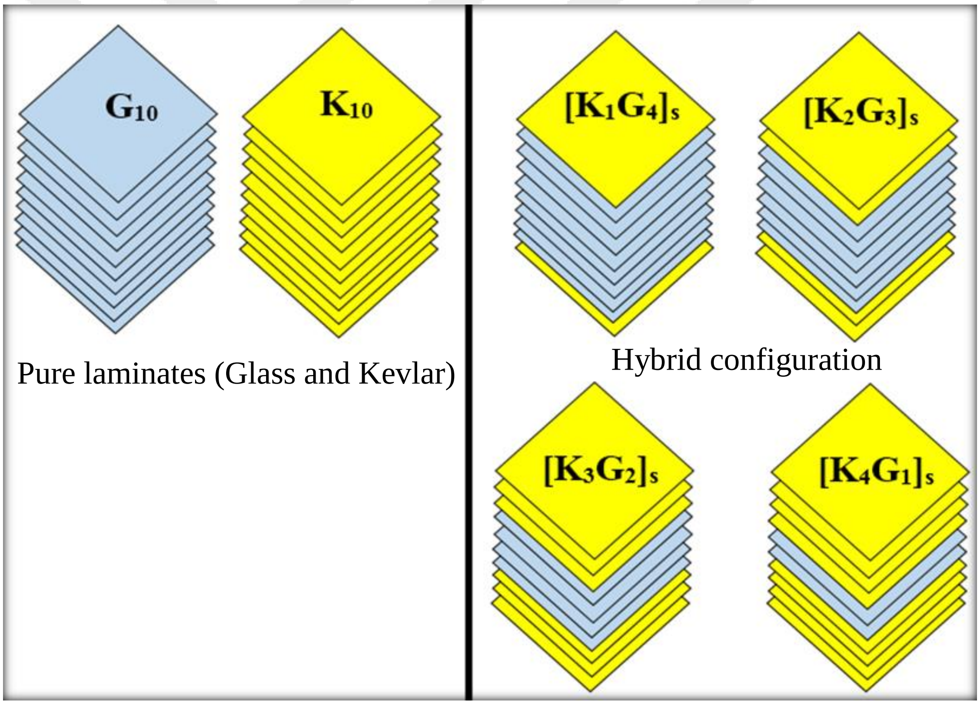


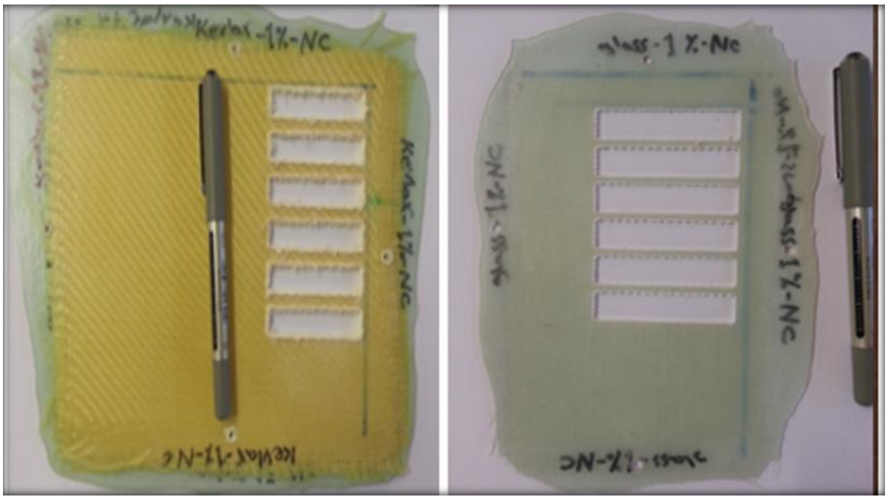
Figure 3.15 Hybrid configuration

3.5.5 CNC Machine

CNC machine was used to remove impact test specimens from the fabricated laminates. A high accuracy cutting according to the required dimensions were done with a cutter of 1 mm in diameter. The dimensions of the produced specimens were 55 mm × 10 mm and with two groups, one is with edgewise and the other is without. Figure 3.16 shows the CNC machine, specimens and laminates after cutting.

(a)

(b)



(c)

Figure 3.16 (a) CNC Machine (b) specimens (c) laminate after cutting.

3.6 Impact Test

3.6.1 Introduction

Izod, Charpy pendulum impact test, drop weight test and gas gun test are the common test methods to measure the impact response of composite structures [109]. In this study Charpy impact test were used.

3.6.2 Charpy Impact Test

Charpy impact test was conducted according ISO 179/92 standard. A Köger 3/70 Charpy impact test machine, as shown in Figure 3.17 was used in the tests. Before starting test, the device was calibrated and scaled by putting the device on a smooth and flat surface to obtain more reliable results during testing as shown in Figure 3.18. Flatwise and edgewise specimens are illustrated in Figure 3.19.

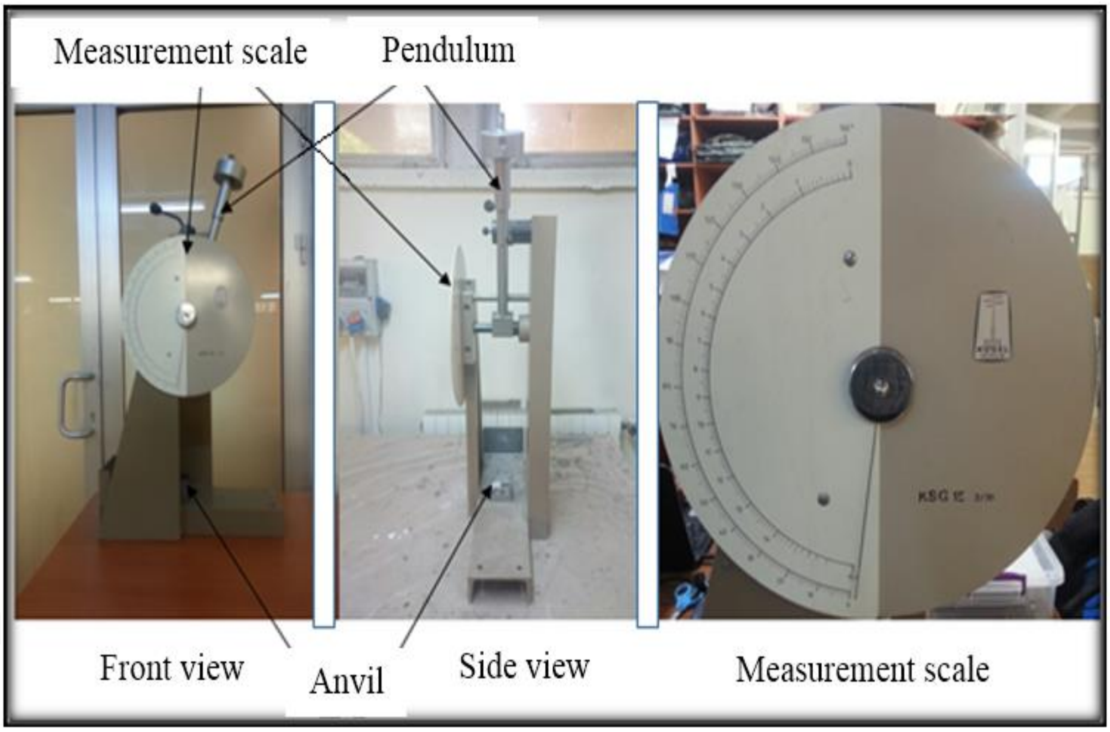


Figure 3.17 Charpy impact test machine.

Figure 3.18 Charpy impact test machine scaling.

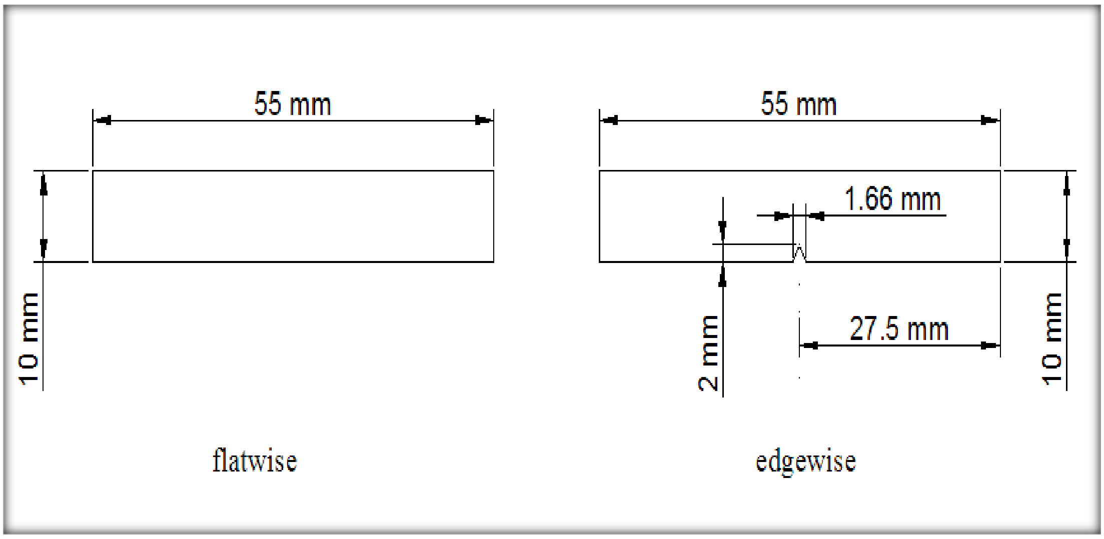


Figure 3.19 Flatwise and edgewise specimens.

Flatwise and edgewise specimens were subjected to impact loads while they are put in positions shown in Figure 3.20. For each laminate structure and test configuration (edgewise and flatwise), five specimens were tested. All tests were performed at standard weather conditions. The sample was supported on a horizontal plane and exposed to oscillating loading by a pendulum blow from the opposite of the edgewise.

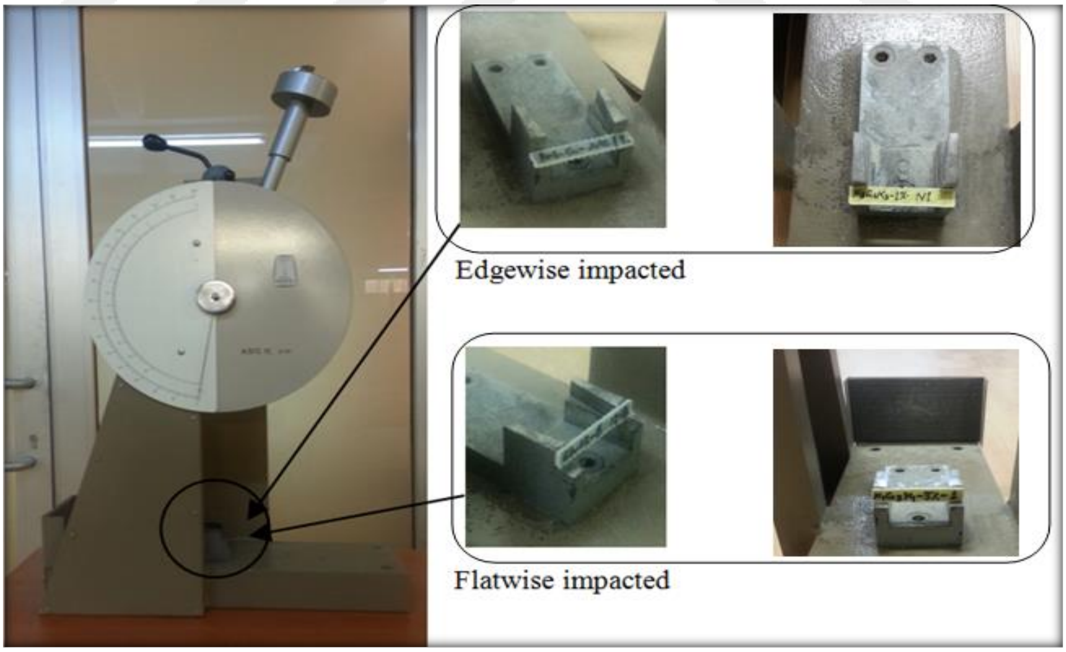


Figure 3.20 Flatwise and edgewise impact loadings.

The absorbed impact energy and impact toughness of specimens were determined according to the following equations:

$$E = E_a - E_b \tag{1}$$

$$a_{cu} = \frac{E}{b \times h} \tag{2}$$

where, E, E_a, E_b, in Equation (1) represent the absorbed impact energy, potential energy of the weighted pendulum before and after impact respectively, and a_{cu} , h and b in Equation (2) represent impact toughness, thickness and width of the test specimen, respectively. Figure 3.21 shows all the parameters.

Average values and standard deviations for the absorbed impact energy and impact toughness were used to assess the effect of nanoclay and nanosilica particles.

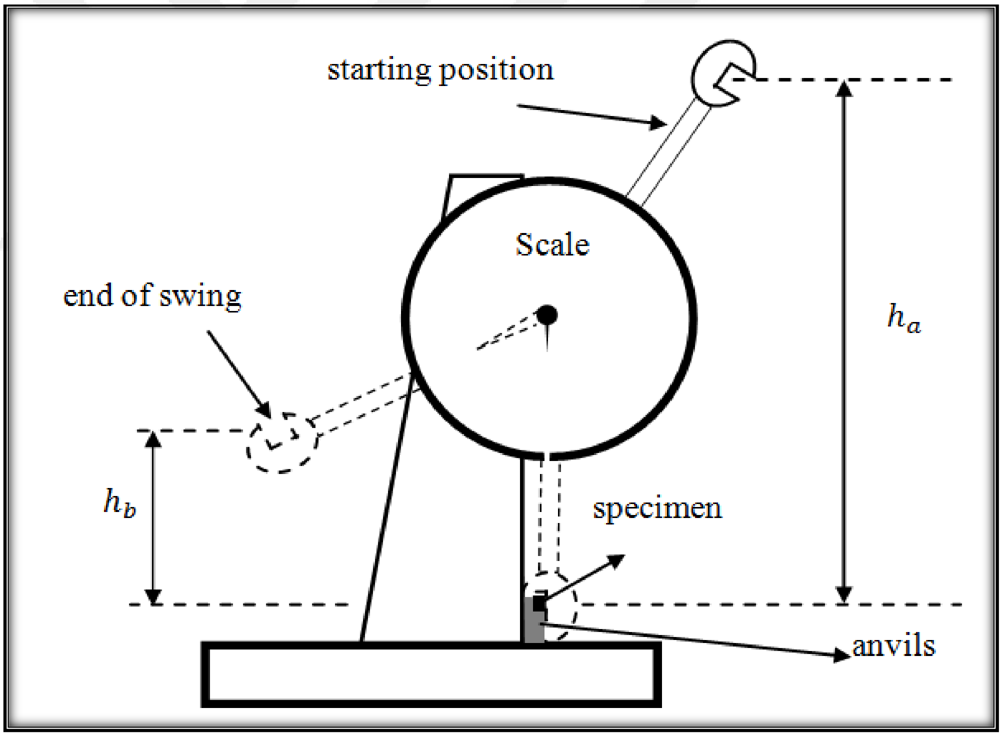


Figure 3.21 Pendulum before and after impact.

CHAPTER 4

EXPERIMENT RESULTS AND DISCUSSION

4.1 Introduction

The results obtained from the experimental work on the impact testing of different laminate composites were presented using several tables and figures, which represent the value of the absorbed energy of the prepared composite laminates of nanoclay modified glass/epoxy, Kevlar/epoxy and several configuration glass/Kevlar/epoxy hybrid fiber reinforced composites, and nanosilica modified glass/epoxy composite laminates.

4.2 Impact Test Results of 12 ply Glass with Nanoclay

The Charpy impact test was performed to measure the absorbed impact energy for 12 layers glass/epoxy nanoclay composite. The impact energy values for edgewise impacted specimens are recorded in Table 4.1 and plotted against nanoclay contents as shown in Figure 4.1.

Table 4.1 Absorbed impact energy values for edgewise specimens of glass with nanoclay.

	Absorbed impact energy (J)				
	Nanoclay percentage %				
Specimen No.	0	1	2	3	5
1	3.80	3.80	4.60	4.00	4.00
2	3.3	3.70	4.40	3.90	3.90
3	3.50	3.60	4.10	3.80	3.60
4	3.90	3.60	4.40	3.90	4.00
5	3.50	3.80	4.00	4.15	4.00
Average	3.60	3.70	**4.30**	3.95	3.90
Deviation	0.24	0.10	0.24	0.13	0.17
	Percentage variation, compared to neat glass specimens				
	0.00	2.78	**19.44**	9.72	8.33

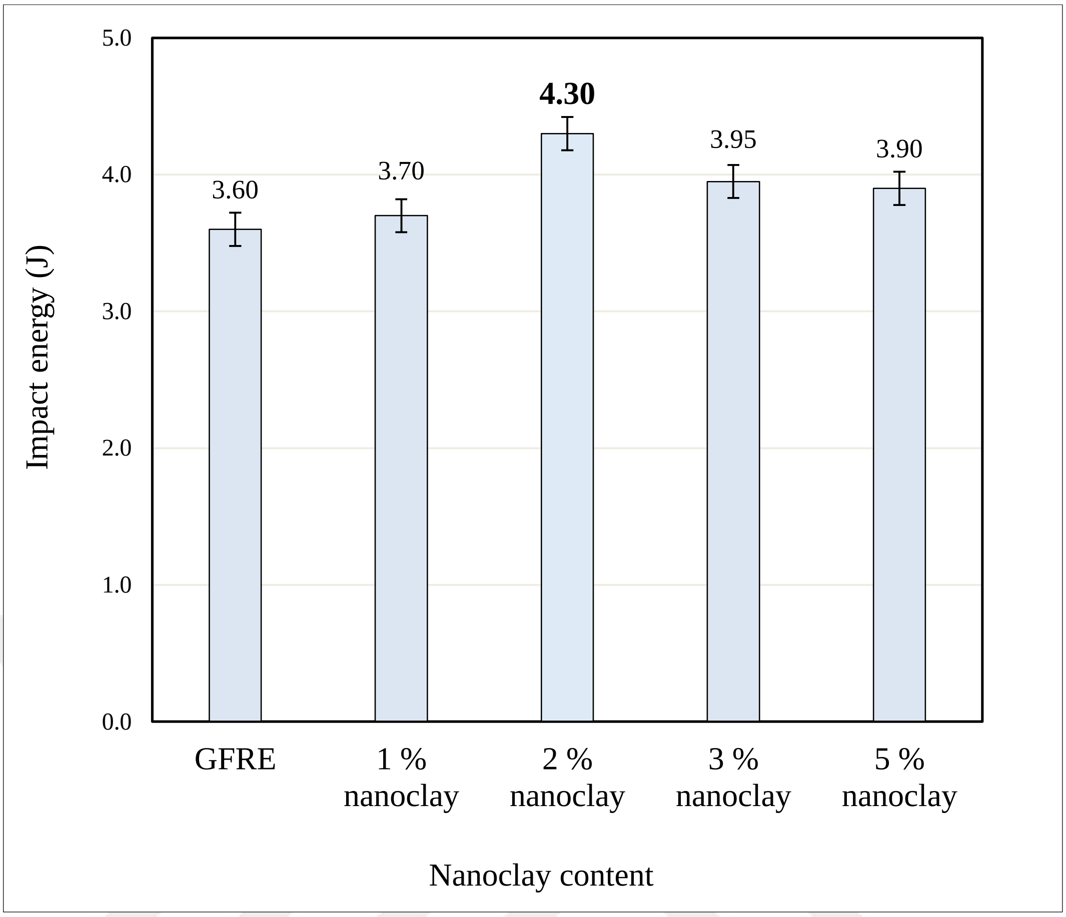


Figure 4.1 Absorbed impact energy values for edgewise specimen against nanoclay contents (G_{12}).

The impact toughness values for edgewise impacted specimens are given in Table 4.2 and plotted against nanoclay contents as shown in Figure 4.2.

Table 4.2 Impact toughness values for edgewise specimens of glass with nanoclay

(wt.%) of Nanoclay	Thickness (mm)	Impact toughness (kJ/m^2)	Percentage variation with neat specimen
0	2.24	160.71	0.00
1	2.58	143.13	-10.93
2	2.70	159.26	-0.90
3	2.83	139.18	-13.39
5	2.74	142.08	-11.59

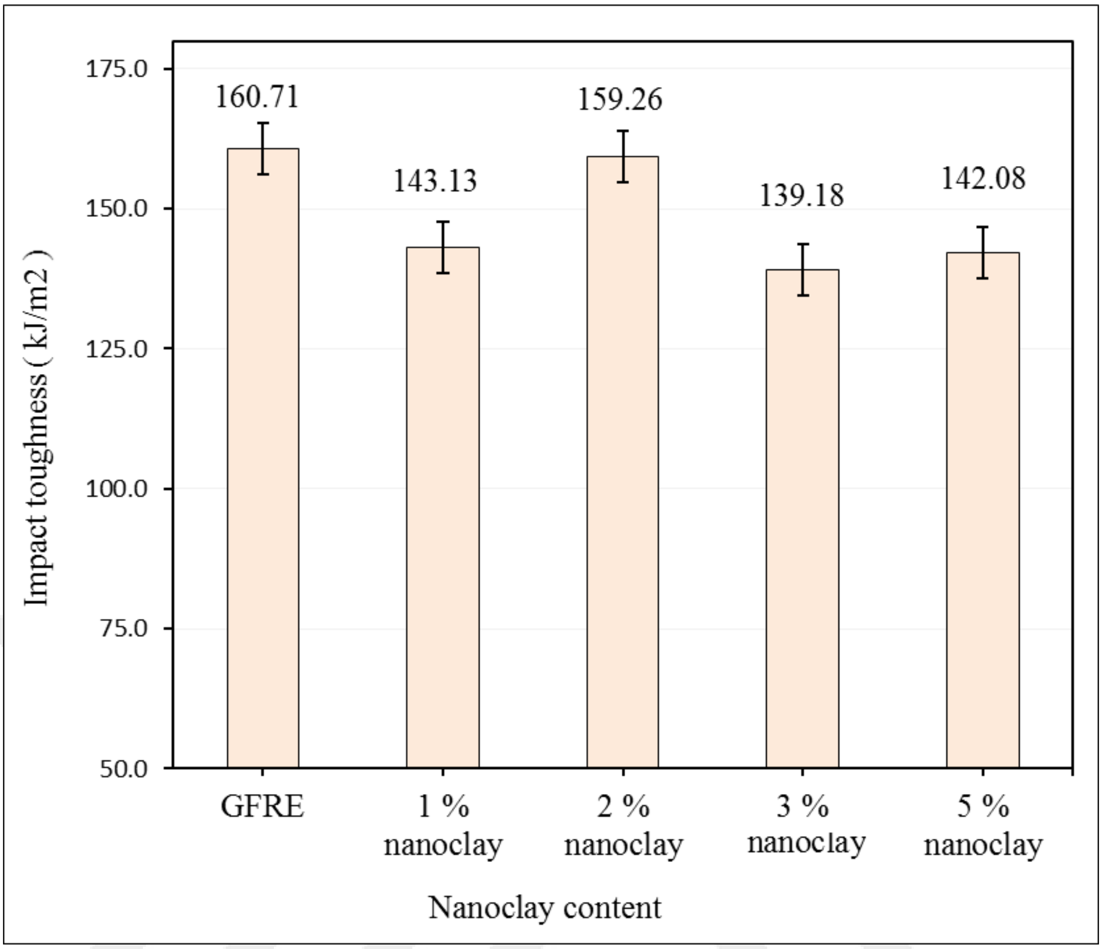


Figure 4.2 Impact toughness values for edgewise against nanoclay contents (G_{12}).

The Figure 4.3 and Figure 4.4 show the sample of edgewise specimen before and after test respectively.

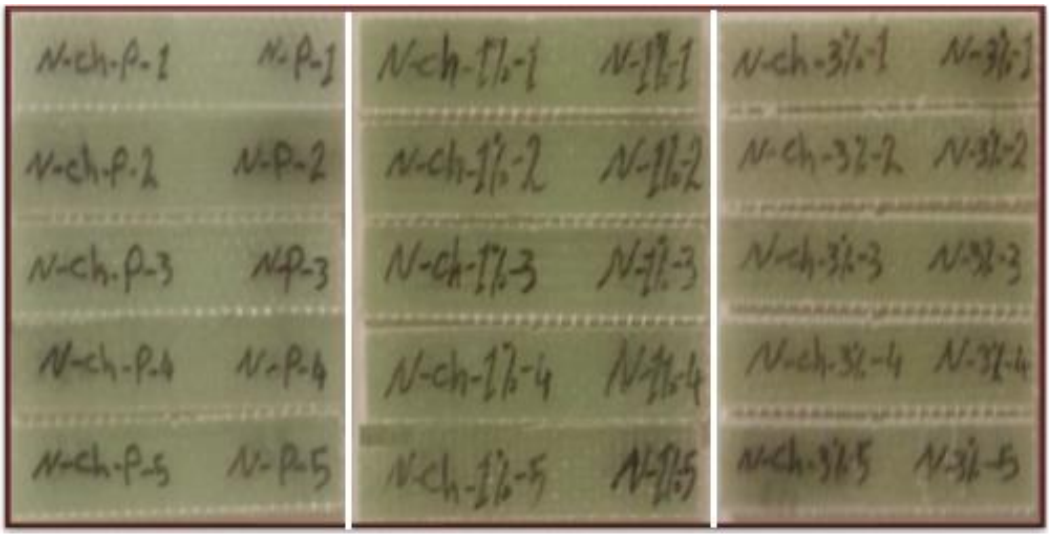


Figure 4.3 Sample of edgewise specimen before test (G_{12}).

Figure 4.4 Sample of edgewise specimen after test (G_{12}).

The impact energy values for flatwise impacted specimens are recorded in Table 4.3 and plotted against nanoclay contents as shown in Figure 4.5.

Table 4.3 Absorbed impact energy values for flatwise specimens of glass with nanoclay.

Absorbed impact energy (J)					
Specimen No.	Nanoclay percentage %				
	0	1	2	3	5
1	3.00	3.10	3.20	2.40	2.70
2	2.80	3.30	3.15	2.30	2.90
3	2.90	3.10	3.30	2.40	2.50
4	3.00	3.00	3.50	2.30	3.10
5	2.80	3.15	3.00	2.35	2.40
Average	2.90	3.13	**3.23**	2.35	2.72
Deviation	0.10	0.11	0.19	0.05	0.29
	Percentage variation, compared to neat glass specimens				
	0.00	7.93	**11.38**	-18.97	-6.21

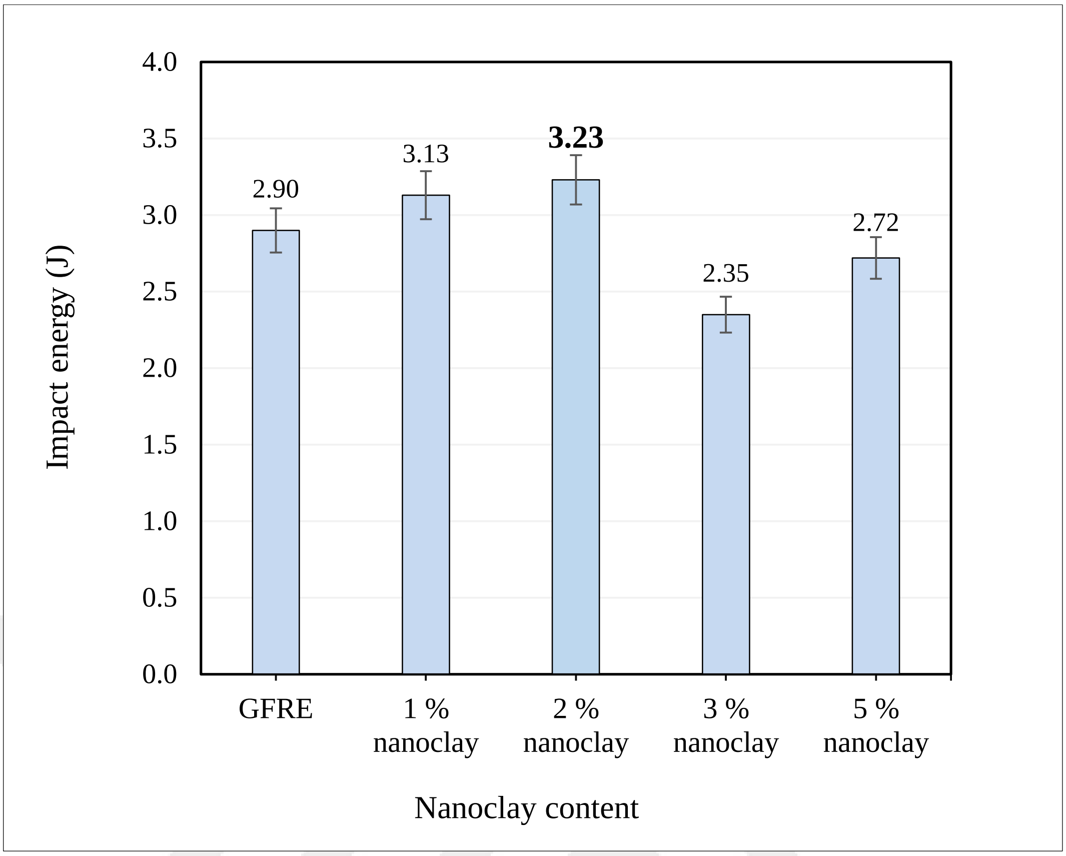


Figure 4.5 Absorbed impact energy values for flatwise specimen against nanoclay contents (G_{12}).

The impact toughness values for flatwise impacted specimens of glass are recorded in Table 4.4 and plotted against nanoclay contents as shown in Figure 4.6.

Table 4.4 Impact toughness values for flatwise specimens of glass with nanoclay

(wt.%) of Nanoclay	Thickness (mm)	Impact toughness (kJ/m^2)	Percentage variation with neat specimen
0	2.20	131.82	0.00
1	2.71	115.50	-12.38
2	2.71	119.19	-9.58
3	2.58	91.09	-30.89
5	2.72	100.00	-24.13

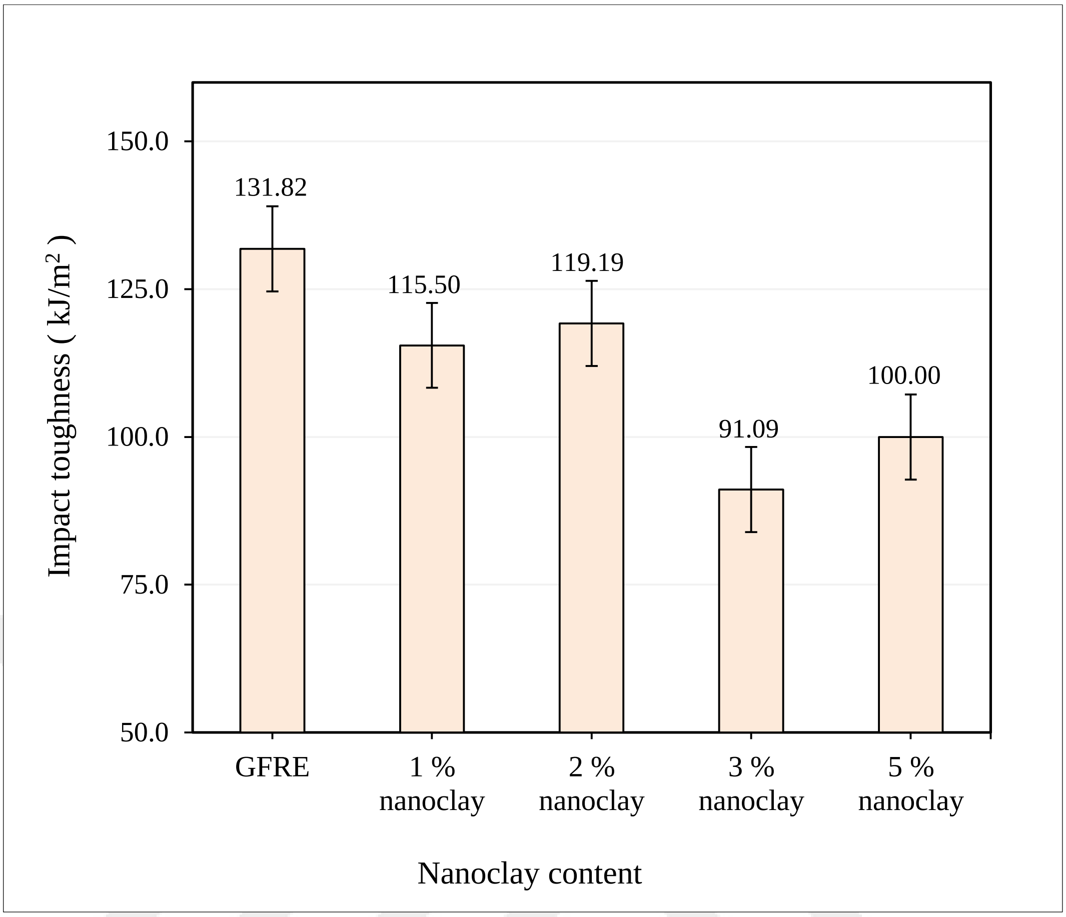


Figure 4.6 Impact toughness values for flatwise specimen against nanoclay contents (G_{12}).

Figure 4.7 and Figure 4.8 show the sample of flatwise specimen before and after test respectively.

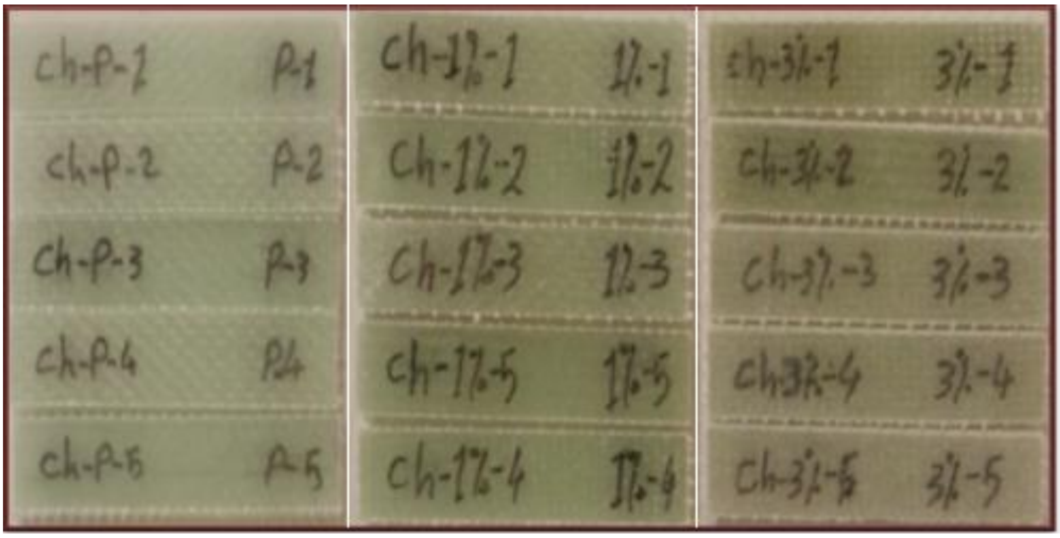


Figure 4.7 Sample of flatwise specimen before test (G_{12}).

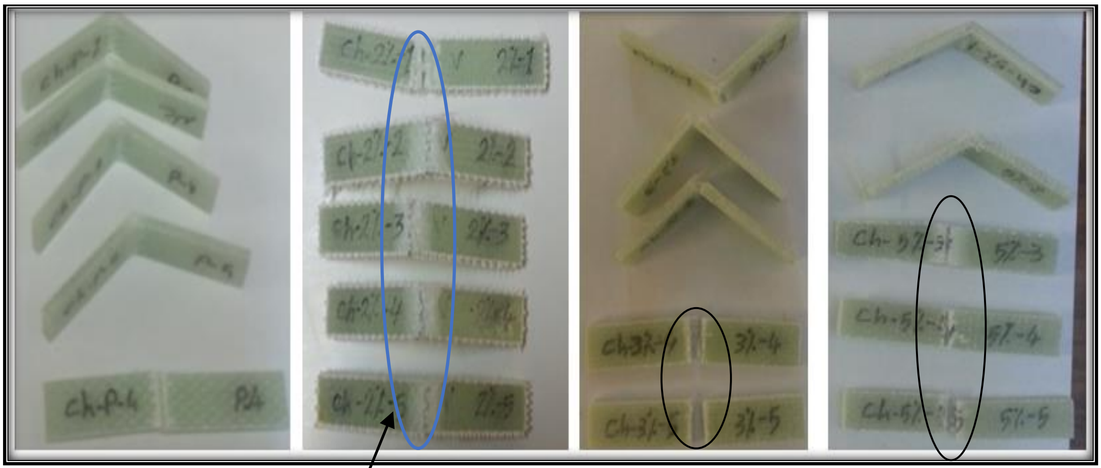


Figure 4.8 Sample of flatwise specimen after test (G_{12}).

Compared to impact energy of neat glass fiber reinforced epoxy composite, the achieved increment in absorbed impact energy for the edgewise specimens of nanoclay filled glass fiber reinforced epoxy composites are 2.78%, 19.44%, 9.72% and 8.33% for 1 wt.%, 2 wt.%,3 wt.% and 5 wt.%, respectively. The variation in absorbed impact energies for the flatwise test specimens of nanoclay filled glass fiber reinforced epoxy composites are 7.93%, 11.38%, -18.97% and -6.21% for 1 wt.%, 2 wt.%, 3 wt.% and 5 wt.%, respectively.

It was shown that the addition of nanoclay into glass fiber reinforced epoxy became more significant at 2 wt.% nanoclay content and it led the highest impact energy absorption. From Figure 4.8, the 2 wt.% nanoclay added laminate displayed fiber pullout and matrix cracking at impacted surface near to the point of impact. Fiber breakage and matrix cracking over a comparatively wide region were shown as impact damage on the backside of impact point. However, the fracture surface of 2 wt.% nanoclay filled laminates were larger than those of 3 wt.% and 5 wt.% of nanoclay filled laminates. The nanoclay provides good interfacial properties which in turn enhancement on impact performance and damage control [84]. The nanoclay inclusion increased the stiffness of composite laminates, controlled the crack propagation, and reduced the fiber pull-out failures. All these improvements can be attributed to the interfacial properties which resulted in the enhancement on bonding between matrix and fiber [84]. At higher content, the addition of nanoclay is not so effective in improvement of impact energy absorption. Probably, it can be attributed to the agglomeration of nanoclay particles which resulted with a weak interfacial adhesion [110, 87, 6].

4.3 Impact Test Results (10 ply Glass, Kevlar and Hybrid) with Nanoclay

10 layer glass/epoxy, Kevlar/epoxy and hybrid configurations were tested with pure and 1 wt.% of nanoclay content. In this section, best hybrid configuration was investigated for constant nanoclay content. The impact energy values for edgewise impacted specimens of G_{10}, $[K_1G_4]_S$, $[K_2G_3]_S$, $[K_3G_2]_S$, $[K_4G_1]_S$ and K_{10} with pure and 1wt.% nanoclay addition are given in Table 4.7 and its variation is shown in Figure 4.9.

Table 4.5 Absorbed impact energy values for edgewise specimens of G_{10}, $[K_1G_4]_S$, $[K_2G_3]_S$, $[K_3G_2]_S$, $[K_4G_1]_S$ and K_{10} with nanoclay.

Absorbed impact energy (J)			
Hybrid Specimens	(0%) Nanoclay	(1%) Nanoclay	Percentage variation, compared to neat specimens
G_{10}	2.42	2.79	15.29
$[K_1G_4]_S$	2.74	3.05	**11.31**
$[K_2G_3]_S$	2.97	3.10	4.37
$[K_3G_2]_S$	3.08	3.12	1.30
$[K_4G_1]_S$	3.28	3.50	6.70
K_{10}	3.02	3.58	**18.54**

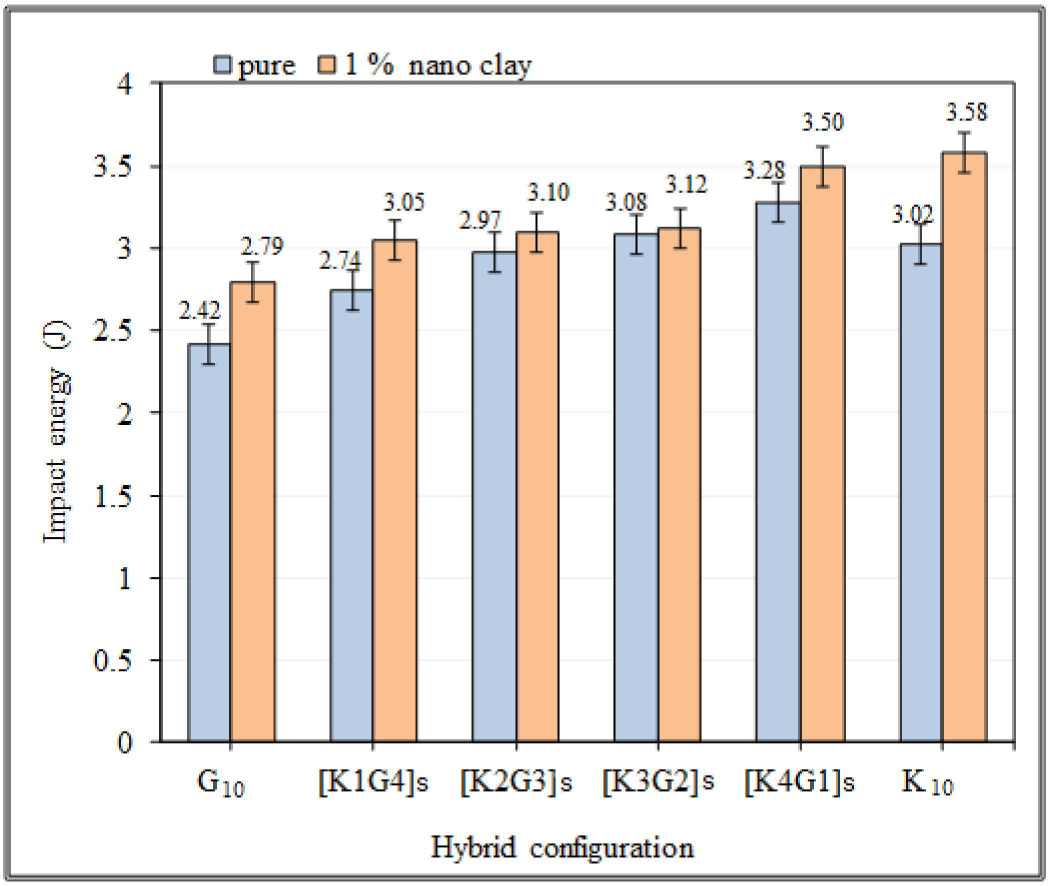


Figure 4.9 Absorbed impact energy values for edgewise specimen against nanoclay contents for (G, K and hybrid) with 0 wt.% and 1wt.% nanoclay.

The impact toughness values for edgewise impacted specimens of G_{10}, $[K_1G_4]_S$, $[K_2G_3]_S$, $[K_3G_2]_S$, $[K_4G_1]_S$ and K_{10} are recorded in Table 4.8 and plotted against nanoclay contents as shown in Figure 4.10.

Table 4.6 Impact toughness values for edgewise specimens of G_{10}, $[K_1G_4]_S$, $[K_2G_3]_S$, $[K_3G_2]_S$, $[K_4G_1]_S$ and K_{10} with nanoclay.

Laminates	Thickness (mm) 0 wt.% nanoclay	Impact toughness (kJ/m^2) 0 wt.% nanoclay	Thickness (mm) 1 wt.% nanoclay	Impact toughness (kJ/m^2) 1 wt.% nanoclay
Glass	2.02	119.80	2.00	139.50
$[K_1G_4]_S$	2.23	122.87	2.30	132.61
$[K_2G_3]_S$	2.18	136.24	2.37	130.80
$[K_3G_2]_S$	2.28	135.09	2.50	124.80
$[K_4G_1]_S$	2.50	131.20	2.50	140.00
Kevlar	2.04	148.04	2.02	177.23

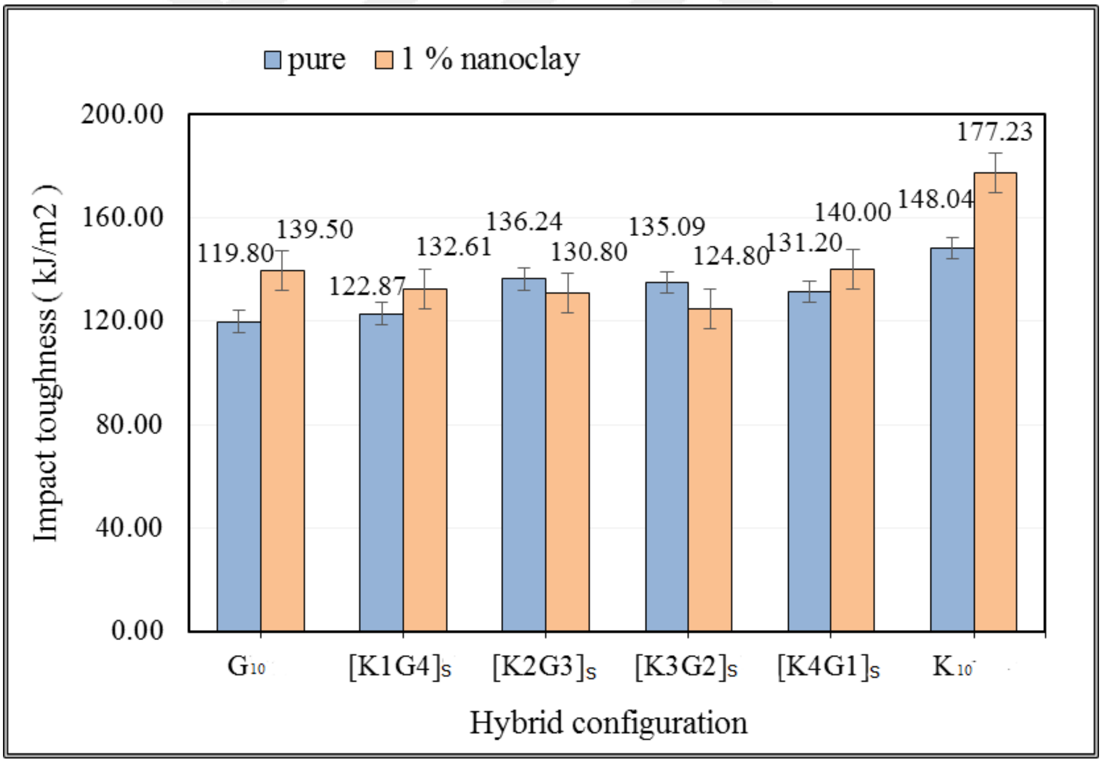


Figure 4.10 Impact toughness values for edgewise specimen against nanoclay contents for (G, K and hybrid) with 0 wt.% and 1 wt.% nanoclay.

The Figure 4.11 and Figure 4.12 show the sample of the edgewise specimen of hybrid with 0 wt.% and 1 wt.% nanoclay before and after test respectively.

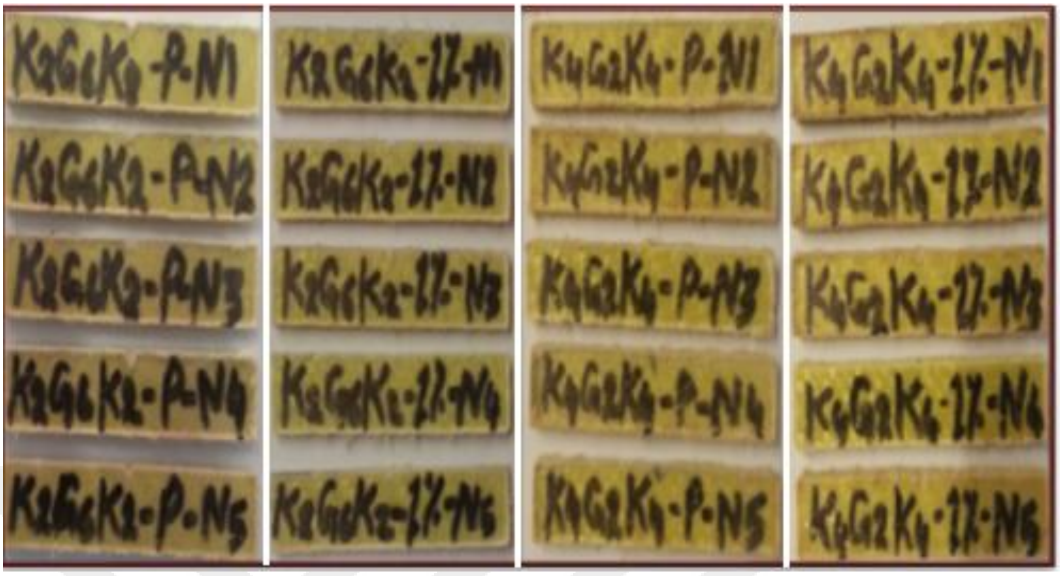


Figure 4.11 Sample of the edgewise specimen of hybrid with 0 wt.% and 1 wt.% nanoclay before test.

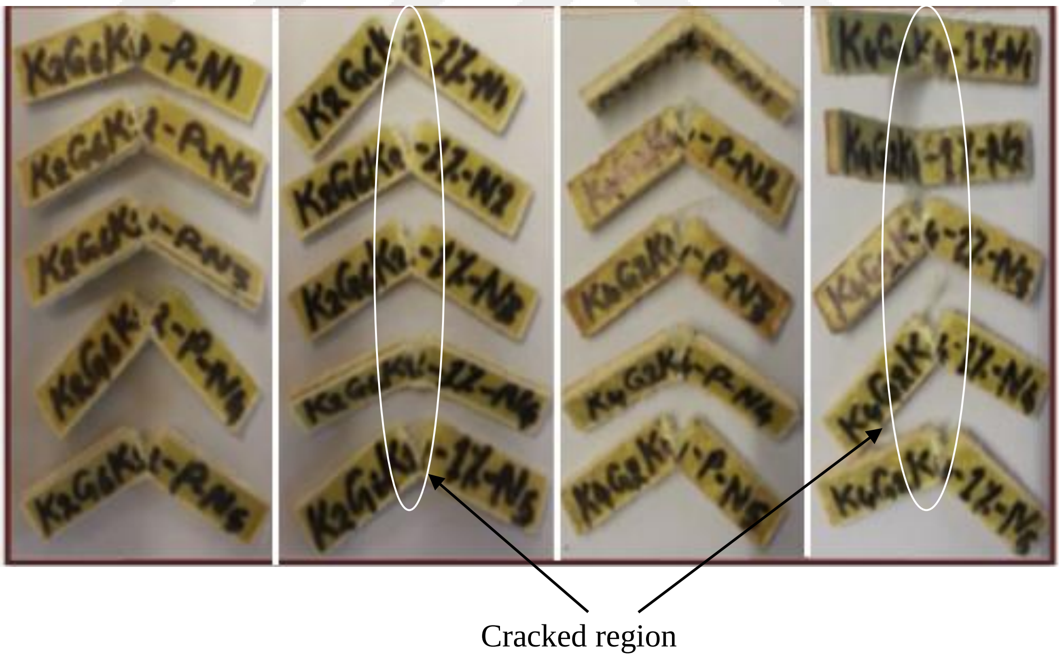


Figure 4.12 Sample of the edgewise specimen of hybrid with 0 wt.% and 1 wt.% nanoclay after test.

The results showed that the addition of nanoclay into hybrid edgewise specimens of $[K_1G_4]_S$ reinforced epoxy became more significant at 1 wt.% nanoclay content exhibited the highest impact energy absorption. The achieved increase in absorbing impact energy of the specimen $[K_1G_4]_S$ is 11.31 % and 15.29 % higher than neat G_{10} and 18.54% higher than neat K_{10}. From Figure 4.12, the edge side view indicates that the fracture damage of 1 wt.% nanoclay added laminates was larger than other and fiber pull-out of 1 wt.% nanoclay modified specimen was less that the others. The impact energy values for flatwise impacted specimens of G_{10}, $[K_1G_4]_S$, $[K_2G_3]_S$, $[K_3G_2]_S$, $[K_4G_1]_S$ and K_{10} with 0 wt.% and 1 wt.% nanoclay inclusions are recorded in Table 4.9 and plotted against nanoclay contents as shown in Figure 4.13.

Table 4.7 Absorbed impact energy values for flatwise specimens of G_{10}, $[K_1G_4]_S$, $[K_2G_3]_S$, $[K_3G_2]_S$, $[K_4G_1]_S$ and K_{10} with nanoclay.

	Absorbed impact energy (J)		
Hybrid Specimens	(0 wt.%) Nanoclay	(1 wt.%) Nanoclay	Percentage variation, compared to neat specimens
G_{10}	1.98	2.3	16.16
$[K_1G_4]_S$	2.18	2.68	**22.93**
$[K_2G_3]_S$	2.52	2.86	13.49
$[K_3G_2]_S$	2.56	2.88	12.50
$[K_4G_1]_S$	2.58	2.92	13.17
K_{10}	2.26	2.36	4.42

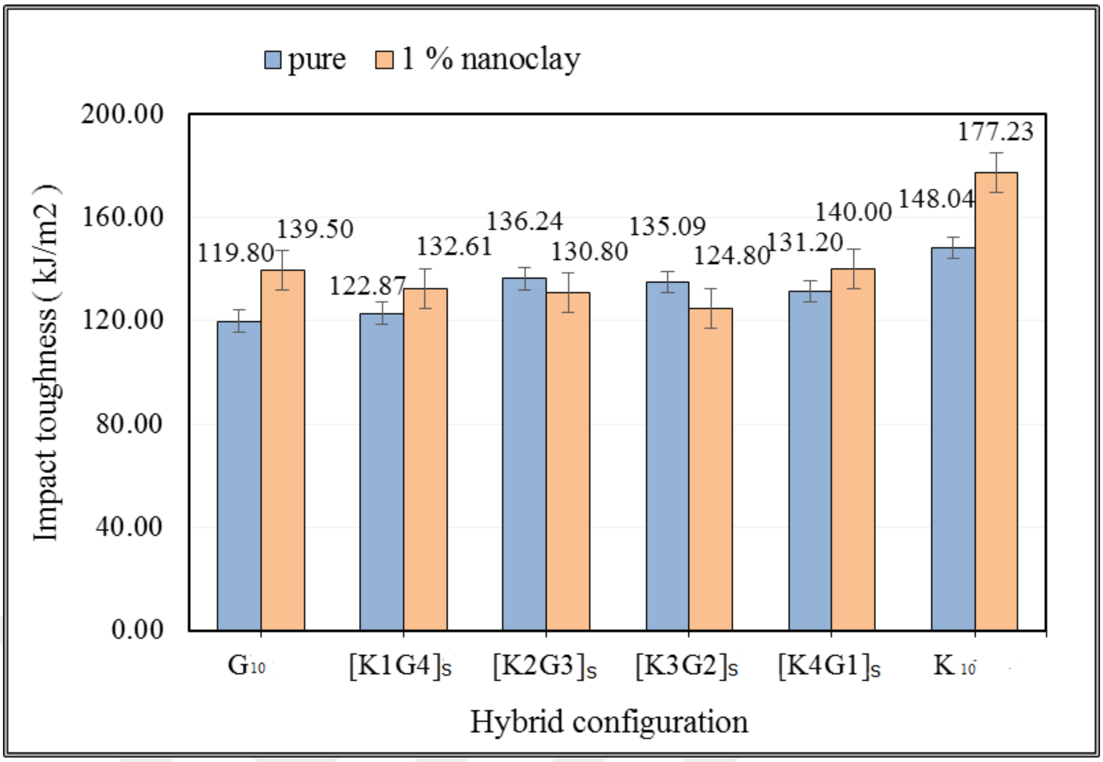


Figure 4.13 Absorbed impact energy values for flatwise specimen against nanoclay contents for (G, K and hybrid) with 0 wt.% and 1 wt.% nanoclay.

The impact toughness values for flatwise impacted specimens of G_{10}, $[K_1G_4]_S$, $[K_2G_3]_S$, $[K_3G_2]_S$, $[K_4G_1]_S$ and K_{10} are recorded in Table 4.10 and plotted against nanoclay contents as shown in Figure 4.14.

Table 4.8 Impact toughness values for flatwise specimens of G_{10}, $[K_1G_4]_S$, $[K_2G_3]_S$, $[K_3G_2]_S$, $[K_4G_1]_S$ and K_{10} with nanoclay.

Hybrid Specimens	Thickness (mm) 0 wt.% Nanoclay	Impact toughness (kJ/m^2) 0 wt.% Nanoclay	Thickness (mm) 1 wt.% Nanoclay	Impact toughness (kJ/m^2) 1 wt.% Nanoclay
G_{10}	2.00	99.00	2.00	115.00
$[K_1G_4]_S$	2.18	100.00	2.29	117.03
$[K_2G_3]_S$	2.17	116.13	2.33	122.75
$[K_3G_2]_S$	2.23	114.80	2.46	117.07
$[K_4G_1]_S$	2.50	103.20	2.56	114.06
K_{10}	2.55	88.63	3.00	78.67

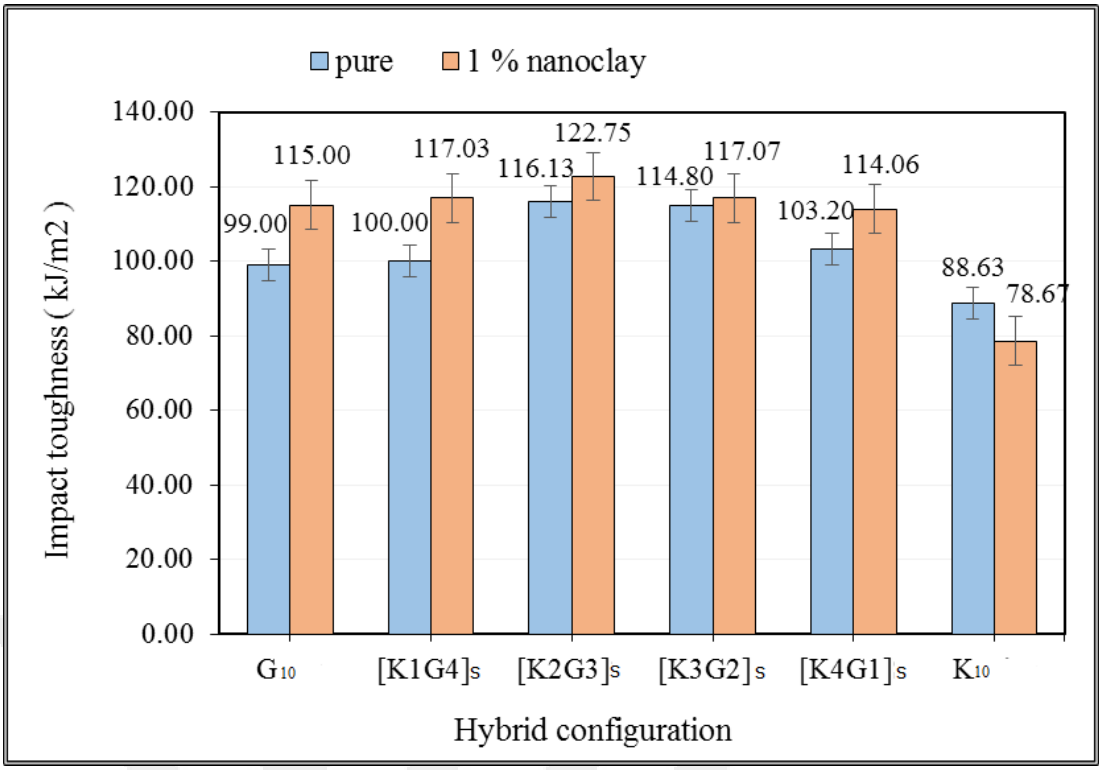


Figure 4.14 Impact toughness values for flatwise specimen against nanoclay contents for (G, K and hybrid) with 0 wt.% and 1wt.% nanoclay.

The Figure 4.15 and Figure 4.16 show the sample of the flatwise specimen of hybrid with 0 wt.% and 1wt.% nanoclay before and after test respectively.

Figure 4.15 Sample of the flatwise specimen of hybrid with 0 wt.% and 1wt.% nanoclay before test.

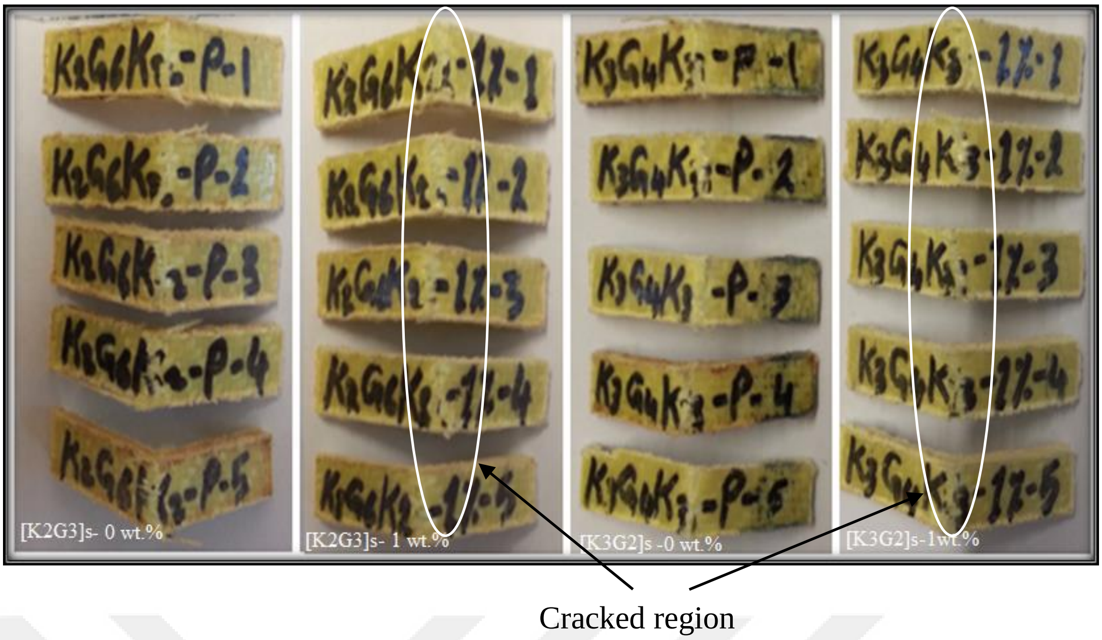


Figure 4.16 Sample of the flatwise specimen of hybrid with 0 wt.% and 1 wt.% nanoclay before and after test.

The results showed that the addition of nanoclay into hybrid flatwise specimens of $[K_1G_4]_S$ reinforced epoxy become more significant at 1 wt.% clay content at which the highest impact energy absorption was observed. The achieved increase in absorbing impact energy of the specimen $[K_1G_4]_S$ is 22.93% and 16.16% for G_{10} and 4.42% for K_{10}. From Figure 4.16, all specimens displayed fiber pullout and matrix cracking at the backside of impact point. The fiber pull-out characteristics of all specimens were similar but there were decrease on matrix cracking surface region with the addition of nanoclay.

The effect of nanoclay has examined with neat glass, neat Kevlar and hybrid configuration with 1 wt.% of nanoclay content. Depending on the results, the suitable hybrid configuration would be selected. As a result, hybrid composite laminates with $[K_1G_4]_S$ configuration provided the highest increase in impact energy with a percentage of 22.93 percent compared to specimens with zero nanoclay filler. Thus, the effect of nanoclay content on Charpy impact behavior is investigated using $[K_1G_4]_S$ hybrid configuration.

4.4 Impact Test Results for $[K_1G_4]_S$ with Various Nanoclay Content

The impact energy values for edgewise impacted specimens of hybrid $[K_1G_4]_S$ are recorded in Table 4.11 and plotted against nanoclay contents as shown in Figure 4.17.

Table 4.9 Absorbed impact energy values for edgewise specimens of hybrid $[K_1G_4]_S$ with nanoclay.

Absorbed impact energy (J)						
Specimen No.	Nanoclay percentage %					
	0	0.5	1	2	3	5
1	2.75	2.70	3.10	2.85	2.75	2.80
2	2.80	2.70	3.05	2.80	2.60	2.70
3	2.70	2.90	2.80	2.90	2.80	2.70
4	2.75	2.70	3.30	2.80	2.70	2.80
5	2.70	2.75	3.00	2.90	3.00	2.75
Average	2.74	2.75	**3.05**	2.85	2.77	2.75
Deviation	0.04	0.08	0.16	0.04	0.13	0.04
Percentage variation, compared to neat specimens						
	0.00	0.36	**11.31**	4.01	1.09	0.36

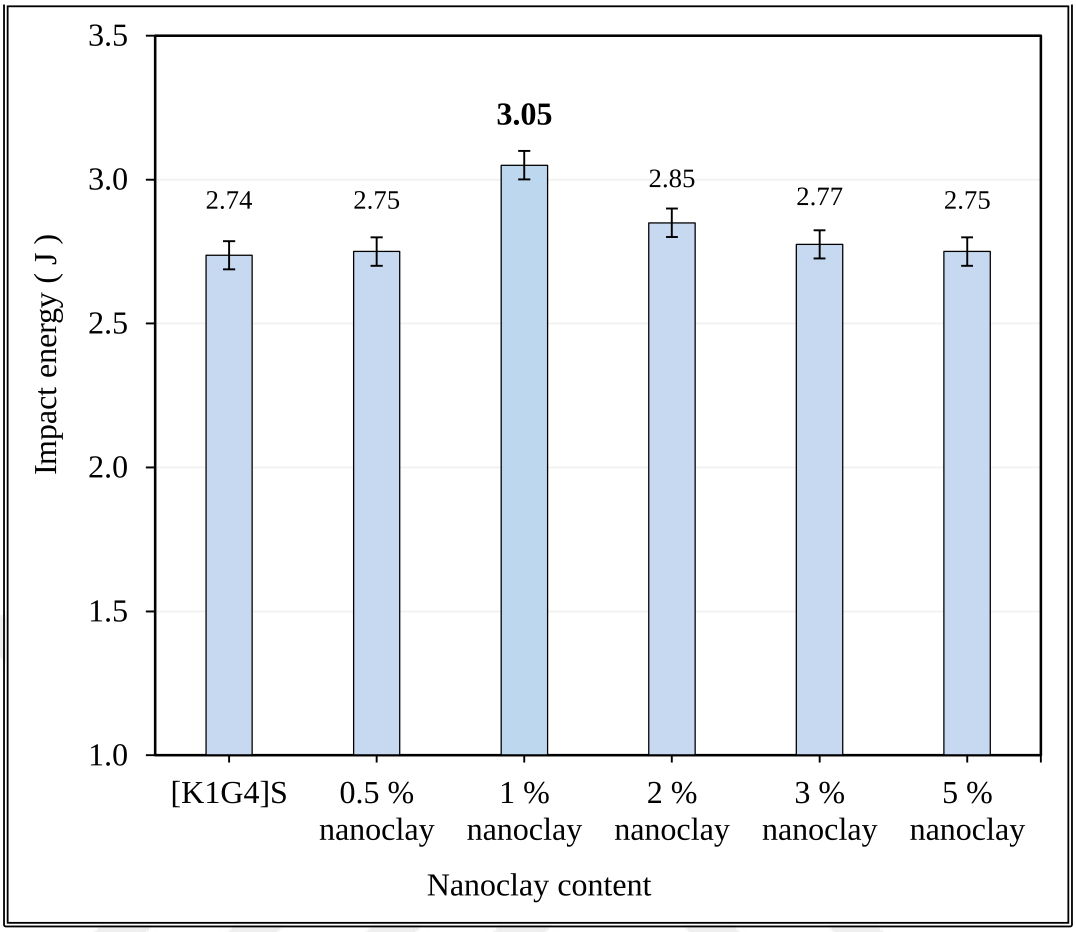


Figure 4.17 Absorbed impact energy values for edgewise specimen against nanoclay contents for $[K_1G_4]_S$.

The impact toughness values for edgewise impacted specimens of hybrid $[K_1G_4]_S$ are recorded in Table 4.12 and plotted against nanoclay contents as shown in Figure 4.18.

Table 4.10 Impact toughness values for edgewise specimens of hybrid $[K_1G_4]_S$ with nanoclay

(wt.%) of Nanoclay	Thickness (mm)	Impact toughness (kJ/m^2)	Percentage variation compared with neat specimen
0	2.23	122.87	0.00
0.5	2.20	125.00	1.73
1	2.30	132.61	7.92
2	2.20	129.55	5.43
3	2.17	127.65	3.89
5	2.19	125.57	2.19

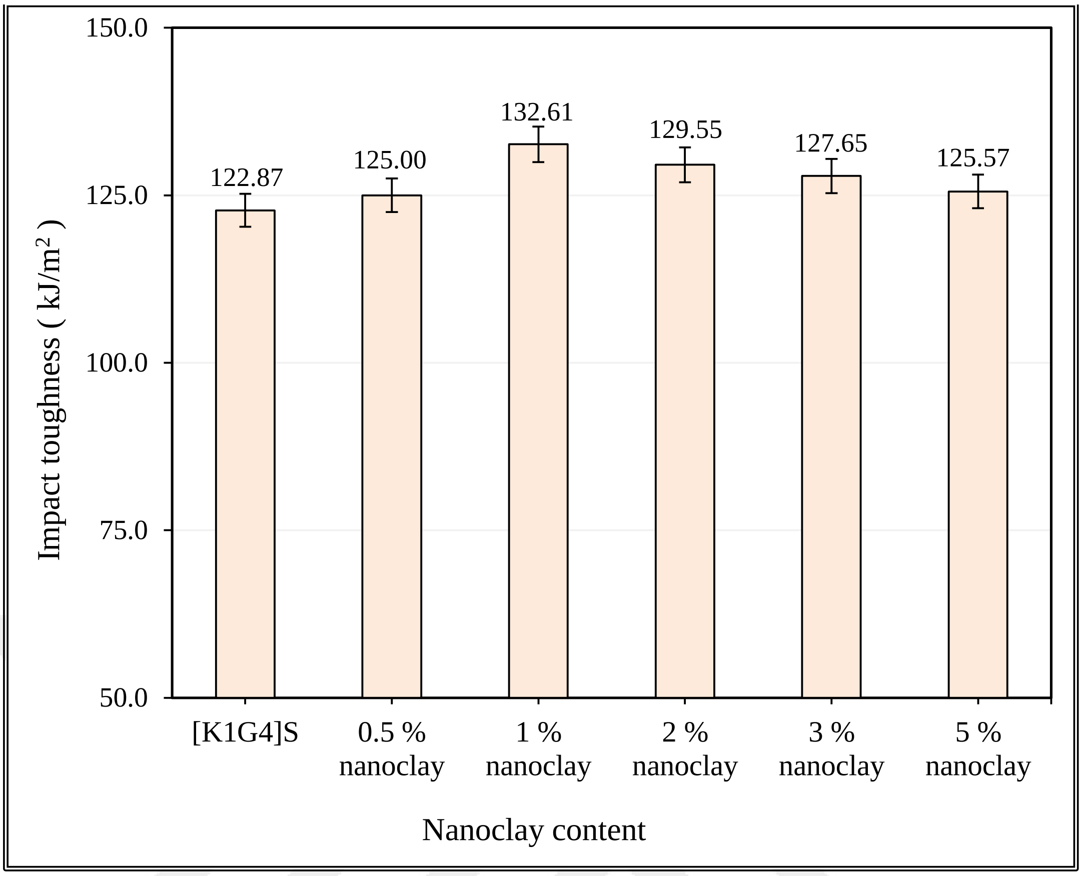


Figure 4.18 Impact toughness values for edgewise specimen against nanoclay contents for $[K_1G_4]_S$.

The Figure 4.19 and Figure 4.20 show the sample of the edgewise specimen of $[K_1G_4]_S$ before and after test respectively.

Figure 4.19 Sample of the edgewise specimen of $[K_1G_4]_S$ before test.

Figure 4.20 Sample of the edgewise specimen of $[K_1G_4]_S$ after test.

From the Figure 4.20, the edge side view indicates that the 1 wt.% nanoclay added laminate undergoes the highest degree of deformation. The 3 wt.% and 5 wt.% nanoclay added laminates displayed more fiber breakage, more matrix cracking and a small amount of delamination compared with 1 wt.%. The impact energy values for flatwise impacted specimens of hybrid $[K_1G_4]_S$ are given in Table 4.13 and plotted against nanoclay contents as shown in Figure 4.21.

Table 4.11 Absorbed impact energy values for flatwise specimens of hybrid $[K_1G_4]_S$ with nanoclay.

Absorbed impact energy (J)						
Specimen No.	Nanoclay percentage %					
	0	0.5	1	2	3	5
1	2.00	2.60	2.50	2.35	2.10	2.00
2	2.60	2.20	2.90	2.60	2.20	2.10
3	2.00	2.30	2.70	2.80	2.25	2.00
4	2.00	2.40	2.90	2.90	2.40	2.30
5	2.30	2.50	2.40	2.50	2.20	2.20
Average	2.18	2.40	**2.68**	2.63	2.23	2.12
Deviation	0.24	0.14	0.20	0.20	0.11	0.13
Percentage variation, compared to neat specimens						
	0.00	10.09	**22.94**	20.64	2.29	-2.75

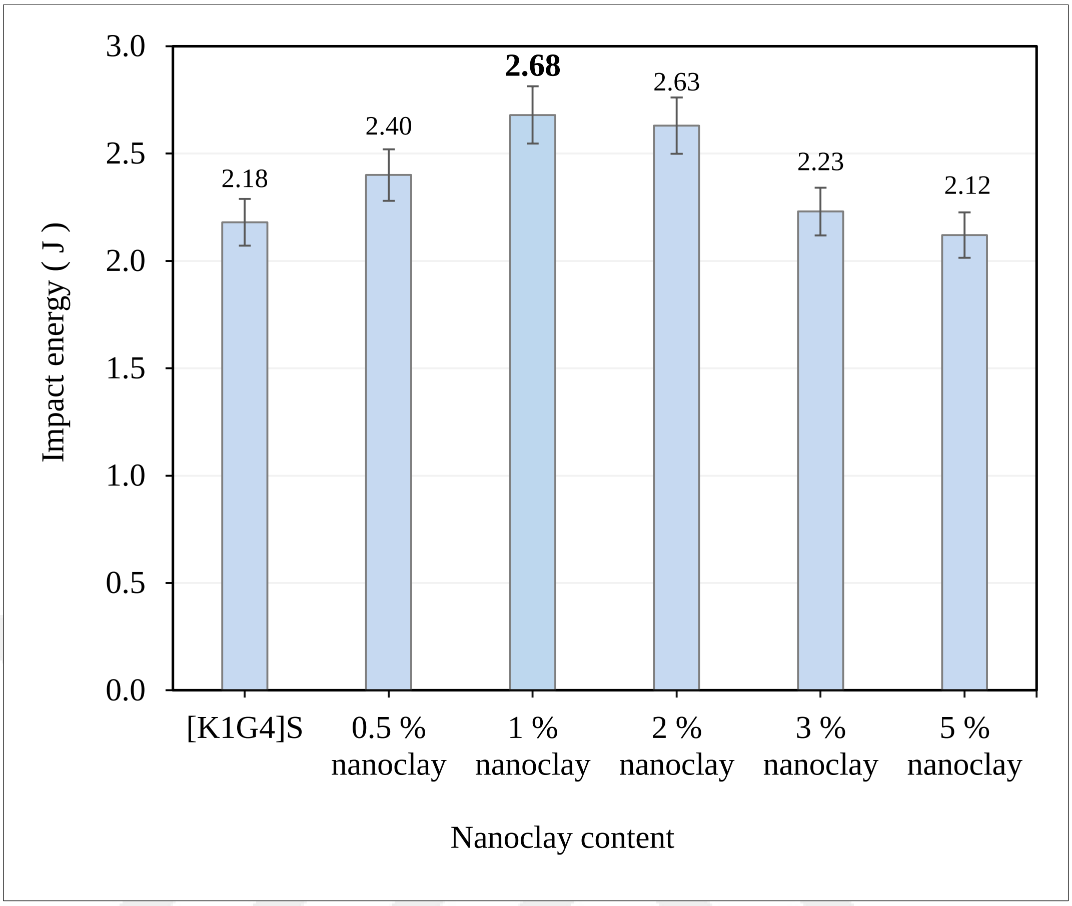


Figure 4.21 Absorbed impact energy values for flatwise specimen against nanoclay contents for $[K_1G_4]_S$.

The impact toughness values for flatwise impacted specimens of hybrid $[K_1G_4]_S$ are recorded in Table 4.14 and plotted against nanoclay contents as shown in Figure 4.22.

Table 4.12 Impact toughness values for flatwise specimens of hybrid $[K_1G_4]_S$ with nanoclay.

(wt.%) of Nanoclay	Thickness (mm)	Impact toughness (kJ/m^2)	Percentage variation compared with neat specimen
0	2.18	100.00	0
0.5	2.20	109.09	9.09
1	2.29	117.03	17.03
2	2.20	119.55	19.55
3	2.16	103.24	3.24
5	2.18	97.25	-2.75

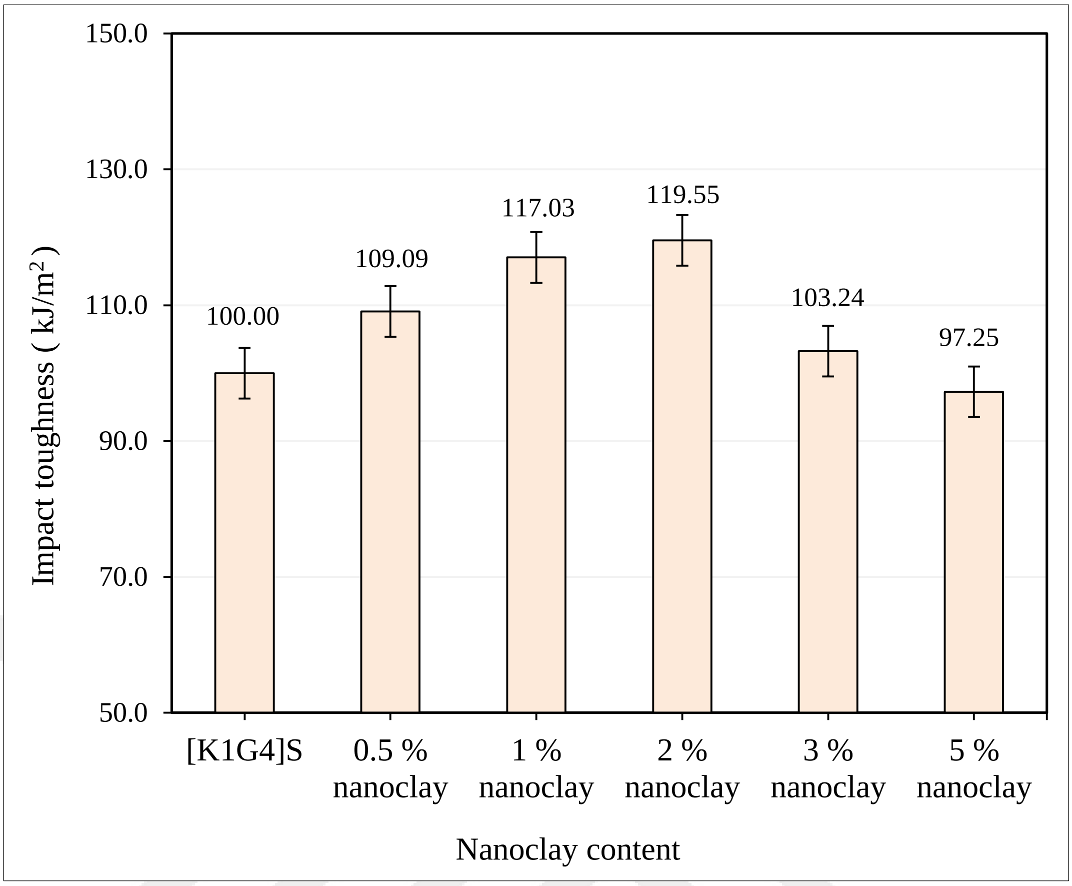


Figure 4.22 Impact toughness values for flatwise specimen against nanoclay contents for $[K_1G_4]_S$.

The Figure 4.23 and Figure 4.24 show the sample of the flatwise specimen of $[K_1G_4]_S$ before and after test respectively.

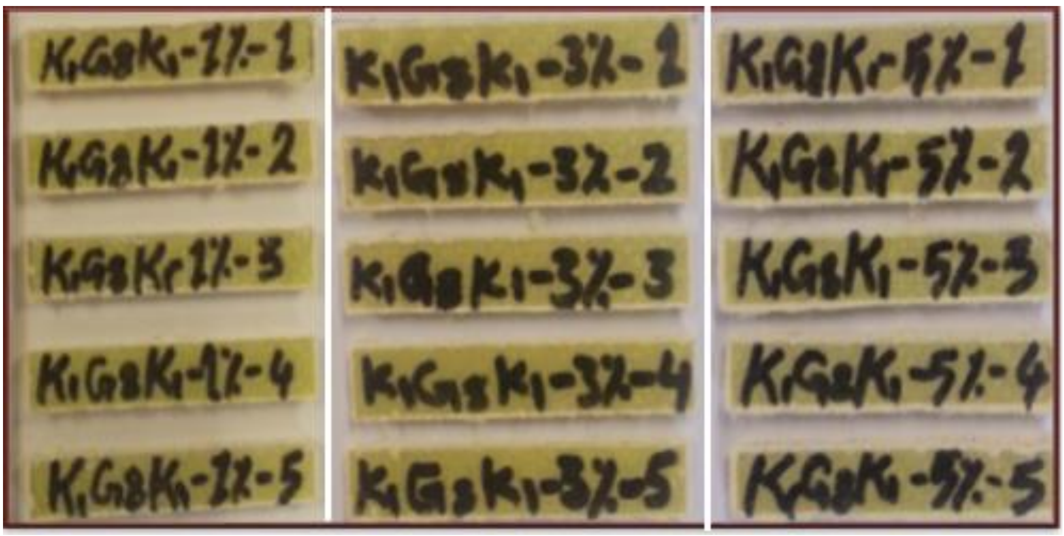


Figure 4.23 Sample of the flatwise specimen of $[K_1G_4]_S$ before test.

Figure 4.24 Sample of the flatwise specimen of $[K_1G_4]_S$ after test.

Compared to impact energy of glass fiber reinforced epoxy composite, the achieved increase in absorbing impact energy of the edgewise specimens are 0.36%, 11.31%,-4.01%, 1.09% and 0.36% for 0.5 wt.%, 1 wt.%, 2 wt.%, 3wt.% and 5 wt.% nanoclay filled hybrid fiber $[K_1G_4]_S$ reinforced epoxy composites, respectively. The variation in absorbing impact energy of the edgewise specimens is 10.09%, 22.94%, 20.64%, 2.29% and -2.75% for 0.5 wt.%, 1 wt.%, 2 wt.%, 3 wt.% and 5 wt.% nanoclay filled hybrid fiber $[K_1G_4]_S$ reinforced epoxy composites, respectively.

From the Figure 4.24, all specimens displayed fiber pullout and matrix cracking at the backside of impact point. The fiber pull-out characteristics of all specimens were similar but there were decrease on matrix cracking with the addition of nanoclay.

It is shown that the addition of nanoclay into hybrid fiber $[K_1G_4]_S$ reinforced epoxy became more significant at 1 wt.% nanoclay content exhibited the highest impact energy absorption. Nanoclay enhanced interfacial properties by improving the adhesion between matrix and fiber which led in the laminates carrying higher absorbed energy and load. Another significant cause for this enhancement in impact performance can be attributed to the unique phase morphology and good interfacial characteristics between matrix materials and fiber [84]. At higher content, the addition of nanoclay is not so efficient in enhancement of impact energy absorption. Probably, it can be attributed to the aggregation of nanoclay particles which resulted with a weak interfacial bonding [110, 87, 6].

4.5 Impact Test Results (10 ply Glass) with Nanosilica

The impact energy values for edgewise impacted specimens of glass are recorded in Table 4.15 and plotted against nanosilica contents as shown in Figure 4.25.

Table 4.13 Absorbed impact energy values for edgewise specimens of glass with nanosilica.

	Absorbed impact energy (J)					
Specimen No.	Nanosilica percentage %					
	0	0.5	1	1.5	2	3
1	2.40	2.50	2.70	3.10	2.40	2.50
2	2.60	2.80	2.60	3.30	3.00	2.50
3	2.40	2.90	2.80	3.35	2.70	2.50
4	2.20	2.80	2.90	3.40	2.80	2.50
5	2.50	2.70	2.80	3.55	2.60	2.30
Average	2.42	2.74	2.76	**3.34**	2.70	2.46
Deviation	0.15	0.15	0.11	0.16	0.22	0.09
	Percentage variation, compared to neat glass specimens					
	0.00	13.22	14.05	**38.02**	11.57	1.65

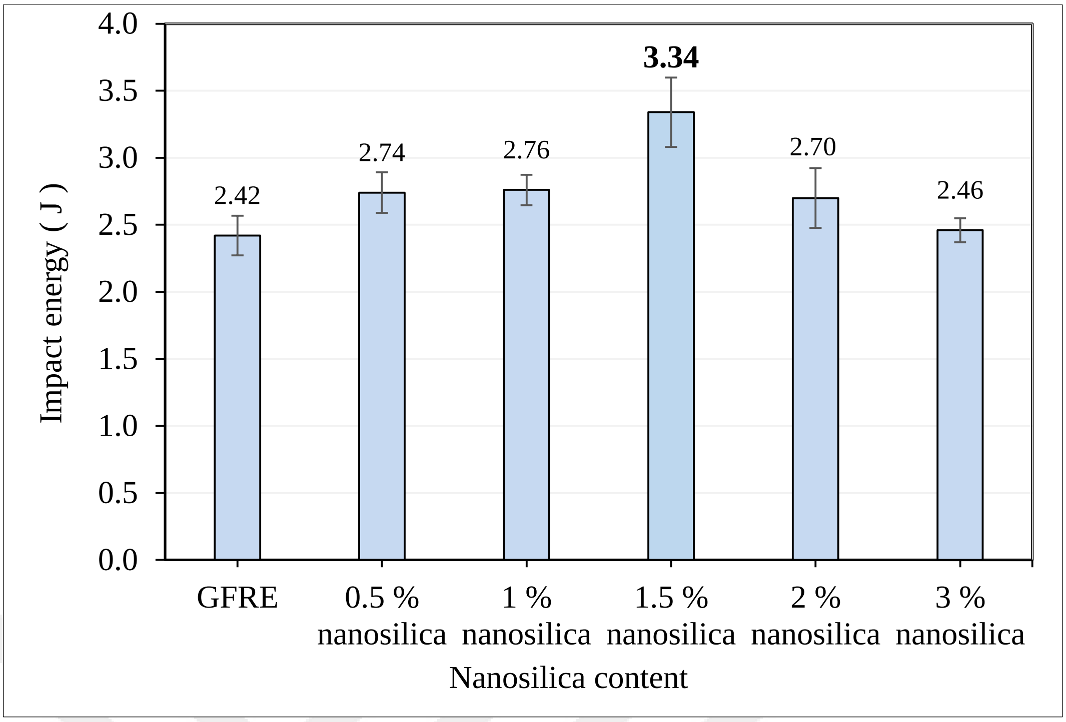


Figure 4.25 Absorbed impact energy values for edgewise specimen against nanosilica contents (10 ply glass).

And the impact toughness values for edgewise impacted specimens are recorded in Table 4.16 as shown below and plotted against nanosilica contents as shown in Figure 4.26.

Table 4.14 Impact toughness values for edgewise specimens of glass with nanosilica.

(wt.%) of Nanosilica	Thickness (mm)	Impact toughness (kJ/m^2)	Percentage variation compared with neat specimen
0	2.02	119.80	0.00
0.50	2.10	130.48	8.91
1	2.10	131.43	9.70
1.50	2.15	155.35	29.67
2	2.15	125.58	4.82
3	2.05	120.00	0.16

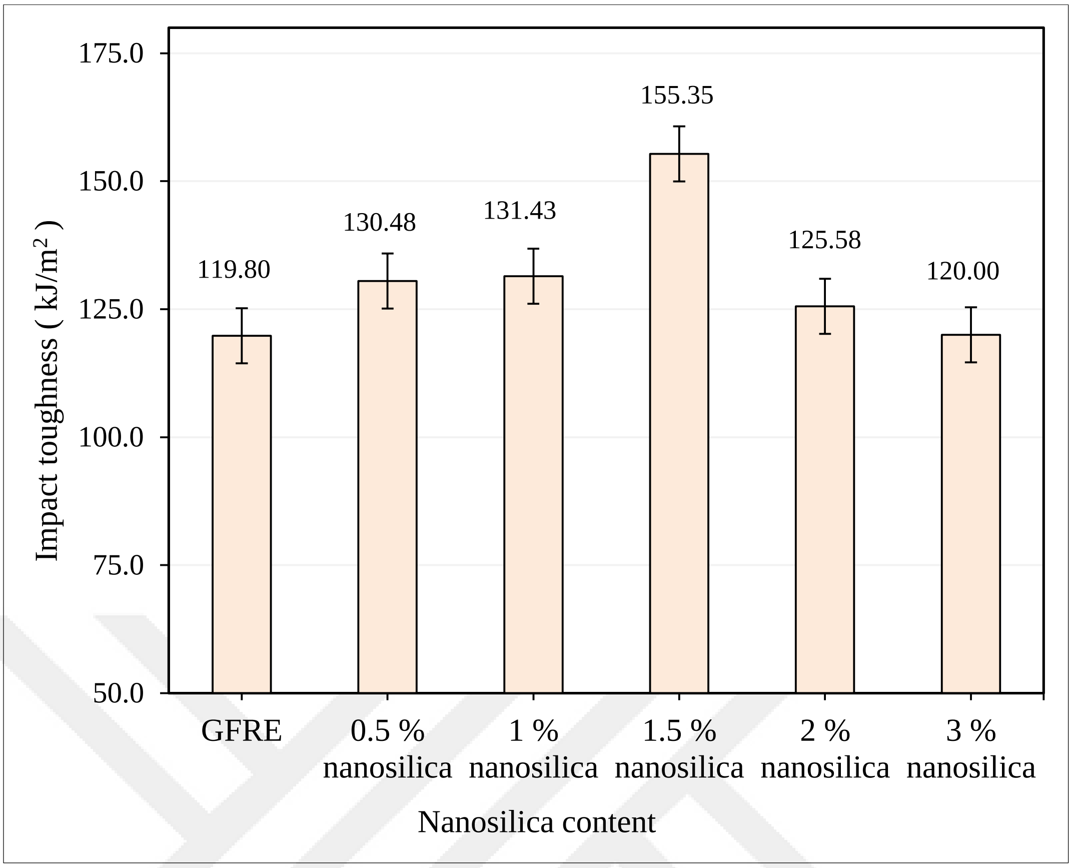


Figure 4.26 Impact toughness values for edgewise specimen against nanosilica contents 10 ply glass.

The Figure 4.27 and Figure 4.28 show the sample of the edgewise specimen of glass with nanosilica before and after test respectively.

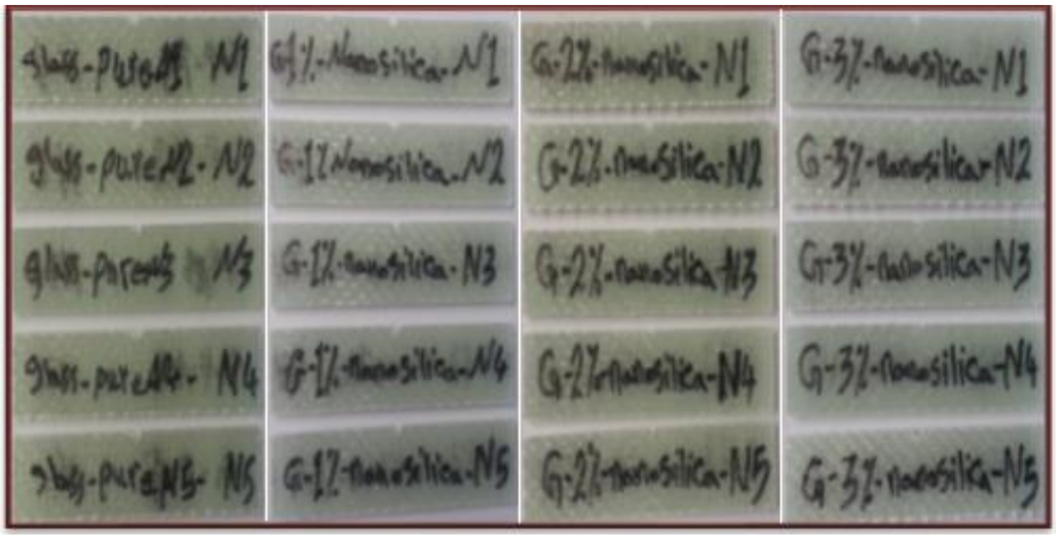


Figure 4.27 Sample of the edgewise specimen of glass with nanosilica before test.

Figure 4.28 Sample of the edgewise specimen of glass with nanosilica after test.

The impact energy values for flatwise impacted specimens of glass are recorded in Table 4.17 and plotted against nanosilica contents as shown in Figure 4.29.

Table 4.15 Absorbed impact energy values for flatwise specimens of glass with nanosilica.

	Absorbed impact energy (J)					
	Nanosilica percentage %					
Specimen No.	0	0.5	1	1.5	2	3
1	2.20	2.30	2.40	2.50	2.20	1.80
2	1.90	2.50	2.50	2.80	2.45	2.20
3	1.80	2.20	2.30	2.70	2.20	2.20
4	2.00	2.50	2.40	2.55	2.00	2.30
5	2.00	2.30	2.40	2.60	2.10	2.00
Average	1.98	2.36	2.40	**2.63**	2.19	2.10
Deviation	0.15	0.13	0.07	0.12	0.17	0.20
	Percentage variation, compared to neat glass specimens					
	0.00	19.19	21.21	**32.83**	10.61	6.06

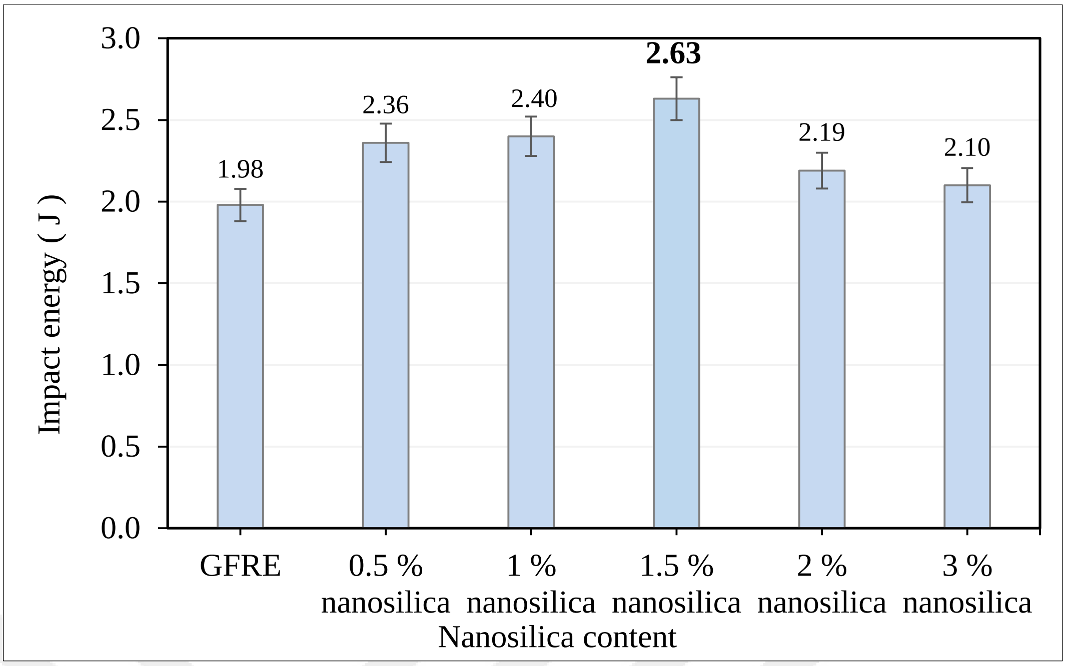


Figure 4.29 Absorbed impact energy values for flatwise specimen against nanosilica contents for 10 ply glass.

The impact toughness values for flatwise impacted specimens of glass are recorded in Table 4.18 and plotted against nanosilica contents as shown in Figure 4.30.

Table 4.16 Impact toughness values for flatwise specimens of glass with nanosilica.

(wt.%) of Nanosilica	Thickness (mm)	Impact toughness (kJ/m2)	Percentage variation compared with neat specimen
0	2.00	99.00	0.00
0.50	2.10	112.38	13.51
1	2.10	114.29	15.44
1.50	2.11	124.64	25.89
2	2.10	104.29	5.43
3	2.05	102.44	3.47

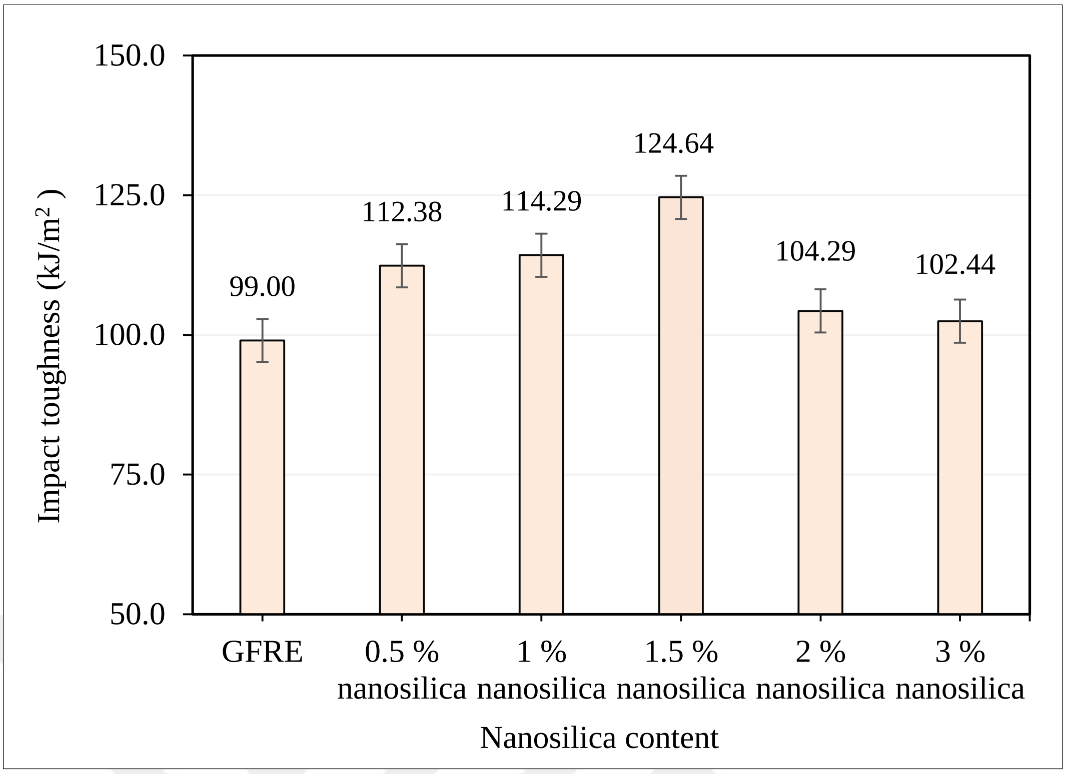


Figure 4.30 Impact toughness values for flatwise specimen against nanosilica contents for 10 ply glass.

The Figure 4.31 and Figure 4.32 show the sample of the flatwise specimen of glass with nanosilica before and after test respectively.

Figure 4.31 Sample of the flatwise specimen of glass with nanosilica before test.

Figure 4.32 Sample of the flatwise specimen of glass with nanosilica after test.

Compared to impact energy of glass fiber reinforced epoxy composite, the achieved increase in absorbed impact energy of the edgewise specimens are 13.22 %, 14.05 %, 38.02 %, 11.57 % and 1.65 % for 0.5 wt.%, 1wt.%, 1.5 wt.%, 2 wt.% and 3 wt.% nanosilica filled glass fiber reinforced epoxy composites, respectively.

The variation in absorbing impact energy of the flatwise specimens are 19.19 %, 21.21 %, 32.83 %, 10.61 % and 6.06 % for 0.5 wt.%, 1 wt.%, 1.5 wt.%, 2 wt.% and 3 wt.% nanosilica filled glass fiber reinforced epoxy composites, respectively.

The results showed that the addition of nanosilica into glass fiber reinforced epoxy became more significant at 1.5 wt.% nanosilica content at which the highest impact energy absorption was determined. At higher content, the addition of nanosilica is not so influence in improvement of impact energy absorption. Probably, it can be attributed to the agglomeration of nanosilica particles which cause with a weak interfacial adhesion [103, 94, 97].

Agglomerated nanoparticles in the matrix introduces local stress concentration and a weak particle-matrix adhesion decreases the capability of load transfer between them. These lead to a premature failure of the polymer and thus decrease its strain and strength to failure. [103].

CHAPTER 5

CONCLUSION

5.1 Introduction

In this study, the low velocity impact behavior of nanocomposites consisting of an epoxy matrix filled with different amount of nanoclay and nanosilica were investigated. The impact behavior of each specimen were determined by performing Charpy impact test. The nanoclay and nanosilica modified glass, Kevlar and glass/Kevlar hybrid fiber reinforced composites laminates were fabricated using hand layup technique. The hybrid composite laminates were prepared with different stacking configurations. The following conclusions can be highlighted from the study.

- The addition of 2 wt.% nanoclay into $[G_{12}]$ composite laminates resulted in an increase in absorbing impact energy of 19.44 % and 11.38 % for the edgewise and flatwise test specimens, respectively.
- The addition of 1 wt.% nanoclay into $[K_1G_4]_S$, $[K_2G_3]_S$, $[K_3G_2]_S$ and $[K_4G1]_S$ hybrid configuration resulted that the configuration of $[K_1G_4]_S$ reinforced epoxy with nanoclay have highest improvement of impact energy.
- The addition of 1 wt.% nanoclay into $[K_1G_4]$s composite laminates provided 11.31 % and 22.94 % increases in absorbed impact energy of the edgewise and flatwise test specimens, respectively.
- The addition of 1.5 wt.% nanosilica into $[G_{10}]$ composite laminates led to 38.02 % and 32.83 % increase in absorbed impact energy for the edgewise and flatwise test specimens, respectively.

- The increase in the impact energy values due to a uniformly disperse of nanoclay and nanosilica particles in the resin and there is a powerful interfacial bonding between the nanoparticles and the epoxy matrix which enabled efficient load transfer between matrix and reinforcements.

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