DEVELOPMENT OF GLASS/KEVLAR /SISAL HYBRID POLYMER NANOCOMPOSITE FOR MECHANICAL AND TRIBOLOGICAL APPLICATIONS

A thesis submitted in the partial fulfillment of the requirements for the award of

DOCTOR OF PHILOSOPHY
In
MECHANICAL ENGINEERING
By
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DECLARATION

This is to certify that the thesis entitled “**Development of Glass/Kevlar/Sisal hybrid Polymer Nanocomposite for Mechanical and Tribological Applications**”, is a bonafide work done by me under the supervision of Dr. Gujjala Raghavendra & Dr. MSR Niranjan Kumar and was not submitted elsewhere for the award of and degree.

I declare that this written submission represents my idea in my own words and where other’s ideas or words have not been included. I have adequately cited and referenced the original sources. I also declare that i have adhered to all principles of academic honesty and integrity and have not misinterpreted or fabricated or falsified any idea/data/fact/source in my submission. I understand that any violation of the above will be a cause for disciplinary action by the institute and can also evoke penal action from the sources which have thus not been properly cited or from whom proper permission has not taken when needed.

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CERTIFICATE

This is to certify that the thesis entitled “**Development of Glass/Kevlar/Sisal hybrid Polymer Nanocomposite for Mechanical and Tribological Applications**” being submitted by **Mr. Mallampati Somaiah Chowdary** in partial fulfillment for the award of the degree of Doctor of Philosophy (PhD) in the Department of Mechanical Engineering, National Institute of Technology Warangal, India, is a record of the bonafide research work carried out by her under my guidance and supervision. **Mr. Mallampati Somaiah Chowdary** fulfils the requirement of regulations laid down by the National Institute of Technology, Warangal, Telangana State. This work has not been submitted elsewhere for the award of any degree.

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Mallampati Somaiah Chowdary

ABSTRACT

Composite materials are formed by reinforcing two or more materials of varying properties. Hybrid composites are materials that are fabricated by combining two or more different types of fibers of fillers within a common matrix which enhances the properties due to this hybrid composites have become a hot topic among researchers. Hybridization is a helpful process for improving the strength and performance of composite materials. Hybrid polymer composite is a combination of natural fibers/ synthetic fibers/ fillers with Epoxy, Polyester, phenolic, polyvinyl ester, polyurethane resins, etc. Natural fibers may play a vital part in the improvement of eco-friendly composites to address recent ecological and environmental challenges. Natural fibers are lighter and cheaper, but their mechanical properties are poor when compared with synthetic fibers. The combination of materials is chosen based on specific strengths and weaknesses, which, when combined, results in a material with more balanced and advanced properties. The deficiencies of natural fiber are supported by synthetic fiber.

Traditionally, fillers were known as additives that could increase tensile and bending strength (upon adding filler content to a certain extent). The fillers can improve the dimensional stability of the composite materials, reducing shrinkage and increasing thermal and electrical conductivity. Fillers can be Micro and Nano-fillers, and combining nanomaterial as a filler material with natural/synthetic reinforcement gives new three-phase composite materials. The properties of the polymers can be enhanced by reinforcing various synthetic/natural fibers and fillers. There are many applications where polymer hybrid composites are in direct contact with liquid medium. The key downside of polymeric materials is the damage of properties due to contact with liquid media, such as marine atmospheres, in which the properties of polymers are heavily affected by saltwater with a combination of specific salts. So, immersion or straight interaction with polymer composites in any liquid media can cause degradation of mechanical or wear properties and lead to composites' failure.

The current research project aims to create a hybrid composites with combination of synthetic fiber (Glass/ Kevlar), natural fiber(sisal) and different nano fillers (nano silica and nano clay) as particles reinforced with polyester and epoxy. The present work aims to determine how the stacking order of Kevlar/Sisal and Glass/Sisal affects the mechanical characteristics of polyester hybrid composites. The impact of nano clay/nano-silica on Kevlar/sisal(KSSK) and Glass/sisal(GSSG) reinforced polyester hybrid composites is also being studied. Additionally,

experiments were conducted to examine the impact of moisture absorption on the mechanical and tribological characteristics of nano-clay polymer composites reinforced with KSSK and GSSG. The work presented in this dissertation has been carried out with the following scheme.

1. To study the effect of the Stacking sequence of Kevlar/Sisal and Glass/Sisal on the mechanical properties of polyester hybrid composites.
2. Effect of Nanoclay/Nano Silica on Kevlar/Sisal(KSSK) and Glass/Sisal(GSSG) reinforced Polyester Hybrid composites.
3. Effect of moisture absorption on mechanical and tribological properties of KSSK & GSSG reinforced Nano-clay Polymer composites.
4. Comparison of Polyester and epoxy Hybrid composites.

The hybridization of fiber composites with synthetic fiber in the outside layer were found to have improved mechanical properties. Because synthetic fibers are more durable, stiffer, and inter-laminar shear strength is better than natural. The load resisting capacity is also better as compared to natural fiber. So it does not break easily after applying load.

The highest tensile strength is achieved at 4 wt.% of Nano-silica/ KSSK and GSSG hybrid composites. A further increase in silica content there is a reduction in tensile strength. There is an increase in the bending strength in KSSK /GSSG from 0 wt.% to 4 wt.%. The highest tensile strength is achieved at 4 wt.% of Nano clay/ KSSK and GSSG hybrid composites. Similar results was observed for Nano silica wt.% reinforcement. Interestingly for flexural results 2 wt.% inclusion of Nano-clay found to be better.

The samples are fabricated with both polyester and epoxy as matrix materials and GSSG and KSSK as reinforcements with Nano clay as the filler material. The mechanical and wear analysis of fabricated samples was analsyzed followed by the degradation of the properties under various conditions such as ground water, sea water, mineral water and sub-zero conditions. The major degradation of mechanical properties was observed in samples exposed to sea water. The same trend was observed in glass fibers and Kevlar fiber hybrid composites. The 2 wt.% NC hybrid polymer composite showed maximum erosion wear resistance and the composites showed semi ductile behavior. Polyester/Kevlar/NC 2 w.% hybrid composites showed better mechanical and tribological properties among fabricated composites.

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Chapter – 1

Introduction

1.1.BACKGROUND

Composites have emerged as a promising new category of engineering components, providing innovative technological solutions and possibilities for enhancing materials' mechanical and structural properties. The advent of composite materials has allowed engineers and designers to construct lighter, stronger, and more long-lasting structures than conventional materials like steel and concrete. A combination of different elements, such as reinforcing fibres and resin matrices, has allowed engineers to adjust the properties of composites to suit specific design specifications. As a consequence of their high strength-to-weight ratio[1,2], resistance to corrosion, and ability to endure extreme temperatures, the use of composites has expanded rapidly across several industries, such as aerospace[3], transportation[4], and construction[5, 6].

1.2.COMPOSITE MATERIALS

A composite comprises at minimum two materials, commonly ones by opposite qualities. Composites characteristically have unique features with a high strength-to-weight ratio. Due to the composite's ability to be molded into intricate shapes, unique design is another benefit of composites. Numerous composites exist, including nanotubes, glass fibre, glass aluminium, and plastics bonded with carbon fibre[7]. Anisotropic and inhomogeneous materials include composites. Engineers frequently use composite materials. Laminated composites are becoming popular in renewable power, aviation, and automobile industry[8].

Creating new composites results from combining increased stiffness and more robust fibre/filler with a lighter matrix material with better toughness. During World War II, petrochemical industries produced the first composite with glass fibres acting as reinforcement in polymer matrices. The combination of light weight, inexpensive, environmentally friendly polymeric and structural fibres with high stiffness and strength offers excellent durability and mechanical capabilities than the ingredients alone. Due to their increased stiffness, strength, and low density, robust fibre-reinforced composites were marketed in the 1960s and 1970s to suit the demands of many industries[9].

The market for composites was estimated to be 115 billion USD in 2016[10]. Composites are used in industries with a constant need for corrosion-free materials because they are more cost-effective than ferrous and non-ferrous materials. Compared to polymer composites, metal composites demand more significant maintenance cost. As a result, global industry participants are constantly looking for cheaper alternatives to metals. Using fibre/filler-reinforced polymer composites speeds up the production of components using straightforward processes and provides financial gain by lowering the cost of processing. Compared to other materials, composites are generally the most preferred alternatives and cost-effective materials for engineering sectors.

1.3.POLYMER MATRIX

Most degradative activities in composites are controlled by the qualities of the continuous constituent called polymeric matrix, which holds the reinforcement substance in place. Typically, the matrix material is categorized as either thermoset or thermoplastic. The matrix is generally chosen based on factors including adhesiveness, fatigue life, flame retardancy, chemical stability, and water resistance [11]. The mechanical characteristics of the resins must be equivalent to that of reinforcements. Operating during the chosen fabrication process must be simple and withstand the operating condition. In addition to these qualities, the matrix material must be able to penetrate bundles of fibres that serve as reinforcements, replacing any vacant air gaps, and also possess the physical qualities necessary to improve the performance of fibres.

The curing of thermoset polymers produces a three-dimensional crucifix solid architecture with good dimensional/thermal durability and solvent-resistant characteristics. Thermosets offer good fatigue strength and are robust. The physicochemical characteristics of thermoplastics can be shaped, heated, and remoulded without changing them.[12]

Thermoplastics have improved impact protection and higher durability than thermosets because they are more complex and less fragile. Compared to thermoset-based polymeric materials, the fabrication of thermoplastics necessitates more energy and is more expensive.[13]

1.4. FIBER REINFORCEMENT

The creation of composite materials with both mechanical and wear importance can be achieved through fibre reinforcement within polymer matrices. Several types of fibre reinforcement are available. Almost every reinforcing fibre significantly reduces wear and improves mechanical characteristics for polymers with high specific wear rates in the unreinforced state. Common synthetic fibres are reinforced in thermosets and thermoplastics. Continuous synthetic fibres bonded in a thermoset resin stand out for their superior qualities. This is credited to the fact that their characteristics are regulated by fibre reinforcement due to the high fibre contents made feasible by thermosets and the preferred load bearing by fibres. Along with a form of reinforcement, the fibre direction influences the qualities. Figure 1.1 shows the classification of fibre reinforcements.

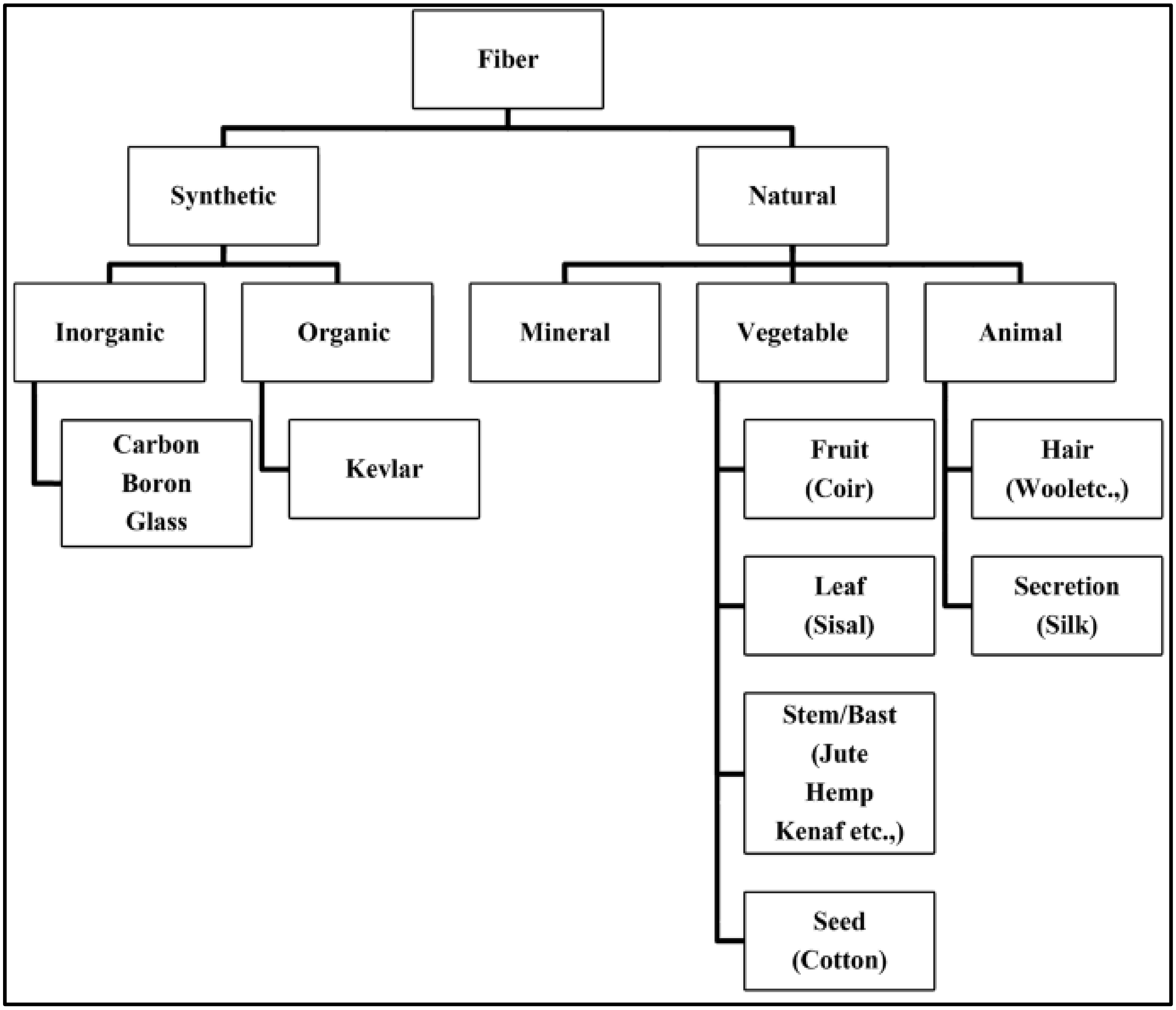


Figure 1.1. Shows the classification of fibre

1.4.1. Natural fiber reinforcement

Natural fibres are used to create various constructions because of their high strength, high stiffness, and low weight. A common technique for different applications, notably in the context of sustainable materials, is the incorporation of natural fibres (NFs), particularly as reinforcement in composite materials[14]. These NFs have several advantages, including replacing many synthetic fibres. Additionally, these NFs have been used to create bio-composites**.**

Vegetable, animal, and mineral fibres are all included under the general phrase "natural fibre." However, the composites business refers to wood pulp and agricultural fibres from stems, leaves, and seeds. When utilised in composite materials, these fibres can significantly reinforce plant structures and positively impact plant performance.[15]

The main component of plant fibres is cellulose, whereas the central part of animal fibres is protein. Due to their scarcity and expensive cost, animal- and mineral-based fibres are rarely used as reinforcement media in NFRPCs as opposed to plant-based fibres. Wool, silk, feathers, and hair are all examples of animal-based fibres. Asbestos and basalt are the minerals from which mineral fibres are derived and found in most significant amounts. The majority of plant-based fibres come from crops and topical plants. Due to their low cost, high mechanical characteristics, and abundance, many fibres, including sisal, flax, ramie, cotton, banana, and hemp, have been used in building and automotive sectors. These fibres favorably impact the environment because they are eco-friendly and biodegradable.

Additionally, these fibres are stiffer, more robust than animal fibres and have a tensile strength comparable to manufactured glass fibres. Animal fibres are also less hydrophilic than plant fibres, more susceptible to some alkalis, and are poor heat conductors. These fibres strengthen synthetic polymers, and the resulting composites have excellent mechanical properties. The source of the fibre, the method of extraction, accessibility, the type of fibre, and the synthesis technique are additional significant factors that affect the mechanical properties of NFRPCs. Another important factor that significantly influences the overall mechanical characteristics of NFRPCs is moisture absorption.

1.4.1.1.Sisal fibre

Sisal fibre is a plant fibre with properties related to glass fibre in strength and stiffness. Sisal fibre is a member of the Agave Sisalana botanical family and is currently grown in Mexico, East Africa, Brazil, Haiti, India, and Indonesia.[16] The plant stands about 1 m tall, has 200-250 leaves, and is 28 mm broad. Each leaf has roughly 1000 fibre bundles, with just 4% employed as fibres. The plant lives for around 7-10 years, after which fibres are extracted from the leaves using a human or mechanical decortication process. Sisal plants are available in four types: Sisalana, Vergross, Istle, and Natale. The fibre outputs of different plant types vary. The first two types of leaves produce more fibres than the other two. The fibre content of plants differs with oldness and origin. The leaf is composed of moisture (89%), fibre (5%), cuticle (0.75%), and miscellaneous dry matter (6.25%). The fibre's length ranges from 65 to 120 mm. The fibre's ends are broad and blunt. An angular cell is generally 500-6000 m in length and 5-40 m in width, with a high aspect ratio (l/d of fibre) of 160. Mechanical, ribbon, and xylem fibres are found in sisal leaves.[17] Figure 1.2. Shows the Sisal and Sisal fiber after extraction.

Figure 1.2. Sisal fiber and Sisal fiber after extraction (Continuous and Mat form)

1.4.2. Synthetic fiber reinforcement

Synthetic fibres are artificial fibres that do not come from nature. Petroleum products are the primary source of synthetic fibres. Synthetic materials outperform natural fibres in terms of characteristics. To make synthetic fibres, many compounds with unique properties are mainly employed. Synthetic fibres from chemical products include nylon, acrylics, polyesters, polyurethanes, and others. These fibres exhibit excellent mechanical characteristics, toughness, consistency, and a lengthy life lifetime. There are different forms of synthetic fibres, with the following three types of synthetic fibres being widely utilised in the composite industry: Carbon, glass fibre, and Kevlar (aramid)

1.4.2.1.Glass fiber

Glass fibres (GF) are frequently used fibres in composites. The key benefits of GF are its remarkable tensile strength, low fabrication cost, and superior chemical resistance. GF has been widely employed in common and critical applications due to their many fascinating properties. Thus, the global annual GF consumption in 2000 was approximately 2.4 million tonnes, which has expanded dramatically since then**.** Many commercially available GF are generated by altering the number of raw components in the consignment. The main element of all GF is silica (SiO2); however, adding other oxides such as Al_2O_3, B_2O_3, CaO, and so on permits for a change of the GF's final properties. Table 1.1 lists the oxide descriptions and weight ranges for several varieties of commercially available GF.

Type of Glass Fiber	**A-Glass**	**C-Glass**	**D-Glass**	**E-Glass**	**S-Glass**
Oxide	**Percentage**				
SiO_2	63	64	73	55	66
Al_2O_3	4	5	1	12	25
B_2O_3	3	4	21	5	-
CaO	6	11	1	25	0.2
Fe_2O_3	0.5	0.8	0.3	0.8	0.1

Table 1.1. Shows the approximate composition of various oxides in Glass fibers

The GF's basic production process can be resumed: These raw components are dry-mixed and melted in a 1410°C oven. The molten glass is then turned into strands by pushing it through a series of apertures to produce filaments with diameters of roughly 10 m. At this stage, each filament is covered with a shielding coating composed of oils, antistatic agents, binders, and, occasionally, coupling agents to facilitate adhesion to the polymeric matrix. As a result, the resulting filaments are collected and piled to form uninterrupted strands. Another type of GF is roving, made by winding several untwisted parallel strands around a cylinder creating a bundle.[18]

1.4.2.2.Kevlar fiber

Kevlar, or aromatic polyamides, were used commercially in the early 1960s, with DuPont marketing a meta-aramid fibre under Nomex. This fibre, which behaves similarly to standard textile garment fibres, is distinguished by its outstanding heat resistance since it does not melt or ignite at normal oxygen levels. It is widely utilised to manufacture protective clothing, air filtration, and thermal and electrical insulation. DuPont, the first business to produce a para-aramid fibre, Kevlar, in 1973, also created a para-aramid fibre with substantially higher tenacity and elastic modulus in the 1960s-1970s & Figure 1.3. Shows the structure of the aramind link. Akzo introduced Twaron, a comparable fibre with essentially the same chemical structure, in 1978. It is woven into fabric textiles and is exceptionally robust and lightweight, with rust and heat resilience. It is utilized in various industries, including aerospace (such as aircraft bodies), body armour, bulletproof vests, automotive braking, and ships. It is typically used as a composite. Kevlar can also be blended with other fibres to form hybrid composites[19].

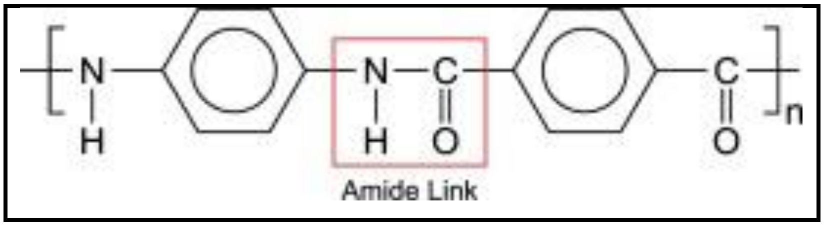


Figure 1.3. Structure of Aramid Link[20]

In the aeronautics area, two types of aramid fibre are used. Kevlar 49 has great rigidity, while Kevlar 29 has little stiffness. Because of their excellent resistance to impact damage, aramid fibres are often operated in places disposed to to impact. Aramid fibres' fundamental problem is their overall weakness in compression and hygroscopy. Conferring to service reports, some Kevlar parts engross up to 10% of their weight in water. As a consequence, aramid fibre pieces must be protected from the elements. Another downside of Kevlar is that it is tough to drill and cut.[21]

1.5.FILLER REINFORCEMENT

1.5.1. Nano clay

"Clay" refers to materials containing stacked silicates or clays and minor amounts of metal oxides and organic material. They are often made of varying concentrations of iron, magnesium, alkaline earth, alkali metals, and other cations. They form due to the weathering and erosion of feldspar rocks over time. Clays can be divided into groups based on their chemical make-up and crystalline form. In Figure. 1.4, a classification of natural clay is shown**.**

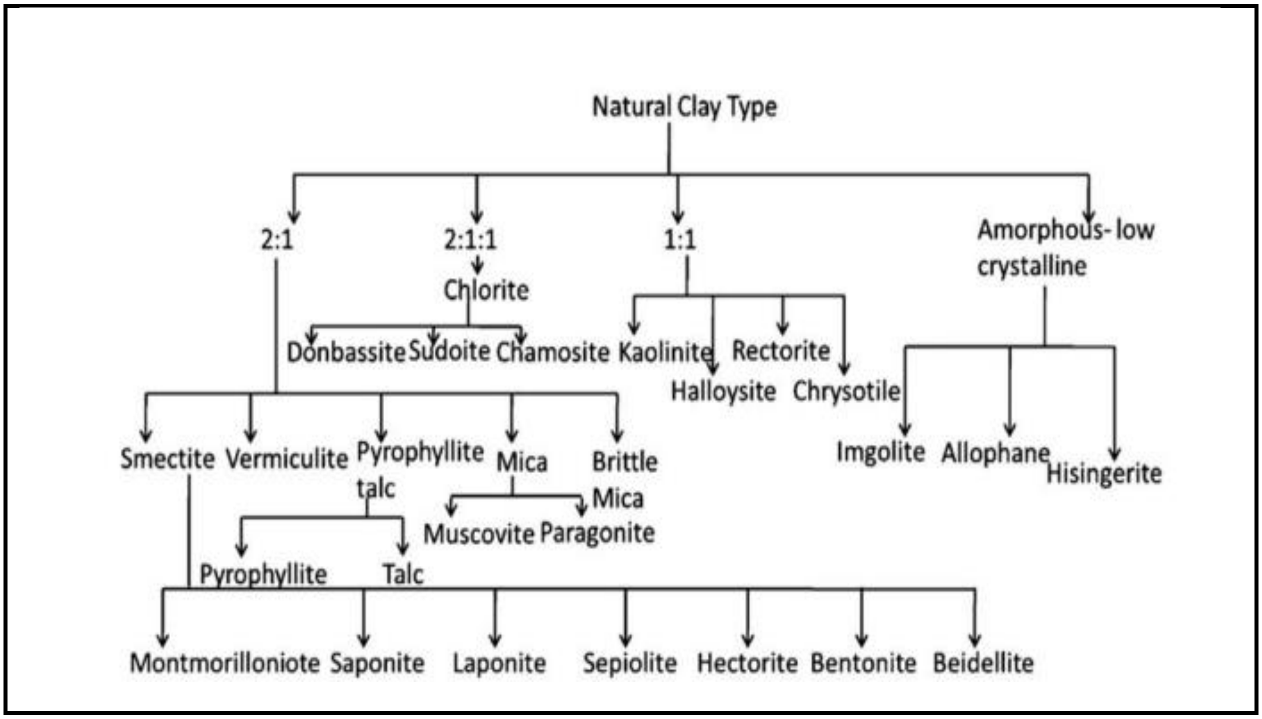


Figure 1.4. Classifications of Clays[22]

The crystalline structure of smectite, a member of the 2:1 siliceous structural family, contains of an octahedral alumina or magnesia sheet placed among two tetrahedral silica sheets; the oxygen ions of an octahedral sheet are also members of the tetrahedral sheet. Since of its great aspect ratio and substantial swelling property in polar regions, Montmorillonite, one of the numerous forms of smectite clays shown in Figure. 1.4., is frequently employed in materials applications. The crystal structure of this layered silicate, also known as T-O-T sheets, is shown in Figure. 1.5. The chemical formula for Mt is $(Na, Ca)_{0:33} (Al, Mg)_2Si_4O_{10} (OH)_2: nH_2O$.

These stacked crystals, known as "nano-clays," possess aspect ratios between 100 and 1000 with a nanometre scale thickness. Weak van der Waals (vdW) and electrostatic attraction hold these nano-platelets together, and the resulting intermediate gap is known as the "Gallery" or the "Interlayer."

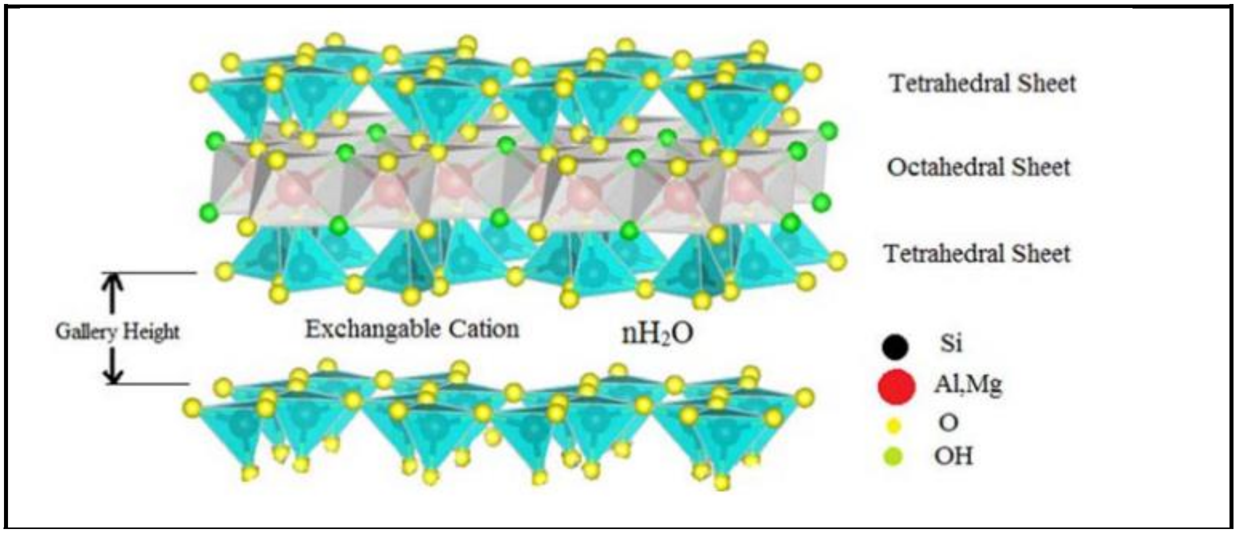


Figure 1.5. Crystalline Structure of Nano clay[23]

1.5.2. Nano silica

Nano silica (SiO_2) is a remarkable nanoparticle widely used in Polymeric materials and the structure of Nano silica can be seen in Figure 1.6. Typically, micron-sized silica was used to create nano silica. Due to its distinctive properties, including its high surface area, high pore volume, variable pore size, outstanding bio - compatibility, capacity to enclose hydrophobic and hydrophilic compounds, and scale chemical accessibility, silica has captured the interest of scientists. The availability of nano silica in a variety of forms, including as solid silica, mesoporous silica, hollow or core-shell frameworks, virus-form silica, rod-shaped particles, and silica gels, as well as the capability to precisely regulate the size of the particles, form, pore volume, and crystalline nature, have made them popular in a wide range of applications.[24]

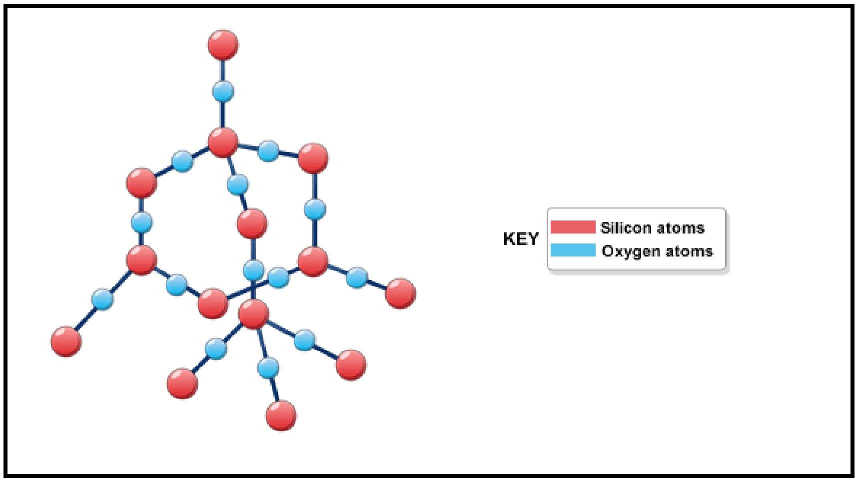


Figure 1.6. Shows the Structure of Nano Silica (SiO$_2$)

1.6.HYBRID POLYMER COMPOSITE

Hybrid polymer composites in the developed world, inparticular, are common. Hybrid polymer composite is defined by reinforcing polymers, for example, epoxy, Polyester, phenolic, polyvinyl ester, polyurethane resins, etc. with reinforcements such as natural fibers/natural fiber, natural fibers/synthetic fibers, synthetic fiber/synthetic fibers, natural fiber/filler, synthetic fiber/filler, natural fiber/synthetic fiber/filler.[25][26].

Natural fibers may play a vital part in the improvement of green composites to address recent ecological and environmental challenges. Natural fibers are lighter and cheaper, but their mechanical properties are poor when matched with synthetic fibers. The use of synthetic fibers as a reinforcement combined with natural fibers which makes the composite Hybrid will solve this issue. The reinforcement of natural fiber to the synthetic fiber will make the composite hybrid, which is relatively cheaper compared to synthetic fibers alone [27–29].

Traditionally, fillers were known as extenders that could increase tensile and bending strength (upon addition of filler content to a certain extent due to their geometric characteristics, surface area or surface chemical composition) and their main contribution was to lower production costs by replacing the costliest polymer. Fillers can be micro filler or nano filler, and the concept of combining nanocomposites as a filler material with natural/synthetic reinforcement in a new three-phase composite reinforcement has been shown to have been very successful[30]. So, the properties of the polymers can be boosted by reinforcement of various synthetic and natural fibers and fillers, mainly nano fillers, since they are replaced by micro fillers[31].

The current research project aims to create a hybrid composites with combination of synthetic fiber (Glass/ Kevlar), natural fiber(sisal) and different nano fillers (nano silica and nano clay) as particles reinforced with polyester and epoxy. The present work aims to determine how the stacking order of Kevlar/Sisal and Glass/Sisal affects the mechanical characteristics of polyester hybrid composites. The impact of nano clay/nano silica on Kevlar/sisal(KSSK) and Glass/sisal(GSSG) reinforced polyester hybrid composites is also being studied. Additionally, experiments were conducted to examine the impact of moisture absorption on the mechanical and tribological characteristics of nano-clay polymer composites reinforced with KSSK and GSSG.

The second chapter includes a detailed explanation of the properties and structure of the synthetic fiber, hybrid polymer nano composites and degradation of properties in liquid media, and a review of literature that serves as an overview of the research relevant to the current topic.

The construction of hybrid polymer composites is covered in detail in the third chapter, as well as the impact of the stacking order of Kevlar/Sisal and Glass/Sisal on the mechanical properties of polyester hybrid composites.

The fourth chapter investigated the mechanical characterization of the effect of Nanoclay/Nano Silica on Kevlar/Sisal (KSSK), and Glass/Sisal (GSSG) reinforced Polyester Hybrid composites.

The fifth chapter investigates the effect of moisture absorption on the mechanical and tribological properties of KSSK and GSSG-reinforced Nano-clay Polymer composites, and a comparison has been made with Epoxy and polyester.

The sixth chapter contains findings gained from the experiments, as well as suggestions for further research.

Chapter – 2

Literature Review

2.1.INTRODUCTION

Literature review was conducted as part of the thesis project to gain a general understanding of the polymer composite's manufacturing procedures, physical characteristics, and tribological behaviour. Compared to their metal equivalents, fibre composites have consistently shown at least 25% savings and lower operational and maintenance costs. It is acceptable to say that composite construction is substantial, preserves structural integrity, resists fatigue stress, and is simple to maintain and repair when data on their service life becomes available. Composite materials will remain to find new uses, but the rapid increase in the demand for these substances will necessitate less expensive production techniques and the need to address the recycling issue.

Composites have emerged as a promising new category of engineering components, providing innovative technological solutions and possibilities for enhancing materials' mechanical and structural qualities during the mid-20th century. The advent of composite materials allowed engineers and designers to construct lighter, stronger, and more long-lasting structures than conventional materials like steel and concrete. The combination of different elements, such as reinforcing fibers and resin matrices, allowed engineers to adjust the properties of composites to suit specific design specifications. As a result of their high strength-to-weight ratio, resistance to corrosion, and ability to endure extreme temperatures, composites have expanded rapidly across several industries, such as aerospace, transportation, and construction.

Typically, a continuous phase is integrated with a discontinuous phase (reinforcement) (matrix). A significant category of composite materials with several applications is polymer-based composite materials (PMC), sometimes known as FRP. By prudently selecting the fibre, matrix, fibre configuration (short, long, strong, woven, braided, laminated, etc.), and fibre surface treatment, they offer desirable features that may be adapted to particular requirements. In addition to being lightweight and having high stiffness and strength in the direction of the reinforcing fibre, PMCs also have dimensional stability and chemical and temperature resistance and are relatively simple to produce.

2.2.SELECTION OF MATERIALS

Most materials have strong strength characteristics in the form of fibres, but to have these characteristics, the fibre needs to be bound by an appropriate matrix. The matrix serves as a link to grip the fibres in place and isolates them from one another to avoid abrasion and the development of new surface defects. A suitable matrix should be able to deform quickly when subjected to load, transfer the load to the fibres, and disperse stress concentration uniformly. At loading, there is a propensity for the adhesive bond between them to reason for high-strength properties of laminates, according to research on the nature of bonding forces in laminates.

The fibres are bound by the polymer matrices, protecting them from the surroundings and maintenance while transferring load to and among them. Thermoplastic and thermosets are the two primary polymer or resin systems used to create polymer materials matrix composites (PMCs).

2.3.PARTICULATE REINFORCED COMPOSITES

Particulates are used as reinforcements in composite materials. They are mainly used for cost reduction of polymer and fiber and also mainly to improve the thermal conductivity, mechanical properties, and wear characteristics. Advancement depends on the type of filler material being used and size, shape, surface chemistry, and content of filler content. Filler loading is a vital factor in improving the properties of the polymer[32].

Alsagayar ZS et al.[33] studied how clay affected the mechanical characteristics of MMT-reinforced epoxy nanocomposite, and tensile and flexural tests were conducted. It is concluded that as the clay loading was raised to 1 phr, the mechanical characteristics of MMT/epoxy nanocomposites were somewhat enhanced. However, the results demonstrated decreased mechanical characteristics for nano clay amounts greater than 1 phr. Young's and flexural moduli were discovered to increase by approximately 6.75 percent and 6.61 percent, respectively, when nano clay was added up to 1 phr. Table 2.1 lists the various researchers who worked on filler-reinforced composites.

Table 2.1. Lists the various researchers who worked on filler-reinforced composites

Reference	Year	Matrix	Filler	Findings
Saharudin MS et al. [31]	2016	Polyester	Nanoclay diluted in methanol	Degradation of mechanical properties
Saharudin MS et al. [34]	2017	Polyester	Nano clay	Degradation of properties in sea water
Suresha B et al.[35]	2019	Epoxy	Nano clay, Nano calcium, carbonate	Tensile, Bending and Impact
Merah N et al. [36]	2019	Polyester	Cloisites, Nanomer	Mechanical and water absorption
Alrobei H et al. [37]	2021	Polyester	Nano Screw pone fiber	Mechanical

2.4.FIBER REINFORCED COMPOSITES

Natural fibers such as jute, sisal, hemp, coconut, kenaf, bamboo, flax, etc., are generally used as reinforcement in polymer-based composites[38]. The wide range of applications of NFRECs is increasing rapidly in various engineering fields. Various forms of natural fibre-reinforced composites have stood well in several automotive applications. Many automotive companies use natural fiber as reinforcement in composites. In addition to automobile industry, standards for Natural fiber composites have also been used in building and construction, sports, and aerospace[4]. One of the disadvantages of NFRECs is they are prone to high water sorption. Natural fiber consists of cellulose, hemicellulose, lignin, pectin, wax, water-soluble compounds, and fat[39]. Cellulose is known to be primary building block of the fiber system. It gives the fiber rigidity, strength, and structural firmness. Nevertheless, cellulose and hemicellulose are critical components of natural fiber that captivate maximum volume of water. Lignin offers active protection for hemicellulose/cellulose despite adverse climatic conditions such as moisture and temperature[40]. Figure 2.1 shows the above-mentioned natural fiber and its constituents and constituents that absorb water, while table 2.2 lists the various researchers who worked on fibre-reinforced composites

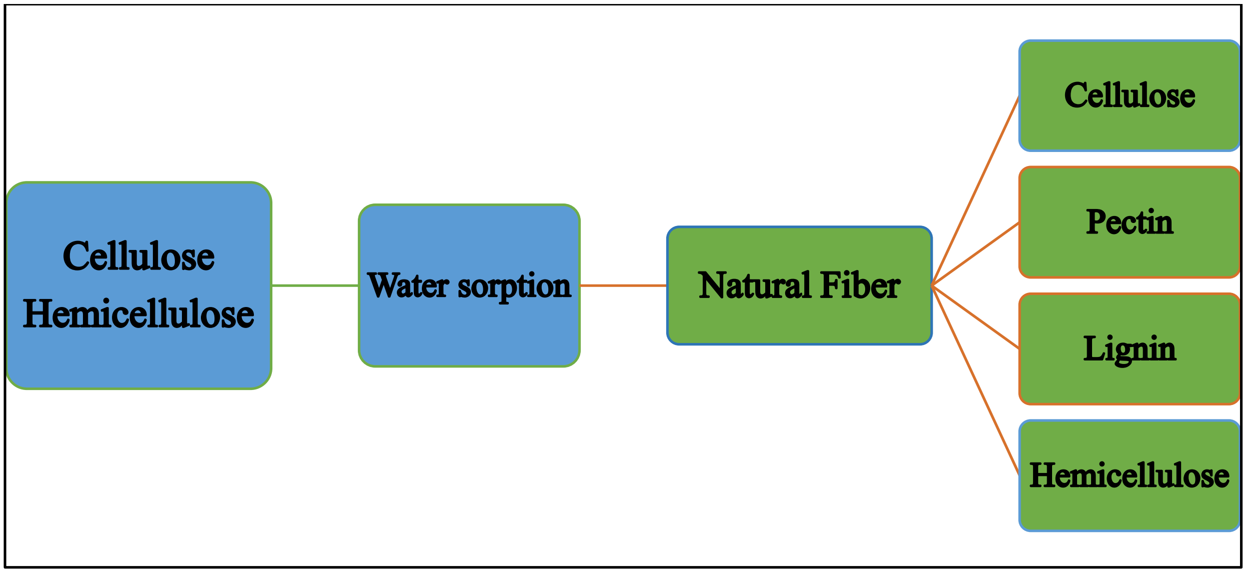


Figure 2.1. Shows the components of Natural fiber and components that absorb water

Mittal V et al. [41] studied Wheat straw fiber reinforced epoxy composites treated and untreated with fiber at a wt.% of 5,10,15,20,25. The fibers were treated with 1,2,3% NaOH solutions. It is concluded that introducing fiber loading to the polymer matrix lowered the tensile, flexural, and impact strength of all WSF-epoxy composites. The mechanical characteristics of all alkali-treated WSF-epoxy composites were superior to those of untreated WSF-epoxy composites with the same fibre loading. This is since each treatment created surfaces with a rough texture, creating a solid link between the fibre and polymer matrix. In composites made with the 3% NaOH-treated fibre and 5% NaOH-treated fibre, an effective enhancement strengths was seen.

Table 2.2. Lists the various researchers who worked on fibre-reinforced composites

Reference	Year	Matrix	Fibers	Study
Raghavendra et al. [42]	2013	Epoxy	Jute E-Glass	Mechanical and tribological
Raghavendra et al. [43]	2014	Epoxy	Jute	Mechanical and water absorption
Muñoz E et al. [44]	2015	Epoxy	Flax Fiber	Mechanical and water absorption
Hamdan MHM et al. [45]	2019	Polyester	Jute Ramie Roselle	Water Absorption and Mechanical

2.5.HYBRID COMPOSITES

Hybrid composites are substances created by fusing several fibres in a single matrix. Many investigators have offered multiple interpretations of hybrid composites[46, 47]. Thwe and Liao[48] defined reinforcing materials mixed with various matrices. In contrast, these composites, according to Fu et al.[49], are made of a reinforcing material combined with one or more filling and reinforcing components to form a single matrix[50, 51]. Compared to other fibre composites, hybrid composites are more sophisticated and offer a more comprehensive range of potential uses[52].

In hybrid composites, there is a good balance between the fundamental benefits and drawbacks due to the weighting factor of the distinct elements' performances. The lack of properties in one type of fibre may compensate by combining the other materials which has better properties. Consequently, effective material selection could be used to strike a compromise between cost and performance. Natural fiber with glass, woven sisal/kevlar, and coconut fiber-reinforced polyester composites with boron are examples of hybrid composites.

The phenomenon of a seeming synergistic development in the qualities of a composite that incorporates two or more types of fibres is known as the hybrid effect, which can be either positive or negative. The goal of hybridization, the demands placed on the material, and the emerging construction all impact the choice of constituents for the hybrid composite[53]. The selection of complementary fibres and the degree of the fibre's qualities present key challenges in designing and manufacturing hybrid composites. Researchers combined two fibres to improve the drawbacks of both fibres to get optimum performance out of hybrid composites. Commercial, industrial, aeronautical, maritime, and recreational structures can utilise hybrid composites for main structural components. It has many advantages in the aerospace industry, including strong impact resistance, significant fatigue and corrosion resistance, and both. The most crucial benefit is weight loss, which could result in 20% to 50% savings. Moreover, the "lay-up" design, with tapering thicknesses of reinforcing fabric and altering orientation, allows for customization of the mechanical properties.

Venkateshwaran et al. [54] studied the mechanical properties of banana and sisal fiber with various proportions reinforced with epoxy resin. It is concluded that using 50:50 banana and sisal fiber ratios provided better mechanical properties than other ratios.

Table 2.3. lists various researchers who worked on hybrid composites

Reference	Year	Matrix	Fibers	Filler	Study
Panneerdhass R et al. [55]	2014	Epoxy	Luffa Fiber	Ground nut	Mechanical
Yahaya R et al. [56]	2016	Epoxy	Kevlar Kenaf	-	Water absorption and Impact properties
Vijay R et al. [57]	2018	Epoxy	Kenaf Sisal Jute Glass	-	Mechanical

Daniel D Jafrey et al. [58]	2019	Epoxy	Bamboo Jute	-	Mechanical and water absorption
Biswas B et al. [59]	2019	Polyester	Sisal Fiber	ZrO_2	Mechanical, thermal and water absorption.
Tejyan S et al. [60]	2022	Epoxy	Cotton fiber	Wooden dust	Physical, mechanical and erosion
Ravikumar P et al. [61]	2020	Polyester	Jute Carbon	-	Tribological

2.5.1. HYBRID NANOCOMPOSITES

A hybrid nanocomposite (NC) is a material created by adding nanoparticles in matrix at the macroscopic level, and is mainly used in automobile, marine and construction sectors. There are three hybrid nanocomposites: binary hybrid nanocomposites, ternary hybrid nanocomposites, and multiple hybrid nanocomposites. A binary hybrid nanocomposite is made up of two components that contain one nanomaterial; a ternary nano composite is made up of three components, one of which is in the nanoscale; and multiple hybrids are made up of more than three components, at least one of which is in the nanoscale and the other components and other may be fiber or filler [62].

Mixing nano-Fillers into the matrix is an essential aspect in the fabrication of composites; there are various ways to blend nano-fillers, such as Shear blending, Mechanical stirring, and Ultra sonicating. Shear blending requires two or three roll mills wherever intense shear stress is exerted on the resin and nanoparticles. However, this approach has the downside of having a limited resin quantity in the mill. Moreover, mechanical stirring helps in the creation of voids.[63] Nano-fillers must first be blended with a mechanical stirrer, followed by ultrasonication. The results obtained by the combined approach have high mechanical properties compared to the individual alone.[64] Ultra sonication is the most common technique, which has shown tremendous promise in breaking down particle clusters and, contributing to improved suspension stability. Ultrasonic processing is used for various reasons, such as the dispersion of nanoparticles into the base liquids, particle de-agglomeration, particle size reduction, particle blend and precipitation, and surface functionality.[65] One of the critical aspects of the Sonicator is the behaviour of solutions shifted from non-Newtonian to Newtonian in terms of sonication time.[66] Ultra-Sonication uses ultrasonic energy for the dispersion of Nano-fillers in the polymer matrix, as ultrasonic high-frequency waves pass through more diminutive packets. Such smaller nanofiller packets slowly exfoliate into smooth reduced bundles as the sonication period rises and become fully dispersed as individual Nano-fillers in the polymer.[67]

Ramesh PK et al.[68] studied the mechanical properties of 30 wt.% treated kenaf fiber reinforced with PLA and varying wt.% of MMT. It is concluded that kenaf fiber-treated PLA reduced the mechanical properties of the composite compared to PLA alone. But when NC was reinforced, the properties tended to increase compared to PLA and PLA/TKF. They also concluded that 1 wt.% NC is the optimum clay loading.

Chee SS et al. [69] compared the mechanical properties of 3 different NC (organically-modified MMT (OMMT), montmorillonite (MMT), halloysite nanotube (HNT) with 1 wt.% reinforced with bamboo and kenaf fiber. It is concluded that 1 wt.% reinforced OMMT provided the maximum mechanical properties compared to other nano clays.

Raju P et al.[70] made composites utilising glass-Caryota intra-ply fibres, SiC, and nanoclay. While introducing SiC particles up to 1.0 vol% increased the hardness to 92 shore-D, incorporating nano clay particles with Curens-glass intra-ply fibre enhanced the composite's tensile, flexural, and impact properties. The mechanical qualities of glass and Caryota fibre were enhanced while maintaining their environmentally benign character. Using natural and highly sustainable fibre makes it easier to manage waste products and recycle biomass made from plant waste. Epoxy composites of high-toughness nano clay and fibre have a wear behaviour that lowers their resistance. Yet the inclusion of SiC increased wear resistance by reducing the friction coefficient.

Prajapati et al.[71] determined the mechanical and dynamic analysis of glass fiber-reinforced Nano-silica epoxy hybrid composites. It is found that glass fiber with 25 wt.% and nano-silica with 3 wt.% have improved mechanical properties equated to other wt.%. The inclusion of nano-silica in glass fiber enhanced the properties

R. A. Mohammed et al. [72] examined the mechanical and tribological properties of Nano silica-reinforced glass fiber polyester composites. The optimum value is for 5% of Nano SiO_2, with the addition of 4% of woven glass fibers.

Table 2.4. Lists the various researchers who worked on hybrid nanocomposites

Reference	Year	Matrix	Fibers	Filler	Study
Mortazavi V et al. [73]	2012	Poly (methyl methacrylate) (PMMA)	E-glass	Nano clay	Flexural strength
Raghavendra G et al [74]	2015	Epoxy	Jute Glass	Micro & Nano Alumina	Mechanical
Naidu PP [75]	2019	Epoxy	Glass	g-C_3N_3	Mechanical
Tay CH et al. [76]	2021	Epoxy	Glass Kenaf	Nano clay	Mechanical
Sathishkumar TP et al. [77]	2022	Epoxy	Jute	Zinc Oxide	Mechanical properties
Gapsari F et al. [78]	2022	Polyester	Timoho fiber	Egg shell powder	Mechanical

2.6.WATER AND SOLVENT ABSORPTION OF COMPOSITES (DEGRADATION OF PROPERTIES)

NFRECs have gained importance because of advantages such as superior mechanical properties, durability, high corrosion resistance, and low cost [5, 79–81]compared to traditional metals. But in applications with contact or immersion in water or solvents like kerosene, saline water, methanol, etc., water and solvent absorption takes place, leading to degradation of mechanical, thermal and tribological properties. [31].The natural fiber consists of hemicellulose, cellulose, lignin, pectin, wax, substances soluble in water, and fat[82–85]. Cellulose is considered the fiber structure's mainframe element. This imparts the fiber stiffness, strength, and structural durability. Cellulose and hemicellulose, however, are the main components of natural fiber, which consume the most significant amount of humidity. Lignin provides efficient hemicellulose/cellulose protection alongside extreme environmental conditions such as moisture and temperature.

The fibers absorb water from the atmosphere through groups of hydroxyl which occur in the fiber. Three main water sorption mechanisms in NFRECs have been established: diffusion, capillary, and transfer of water particles[86, 87]. Diffusion is an unsystematic procedure in which water flows from high absorption regions to low absorption region. The behaviour of Diffusion in epoxy composites follows the Fickian and non-Fickian models of absorption. On the other hand, the capillary carrying process occurs in holes at the interface of the fiber/epoxy. Water intake is problematic since it can lead to matrix cracking, dimensional volatility, and poorer mechanical properties of polymer composites reinforced with fiber. The specific water content increases with excessive water absorption, whereas free water decreases[88]. Water-soluble materials initiate steps to remove water from the fiber and eventually, this result in ultimate debonding among matrix and fiber. Figure 2.2. shows the process of diffusion of water molecules into natural composite structure.

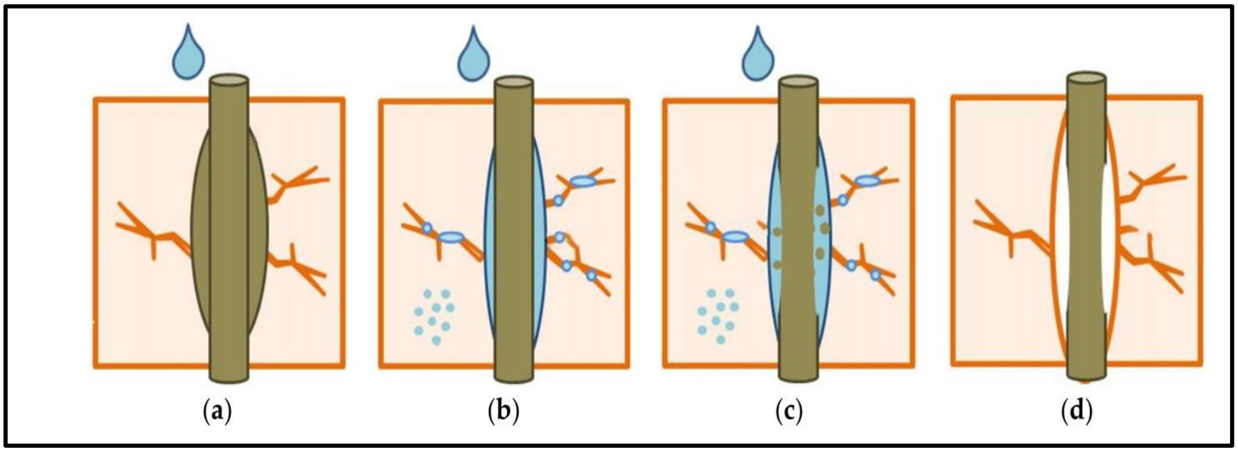


Figure 2.2 Deprivation of interfacial bond due to water sorption: (a) evolution of micro-cracks in epoxy due to the expansion of swollen fiber, (b) distribution of water molecules in the widespread matrix along with the fiber/epoxy interface, (c) escape of water-soluble fiber mechanisms, (d) final matrix-fiber debonding happens[88]

Water absorption content is lower in epoxy and synthetic reinforced composites compared to NFREC [89]. H. Alamri et al.[90] examined the mechanical and water absorption properties of recycled cellulose-reinforced epoxy composites. It is concluded that cellulose-reinforced fiber epoxy composites absorb more water than pure epoxy composites. As fiber content increases, water uptake and also diffusion coefficient is found to increase. This shows the hydrophilic nature of natural fibre-reinforced composites, and cellulose fibers have lumen. This hollow region allows more water to be absorbed, indicating the capillarity effect and water absorption behaviour is fickian. Work on water absorption and solvent absorption activity has been carried out several times. Table 2.5 shows the hybridization effect on the behaviour of Natural fiber-reinforced composites. Water absorption is calculated using the formula—(1)[91–93].

Z. Leman et al.[94] studied the effects of environment on the fiber surface properties of sugar palm fiber-reinforced epoxy composites. To sense and quantify organic contamination and the populace of microbes in both seawater and freshwater, a biochemical oxygen demand (B.O.D.) test was conducted. It is concluded that there are more microorganisms in marine water than in freshwater. This large microbe populace can help to degrade pectin and hemicellulose more efficiently, resulting in a more robust surface and matrix adhesion of the fiber. Using the DO meter, the pH values of seawater and freshwater were also calculated. The more significant the pH value, the faster the deterioration of hemicelluloses would be. Its salinity was another reason why sea water caused further degradation.

$$W\% = \frac{W_2 - W_1}{W_1} \times 100 \quad \text{-- (1)}$$

Where W_1 =Weight of the sample before being soaked in water and W_2 =Weight of the sample after being soaked in water and Sorption coefficients are calculated using the formula [91]

Mohd Shahneel Saharudin et al.[95] studied the deprivation of mechanical properties where halloysite Nano clay is reinforcing material in Polyester. It is found that an the increase of nano clay content in Polyester led to, seawater absorption increase. It is because seawater enters the voids of the polymer. Compared to monolithic Polyester, microhardness reduced from 107 HV to 42 HV (61 % decrease). Young’s modulus showed a 33 % decrease, and the flexural modulus showed a 43 % decrease. Microhardness, tensile properties, flexural properties, and impact toughness were adversely impacted after 168 h in seawater immersion**.** The water absorption is very much apparent if they are exposed to liquid media[96].

Table 2.5. Shows the hybridization effect on the behaviour of Natural fiber-reinforced composites

Reference	Fiber 1	Fiber 2	Findings
[98]	Jute	Banana	Water absorption properties were studied at the immersion of the sample at 23^{o}C. Hybrid composite with weight ratios of 50 /50 showed minor water absorption compared to other composites.
[99]	Banana	Sisal	Water absorption properties were studied at room temperature, and the hybrid samples showed minor water absorption. There is an 18% decrease in water uptake compared to banana-reinforced composites.
[100]	Kenaf	Jute Hemp	The water absorption pattern of these composites was found to follow the behaviour of the non-Fickian. Moreover, their hybridization enhanced the water-resistant properties of woven kenaf, Jute and hemp fiber.
[101]	Woven Jute	Woven Banana	With the different kinds of composites examined, banana composite materials have the least water uptake percent. Because jute fibre is water sensitive, the jute/banana/jute stacking sequence does have the largest moisture absorption % because jute fibre has the greatest coefficient of adsorption, diffusion, and penetration.
[102]	Jute	Coir	Composite samples were prepared with separately treated and untreated fiber, and samples were immersed at 25^{o}C and 50^{o}C temperatures for 120 hrs. Hybridized composites with a fiber ratio 50/50 with treatment showed the least water absorption at 25^{o}C.

[103]	Flax	Bamboo	Hybrid composites with 30% flax and 10% bamboo exhibited less water absorption than other normal and hybrid specimens. Interestingly with higher bamboo content, water absorption is more.

2.7.MANUFACTURING OF COMPOSITES

Open and closed moulding are the two main categories of composite manufacturing methods. The gel coat and laminate are exposed to the environment throughout the fabrication process through open moulding. In closed moulding, the composites are treated either in a vacuum bag or a two-part mould set. There are numerous processing techniques within the divisions of open and closed moulding**.**

2.8.LITERATURE GAP

Despite several studies on composites, there is still a knowledge gap in hybrid nanocomposites and the degradation of properties in liquid media. Based on the literature survey, it was identified that:

- Most research aims to enhance the properties by reinforcing natural or synthetic fiber alone.
- Literature review is available only on hybridization among fibers, but there is very little reliable data regarding the reinforcement of filler and fiber together.
- Few studies have been reported on enhancing the properties of hybrid nanocomposites, but the degradation of hybrid composite properties after exposure to different environments has not been addressed so far.

Based on the literature survey, the present investigation aimed to develop a new hybrid nanocomposite and to study various mechanical, moisture absorption and tribological properties for multiple applications.

2.9.OBJECTIVES

The following are the objectives:

1. To study the effect of the Stacking sequence of Kevlar/Sisal and Glass/Sisal on the mechanical properties of polyester hybrid composites.
2. To study the effect of Nanoclay/Nano Silica on Kevlar/Sisal(KSSK) and Glass/Sisal(GSSG) reinforced Polyester Hybrid composites on the mechanical properties.
3. To study the effect of moisture absorption on mechanical and tribological properties of KSSK & GSSG reinforced Nano-clay Polymer composites.
4. To make a comparison of Polyester and epoxy Hybrid composites.

Chapter- 3

Effect of Stacking sequence of Kevlar/Sisal and Glass/Sisal on the mechanical properties of polyester hybrid composites

3.1.INTRODUCTION

In the present generation of composites, hybrid composites play a vital and dynamic role in several manufacturing application areas. A hybrid composite involves of the polymer as matrix material and, fiber/fibers, and filler as reinforcement. Much research is about creating novel hybrid composites due to their lightweight, strength-to-weight ratio and improved mechanical properties[104].

Synthetic fibre-reinforced composite materials have become popular over the years due to their exceptional mechanical properties, light weight, unique flexibility, corrosion resistance, ease of manufacture, etc. Combined with other conventional metallic materials, synthetic fiber use has become extensive. One of the most durable synthetic fibres, Kevlar fiber, has outstanding properties among synthetic fibers. Kevlar fiber and advanced machinery are used in helicopter blades, ballistic weapons, etc., [105][106][107]. The downsides of natural fibers is poor mechanical properties, such as tensile and flexural, which are much lower than conventional fibers and they have weak resistance to water uptake[108, 109]. Therefore, using natural fiber alone in the polymer matrix is insufficient to please all the methodological requirements of reinforced fiber composites. Our current objective is, therefore, to develop new hybrid composites. Many factors, such as the orientation of the fiber, the ratio of fiber to matrix, the physical bond among the fiber and matrix, etc., affect the strength of the composites[110],[111]. Polymer composites are more likely to fail when applied to mechanical loads, such as tensile and bending.

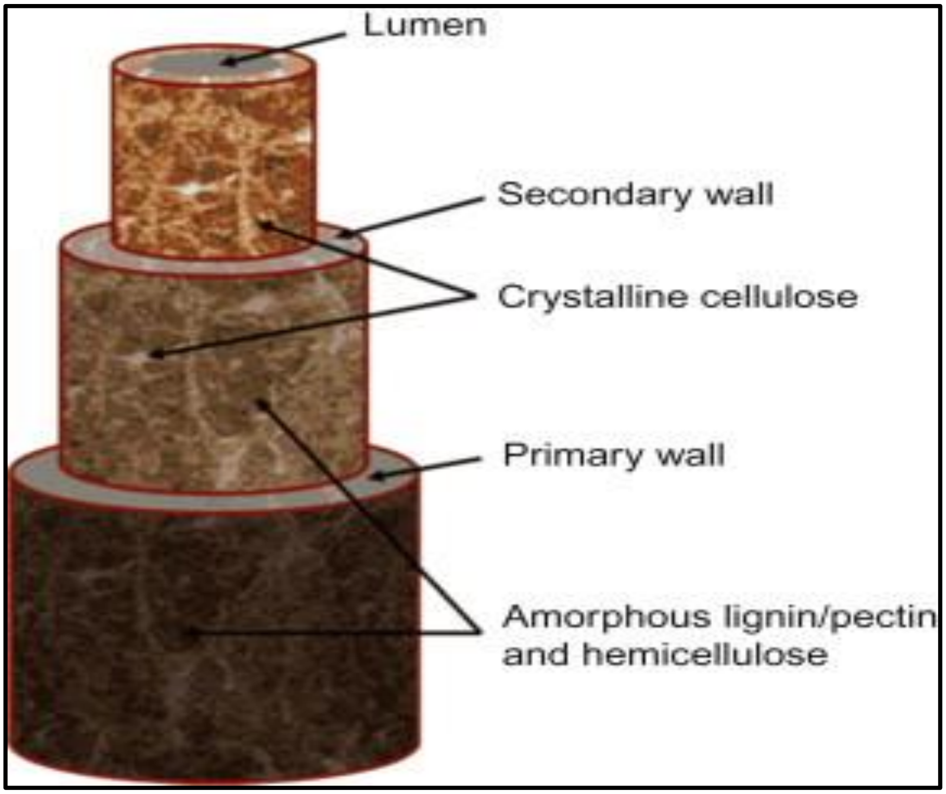


Figure 3.1. Shows the natural fiber structure[112]

Jarukumjorn K et al.[113] reported the mechanical properties of Sisal fibre-reinforced Polypropylene(PP) with Glass fibre hybridization. The mechanical properties of the composites were enhanced by hybridization with glass fibre. The addition of glass fibre to PP composites increased their thermal stability. The temperature of thermal disintegration of the composites rose as the glass fibre concentration increased. PP with 10wt.% of Sisal and 20wt.% of Glass fibre showed maximum mechanical properties associated to other wt.%. Arthanarieswaran VP et al.[114] studied the influence of glass on Banana/Sisal reinforced polymer composites. It is concluded that reinforcement of Banana/Sisal with Glass significantly improved mechanical properties. Glass fibre with 25wt.% showed superior tensile properties compared to other composites. The laminate with a banana–sisal hybrid mixture and three layers of glass fibre has an ultimate tensile strength of 104 MPa.

Therefore, in this work, the main aim is to develop a new hybrid composite, which is a grouping of natural and synthetic fibers, with an altered stacking sequence of Sisal/Kevlar mat and

Sisal/Glass mat fiber reinforced with polyester composites for making low-cost engineering materials.

3.2.MATERIALS AND METHODS

3.2.1. Raw Materials

Materials used in the present research are given below:

1. Polyester
2. Accelerator and catalyst
3. Sisal
4. Glass
5. Kevlar

3.2.2. Polyester

The two types of thermosetting polyesters are alkyds and unsaturated linear polyesters. Alkyds are widely used in coatings, particularly in paints, lacquers, and varnishes. Unsaturated monomers, including maleic anhydride, make linear thermosetting polyesters with unsaturation as the spine. The process is controlled after initial poly-condensation with a diol to a molecular weight of 1100-5100, with high viscosity decreased by dilution with an unsaturated monomer (e.g., styrene or diallyl phthalate), and a resin combined with Fibers/Fillers. Thermal curing, activated by free radicals such as peroxides, produces a strongly cross-linked network. At low operating temperatures, accelerators such as cobalt naphthenate or alkyl mercaptans accelerate peroxide breakdown.

Reinforced polyester materials are increasingly being employed in large construction and infrastructure tasks because they are inexpensive, allow mass production, have general strength, and are chemically inert. Bridges and highway constructions involve extensive use developing use, particularly in coastal areas where corrosion (due to salt application) or seismic safety are issues with metal-reinforced concrete structures but not composites. Another significant application is in chemical resistance confinement containers and their surroundings, particularly in the chemical industry. Swimming pools and yachting are popular recreational activities. Figure 3.2. Shows the chemical structure of Polyester. Polyester was purchased from a local Supplier Bindu agencies, Vijayawada, India.

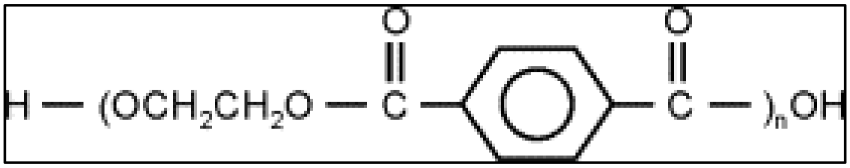


Figure 3.2. Shows the chemical Structure of Polyester[1]

3.2.3. Sisal

Sisal can be quickly grown in a small period of time. The plant cultivates naturally among field borders and railway tracks. Sisal fibre is made from the leaves of Agave sisalana plant. The four varieties of sisal plants found in India are Sisalana, Vergross, Istle, and Natale. Sisal fibre is generally separated using retting, peeling, and physical techniques by decorticators' smart art. Three forms of sisal fibre are removed from the leaves: mechanical, ribbon, and xylem. Mechanical fibres are removed from the leaf's periphery. They resemble a wedge and can be separated during the extraction method. The ribbons variety is the strongest fibre and can be divided horizontally during manufacturing. The xylem fibres have an uneven form and easily break up during processing. These fibres form by linking vascular bundles and run in opposite direction as ribbons fibres.

Furthermore, the chemical composition of sisal fibre varies according to availability, testing techniques, age, and other factors. Like many other natural fibres, Sisal fibre contains cellulose, lignin, hemicellulose, and moisture. Table 2.1 shows the chemical content and moisture content of sisal fibre. Figure 3.3 shows the sisal fiber.

Table 3.1. Chemical composition of Sisal fiber[2]

Fiber	**Cellulose (%)**	**Hemicellulose(%)**	**Lignin (%)**	**Wax (%)**	**Moisture (%)**
Sisal Fiber	60–78	10.0–14.2	8–14	2.0	10–22

Figure 3.3. Sisal Fiber (Mat)

3.2.4. Glass

Glass fibre is a durable material that may be used in both industrial and home environments, which is shown in Figure 3.4. It is obtained from Vruksha composites Glass fibres are a handy material used in various applications. Glass fibre has a lower stiffness than other reinforcing fibres.[9] Still, it combines high strength with low density and, most crucially, low cost.[115, 116] Glass fibres have several drawbacks: warpage, low weld and knit line strength, higher melt viscosity, poor surface quality, and increased abrasion loss to machine and tool.[117].

Figure 3.4. Glass Fiber (Mat)

3.2.5. Kevlar

In the last 20 years, synthetic fibres such as Kevlar, glass, carbon, and boron have become popular. High-performance, rigid synthetic fibre-reinforced plastics are widely employed in aircraft manufacture and automotive sectors. Kevlar fiber are stronger and more hydrophobic than natural fibres (where the moisture absorption content is low). The fact that they are not biodegradable is one downside. Man-made fibre is more durable than natural fibre.[118]. To compensate for the inadequacies of natural and man-made fibres, a new hybrid composite composed of natural and man-made fibres that improve the mechanical strength of polymer composites is often used. [119]. Figure 3.5 shows Kevlar fiber mat.

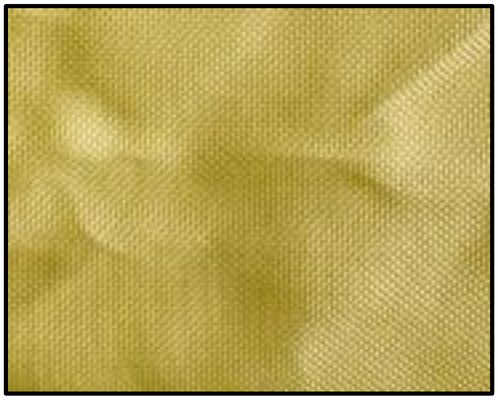


Figure 3.5. Kevlar Fiber (Mat)

3.3.COMPOSITE PREPARATION

In the present investigation, synthetic fibres (Kevlar and glass), natural fibre (Sisal), and matrix material (Polyester) are chosen based on the literature for the fabrication of hybrid polymer composites. Table 3.2. shows various properties of Kevlar, sisal and glass fibres. Polyester / Kevlar(K) / Sisal(S) composites were prepared using hand lay-up technique. Four layers of fibers changing the layer sequence of Kevlar (K) / Sisal(S) as KSKS, SKKS, and KSSK were prepared.

The hybrid composites were prepared by applying the Polyester equally between the four layers with uniform thickness. Proper care was taken to ensure no resin spilt from the mould. The composite was hard pressed with a roller to maintain uniform thickness (3mm)

A similar procedure was carried out for Glass/Sisal hybrid composite. After the fabrication of the specimens, the samples were cut using a diamond cutter for mechanical testing. For tensile Specimens, ASTM D638 and bending specimens ASTM D790 were used for testing the specimens by UTM. The average of five samples was considered for calculating tensile and flexural strength. The entire sequence of fabricating the specimens is shown in Figure 3.6. Figure 3.7 shows the various stacking sequence of fibers with polyester reinforcement.

Table 3.2. Various properties of Kevlar/Sisal/Glass fibers

Properties	Kevlar Woven Mat	Sisal Woven Mat	Glass Fiber
Density(g/cc)	1.50	1.44	2.46
Thickness(mm)	0.38	0.51	0.6
Weight (gsm)	149	215	220

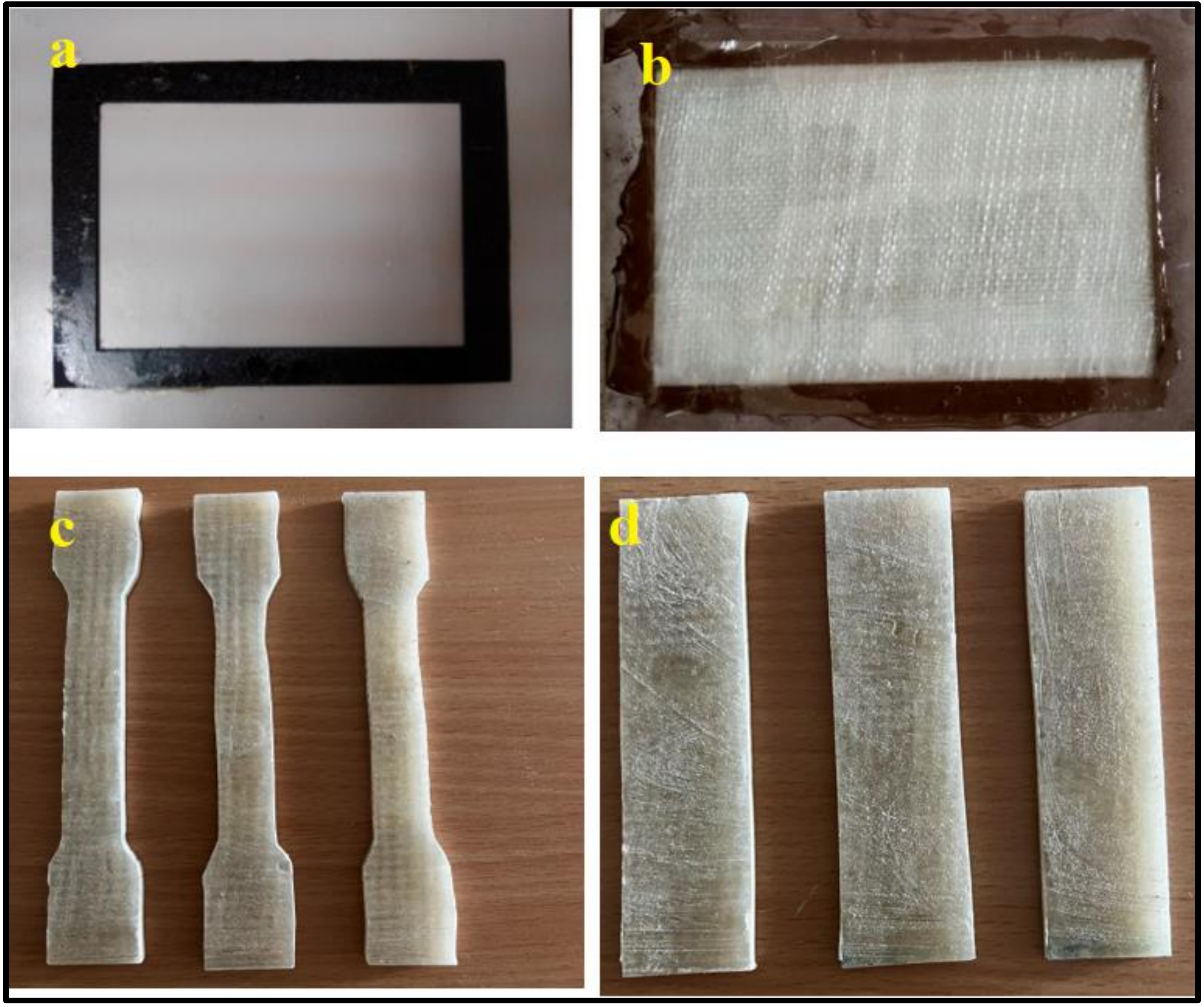


Figure 3.6. Images of Composite fabrication a) Mold b) Composite c) Tensile Specimens d) Flexural specimens.

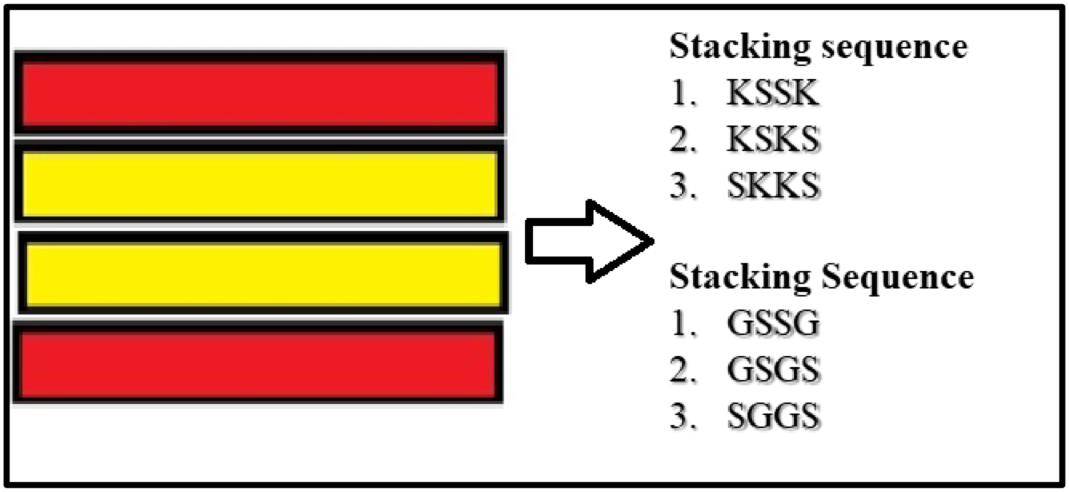


Figure 3.7. Various Stacking sequence of fiber

3.4.MECHANICAL PROPERTIES OF THE HYBRID COMPOSITES

3.4.1. Tensile Properties Characterization

The most important and commonly calculated characteristic for composite material and structural applications is tensile strength[120]. Tensile tests are carried out using a tensometer containing a load capacity of about 0-2000kgs, elongation of 0-200mm, and accuracy of 0. 001. Figure 3.8. shows the samples in testing conditions in tensile and flexural modes

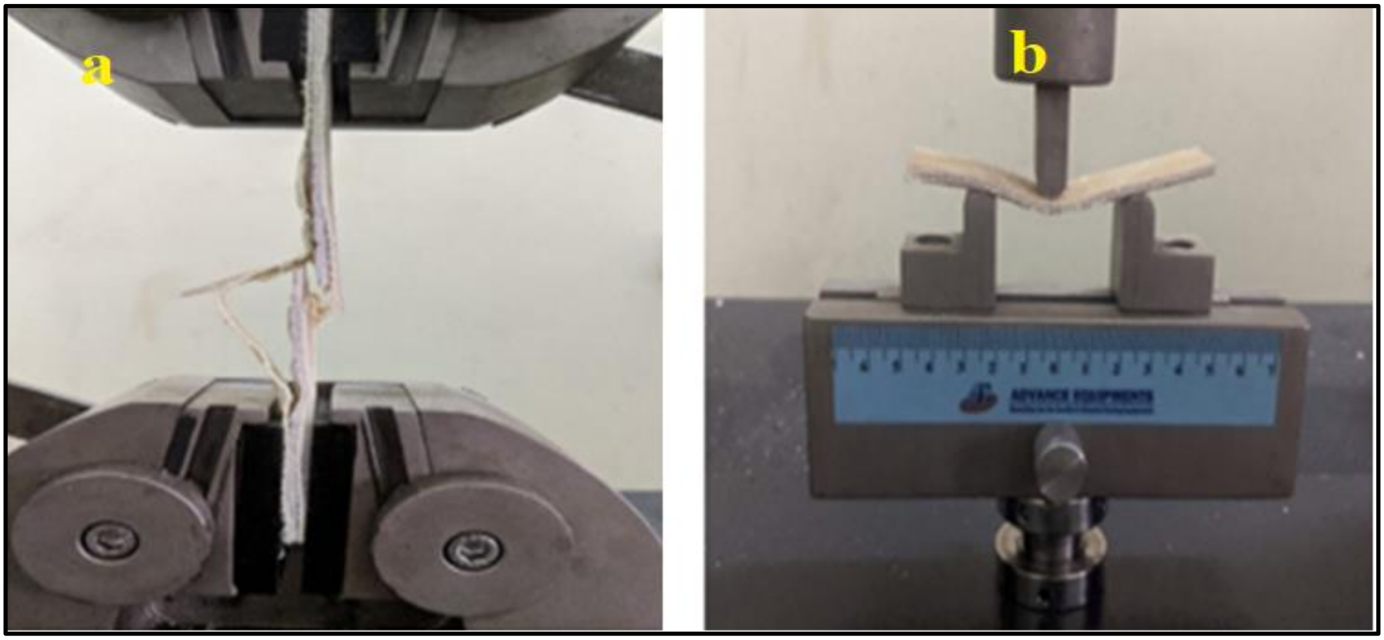


Figure 3.8. shows the samples in a) Tensile testing, b) Flexural testing

3.4.2. Flexural property characterization

A 3-point bending test technique was used to calculate the bending strength of the composite on a tensometer[121]. The size of the specimen used in the test was 100×25×3 mm. All tests were performed at room temperature as per ASTM D790b standards. The average of five samples was considered for calculating the tensile and flexural strength. Samples after testing are shown in Figure 3.9. Both tensile and flexural testing of samples was done in loading conditions. The results found under the above conditions are listed in Table 3.3.

Figure 3.9 Shows the samples after testing a) Tensile b) Flexural

Table 3.3. Tensile and Flexural results of hybrid composites (Polyester/Kevlar/Sisal) and (Polyester/Glass/Sisal)

K: Kevlar **S: Sisal** **G:Glass**	**Polyester Resin**	**KSKS**	**SKKS**	**KSSK**	**GSGS**	**SGGS**	**GSSG**
Tensile Strength(MPa)	19.76	98.65	87.68	110.34	68.36	57.89	79.12
Flexural Strength (MPa)	35.3	320	290	305	301.36	260.13	303.11

3.5.RESULTS AND DISCUSSION

3.5.1. Tensile strength of hybrid composites (Kevlar and Sisal)

The tensile properties of neat polyester resin and sisal/kevlar hybrid composites are presented in Figure 3.10. The results exhibited that the tensile properties of the hybrid composite were found to be more significant in KSSK stacking sequence composites than in neat Polyester and other hybrid laminated composites. Composites with Kevlar on the outside layer were found to have improved mechanical properties compared to other hybrid composites. Kevlar fibers are more durable, stiffer, and their interlaminar shear strength is better than that of sisal fibers. The load-resisting capacity is also better compared to sisal fiber. So Kevlar fibre it does not break easily after applying load. Due to the addition of sisal and Kevlar, the tensile strength of Polyester enhanced by 399% in KSKS, 343% in SKKS, and 458% in KSSK compared to pure polyester.

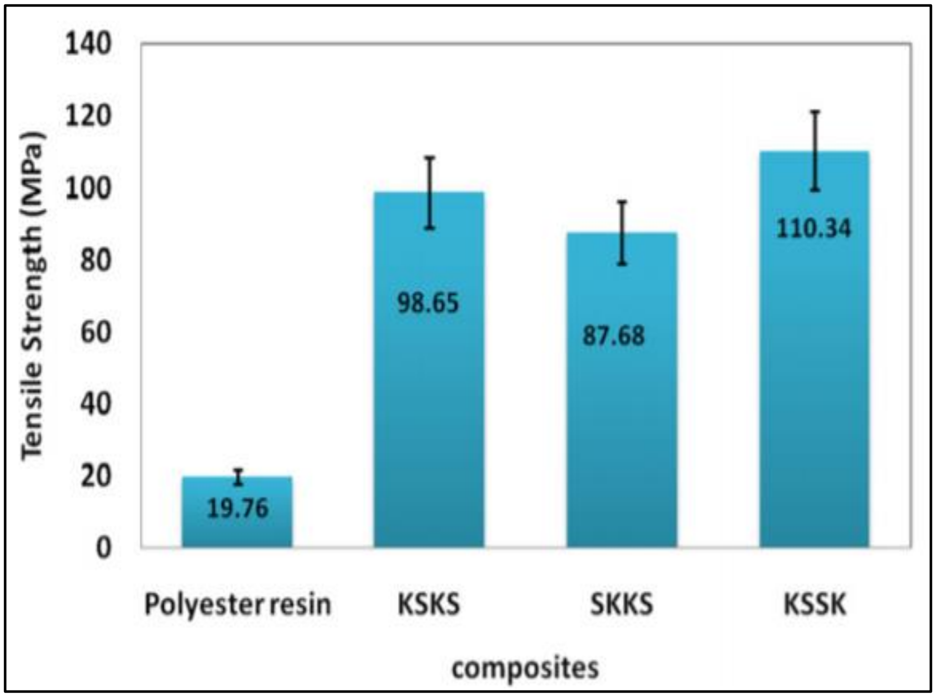


Figure 3.10. Tensile Strength of hybrid composites **(Kevlar and Sisal)**

From the results, it was also observed that the outer layer is sisal fiber; where the strength is lower compared to Kevlar. This may be due to higher hemicellulose and lignin content in the sisal fiber, which does not make a suitable bond with the matrix.[122] Hence it cannot resist the load and break easily after applying load the decrease of strength value due to the fiber breaking and delaminating of the composite.

3.5.2. Tensile strength of hybrid composites (Glass and Sisal)

The tensile properties of neat polyester resin and glass/sisal hybrid composites are presented in Figure 3.11 with various stacking sequences. The results exhibited that the hybrid composite's tensile properties were more significant in GSSG stacking sequence composites than neat Polyester on other hybrid laminated composites. Similar results can be seen from Kevlar/sisal results. Composites with glass on the outside layer were found to have improved mechanical properties than other hybrid composites. Because glass fibers are more durable and stiffer, interlaminar shear strength is better than that of sisal fibers. Adding sisal and glass improved to 259% in GSGS, 204% in SGGS, and 316% in GSSG compared to pure polyester.

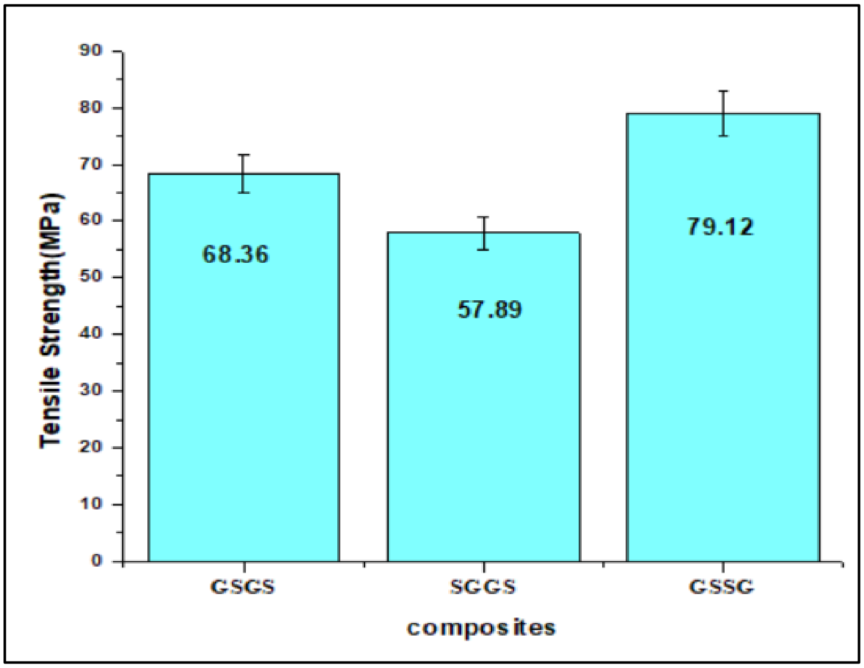


Figure 3.11. Tensile Strength of hybrid composites **(Glass and Sisal)**

3.5.3. Flexural strength of Hybrid composite (Kevlar and Sisal)

Figure 3.12 shows the flexural strength of Kevlar/sisal polyester hybrid composites and pure polyester resin. It is evident from the result that the flexural properties of the hybrid composite were found to be higher in KSKS stacking sequence composites than in neat Polyester and other hybrid laminated composites. But the strength of KSSK and KSKS was almost equal. The strength was 806% in KSKS, 721% in SKKS, and 764% in KSSK compared to pure Polyester. Better strength was observed in KSSK. This may be due to the interphase bonding among polymer and fiber and bending stress transfer from matrix to Kevlar fiber, which may carry the load at loading conditions.

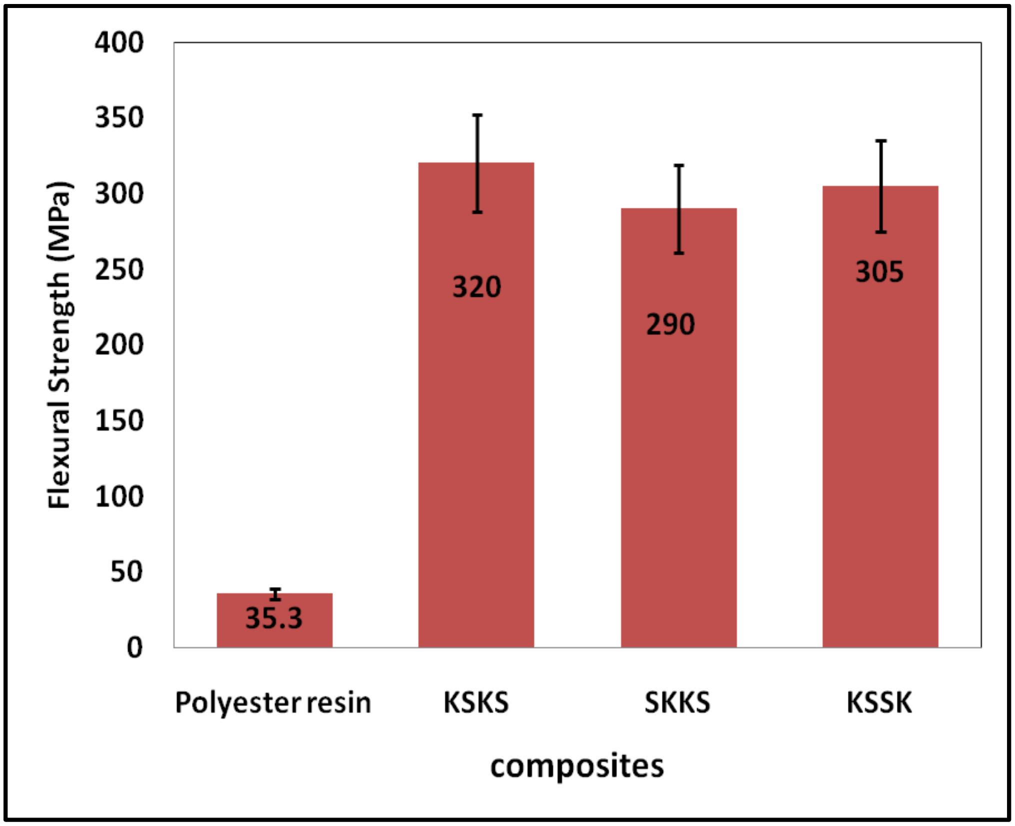


Figure 3.12. Flexural Strength of hybrid composites **(kevlar and Sisal)**

The enhancement of strength not only depends on the hybridization of fibers, it also depends on the stacking sequences; in three different sequences Kevlar as outer shows better mechanical results. Salman S. D et al.[123], in their investigation, also confirmed that Kevlar as outer and kenaf as inner hybrid composites show higher resistance with more energy absorbed (penetration) and maximum load.

3.5.4. Flexural Strength of Hybrid composite (Glass and Sisal)

The effect of stacking sequence on the hybrid glass/sisal reinforced polyester composites can be seen in figure 3.13. It can be concluded that glass as the outer most stacking sequence has better flexural properties compared to other stacking sequences. Sisal has outer most fiber which has less flexural strength. The strength is 760% in GSGS, 642% in SGGS, and 765% in GSSG when compared to pure Polyester.

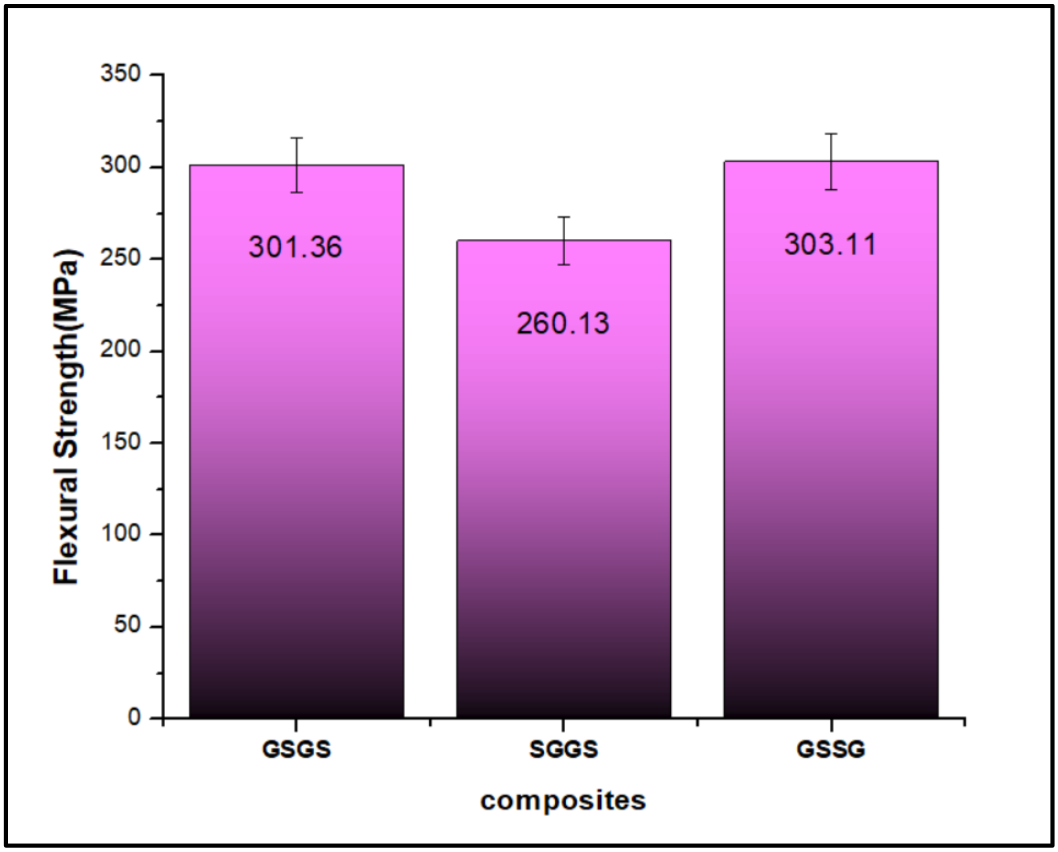


Figure 3.13. Flexural Strength of hybrid composites **(Glass and Sisal)**

3.5.5. SEM Analysis

Figure 3.14 shows the SEM images of the KSSK stacking sequence under 2μm magnification. From the figure, it can be seen that less voids are present in the composites with which we can clearly say there is better interfacial bond between the fiber and the matrix

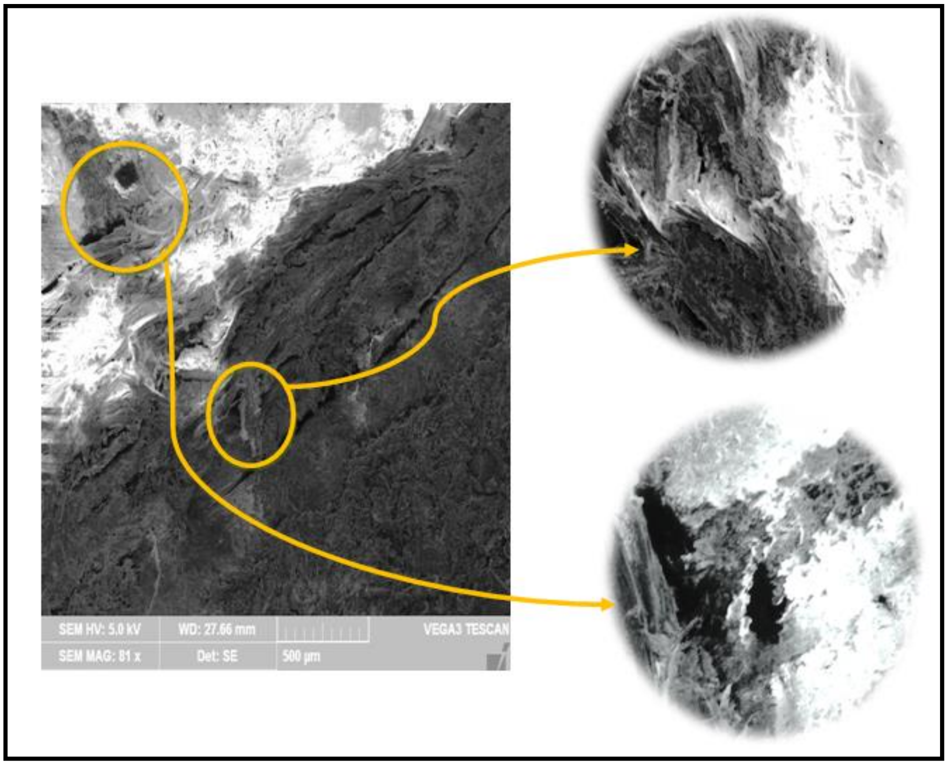


Figure 3.14 Shows the SEM images of Polyester/KSSK composite

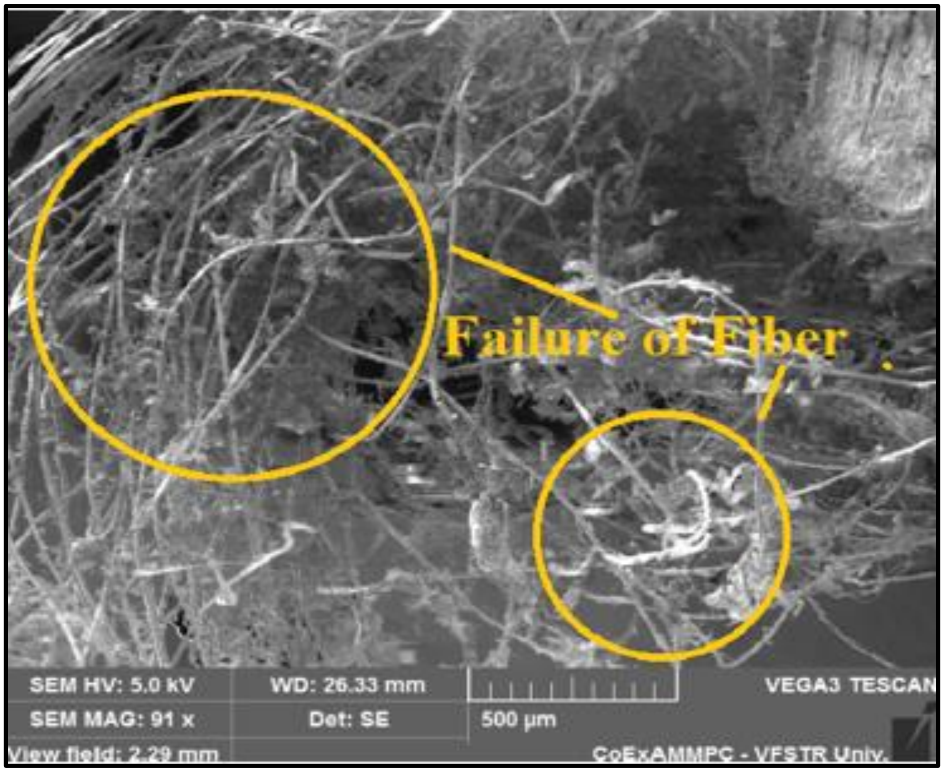


Figure 3.15 Shows the SEM images of tested flexural specimen Polyester/KSSK composite

Figure 3.15 Shows the SEM images of tested flexural specimen of polyester/KSSK stacking sequence and from the figure one can say that there is failure of fiber due the bending load. It was seen that the fiber and the matrix debonding due to bending load is observed. The fracture material fails under stress; the failure planes are always natural to the load. Nevertheless, cross-section failure alone does not affect the composites failure mode. Composite failure mode depends on a variety of variables, including the type of fiber, type of matrix, fiber/matrix communication, reinforcement transfer place of failure, etc.[74].

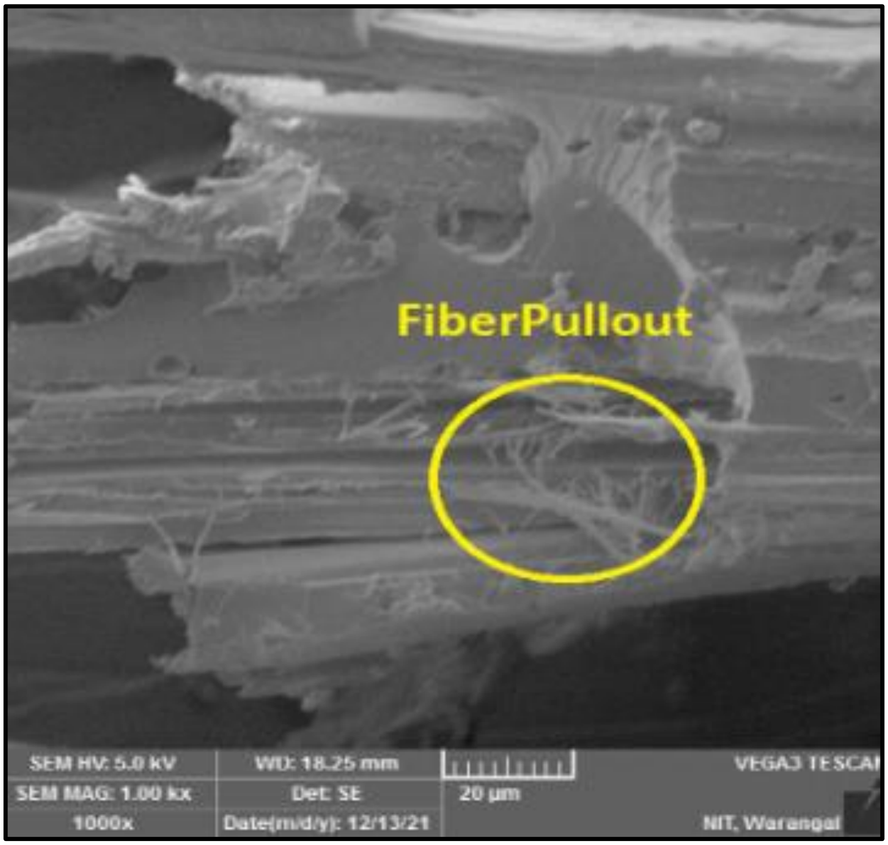


Figure 3.16 Shows the SEM images of tested flexural specimen Polyester/GSSG composite

Figure 3.16 shows the SEM of tested sample in Polyester/GSSG composite and in the samples it is clearly seen that the fiber pull-outs was observed. The brittle nature of Sisal fiber leads to poor bending and which reduced the strength.

3.6.CONCLUSIONS

The effect of stacking sequence on the mechanical properties of Kevlar/Sisal and Glass/Sisal was been studied.

1) Due to the addition of sisal and Kevlar, the tensile strength of Polyester has enhanced to 399% in KSKS, 343% in SKKS, and 458% in KSSK compared to pure polyester.
2) Adding sisal and glass improved to 259% in GSGS, 204% in SGGS, and 316% in GSSG compared to pure polyester.
3) The flexural strength enhanced 806% in KSKS, 721% in SKKS, and 764% in KSSK when compared to pure Polyester.
4) The strength enhanced to 760% in GSGS, 642% in SGGS, and 765% in GSSG when compared to pure Polyester.
5) Hybridization of fiber composites with synthetic fiber in the outside layer led to have improved mechanical properties. Synthetic fibers are more durable, stiffer, and inter-laminar shear strength is better than natural fibers. The load resisting capacity is also better compared to natural fiber. So it does not break easily after applying load.

6) From the results, it is also observed that the outer layer is sisal fiber; the strength is lower compared to Glass/Kevlar. This may be due to the presence of higher hemicellulose and lignin content in the sisal fiber, does not make a suitable bond with the matrix. Hence it cannot resist the load and breaks easily after applying load. The decrease in strength is due to fiber breakage and delaminating of the composite.

Chapter -4

Effect of Nanoclay/Nano Silica on Kevlar/Sisal(KSSK) and Glass/Sisal(GSSG) reinforced Polyester Hybrid composites

4.1.INTRODUCTION

Particulate fillers are powdered compounds with particles typically smaller than 100 m in size that are added to polymers to save costs, improve processing, and/or improve one or more properties. Nanoparticle fillers have at least one dimension in the 1-10 nm range; however, fibres and nanoparticle fillers are not covered in this category. A particle-filled polymer composite is a polymer matrix mixed with particulate fillers. Normally, the filler and polymer have distinct properties, and by blending the two, a range of substances with characteristics halfway between the two elements can be obtained. By looking at commercial polymers on the market, one can see that there are efficiency gaps among them; however, the addition of fillers can bridge such gaps and enhance performance capabilities to target a much broader market. Particulate fillers are required in some applications, such as elastomers[124].

One major obstacle in the production of nanocomposites is ensuring that the nanoparticles are evenly distributed throughout the matrix material[125]. This is crucial since only well-dispersed nanoparticles can give rise to unique composite properties, such as improved toughness and stiffness, even with low amounts of filler material[126]. Several techniques are available to disperse particle agglomerates in a liquid; ultrasonic waves can also be used for dispersion which is discussed in chapter 1. Figure 4.1 shows the most mechanical stirring followed by ultra-sonication which involves directing high-intensity ultrasound into liquid mixture of particles and matrix material, causing cavitation bubbles to form and grow before imploding due to a critical diameter being reached. This implosion creates extremely hot and pressurized hot-spots that can cause agglomerates to split up, resulting in dispersion effects. Shock waves generated by the implosive bubble collapse and micro-streaming from cavitation oscillations contribute to the dispersion process. Different types of information can be found in the literature about the optimal processing time for ultrasonic dispersal of nanoparticles in resin.For instance, Rodgers et al.[127] dispersed SiC nanoparticles for 30 minutes with ultrasound, while Xu et al.[128]observed a deprivation of the mechanical properties profile for extended ultrasonic dispersion times. West and Malhotra[129] also reported an increase in mechanical properties after 5 minutes of ultrasonic dispersal and a reduction after 10 minutes of dispersal. This could be due to the deprivation of the epoxy resin despite enhanced dispersal quality. However, Yasmin et al.[130] sonicated extended graphite in epoxy resin for several hours, and Sandler et al.[131] disseminated carbon nanotubes in ethanol for one hour before adding the resin and evaporating the solvent.

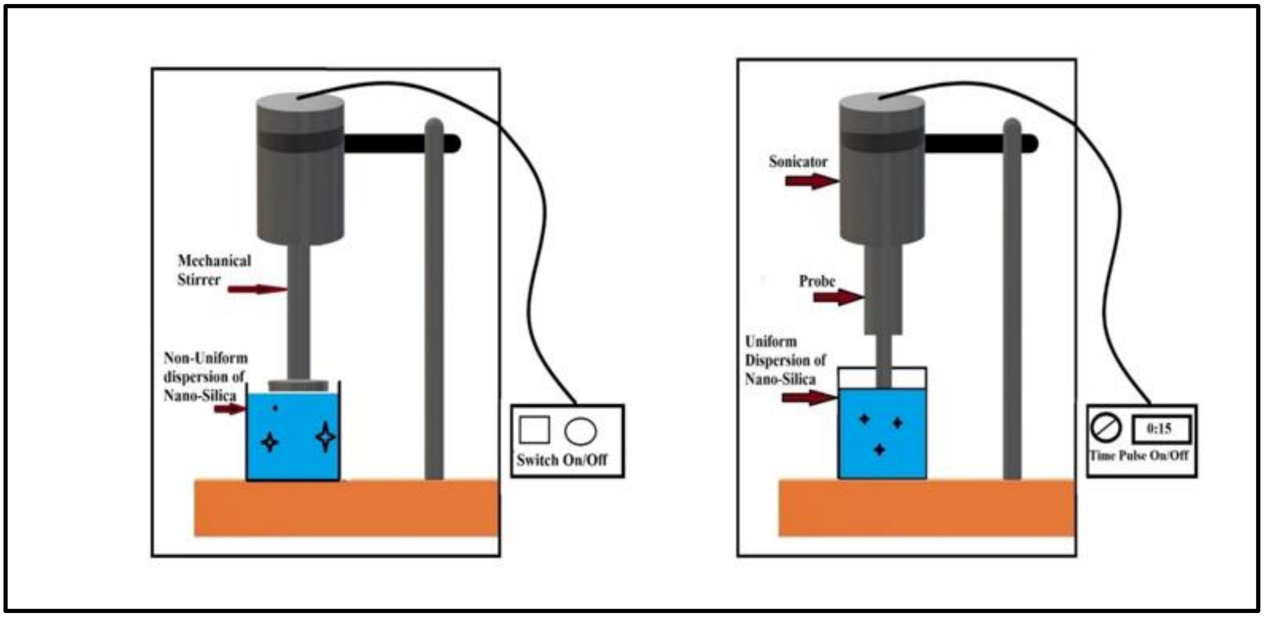


Figure 4.1. (a) Schematic diagram of the mechanical stirring process (b) Ultrasonication process.

J. K. Prajapati et al.[71] determined the mechanical and dynamic mechanical analysis of glass fiber reinforced Nano-silica epoxy hybrid composites. It is found that glass fiber with 25wt.% and nano-silica with 3wt.% improved mechanical properties equated to other wt.%. Inclusion of Nano-silica in glass fiber enhanced the mechanical properties. O. Shakuntala et al.[132] studied the mechanical properties and tribological properties of polymer composite utilizing wood apple shell particulate as filler. And it has been discovered that the amalgamation of wood apple shells as filler increased the mechanical and tribological properties. R. A. Mohammed et al.[72] examined the mechanical properties and tribological properties of Nano silica-reinforced glass fiber polyester composites. The optimum value is for 5% of Nano SiO_2, with the addition of 4 % of woven glass fiber. Chee SS et al.[133] examined the effect of Nano clay on the mechanical properties of Bamboo(B)/Kenaf(K) fibre reinforced epoxy composites and concluded that Nano clay reinforced composites had better strength compared to B/K reinforced composites. The addition of organic modifiers, which improved interlayer spacing, and well-dispersed Nano clay, which provided interfacial solid adhesion strength between the dissimilar elements in a hybrid nanocomposite, improved the tensile characteristics of all hybrid nanocomposites significantly.

Raju P et al.[70] concluded that reinforcing nano clay particle to Caryota urens/glass intra ply fibre increases the composite's tensile, flexural, and impact properties while adding SiC particles up to 1.0 Vol.% increased the hardness to 92 shore-D. Glass and Caryota fibre hybridization showed better mechanical qualities while being environmentally benign.

Therefore, in this chapter, the main aim is to develop a new hybrid nano composite, which is a grouping of natural /synthetic fibers with an optimum stacking sequence based on the conclusions arrived at from chapter I (KSSK and GSSG) i.e. synthetic fiber as outer most reinforcement with polyester composites and a Nano filler (Nano clay and Nano silica) for making low-cost engineering materials.

4.2.RAW MATERIALS

1. Nano Silica
2. Nano clay
3. Polyester
4. Glass
5. Kevlar
6. Sisal

4.2.1. Nano-silica

Silica ($SiO2$) nanoparticles are widely recognized as one of the most significant inorganic nano-fillers for composite materials due to their low cost, high specific surface area, strong adsorption, good dispersal ability, high purity, and excellent stability[134][135]. Compared to other inorganic nano-fillers such as layered silicate, metal nanoparticle, and metal oxide nanoparticle, silica nanoparticle is particularly advantageous because it is abundant on the earth's crust and extensively used in various industries like pharmaceutical and cosmetic. These nanoparticles are used to reinforce polymer, cement, and asphalt composite materials. However, Silica Nano Particles attained from natural assets contain impurities, making them unsuitable for scientific research and manufacturing applications. Therefore, scientists have synthesized silica nano particles including colloidal silica, silica gels, pyrogenic silica, and precipitated silica to produce pure amorphous silica powder since natural mineral silica is crystalline (quartz, cristobalite)[136].

Table 4.1. Comparison of properties of Nano Silica and Nano clay

Properties	**Nano-silica**	**Nano Clay**
Phyisical State	Solid	Solid
Form	White Powder	Light Yellow
Density	2.4 g/cm^3	0.6- 1.1 g/cm^3
Melting point/range	1700 ºC	1750 ºC
SiO_2 content	>99.8%	43.69 , Al_2O_3 18.07
Particle Size	15-20 nm	less than 20 nm

4.2.2. Nano clay

Nano clays are stacked silicates with 0.7 nm thick single layers and 1 nm thick double layers. Surfactants can be used to improve plasticity and swelling capability of the interlayer. Surface properties of Nano clays are determined by Nano sheet charge, surface atom nature, and interlayer exchangeable cations. Because of the substitution of Al^{+3} or Mg^{+2} ions with silicon, the surface of Nano clay is negatively charged.

Nano clay or Nano-layered silicate are enhanced-clay minerals that have become very popular as reinforcing fillers for composites among the many nanoparticles. This is because of their high aspect ratio, potential exfoliating properties, and superior mechanical performance. Nano-clay is similar to montmorillonite, which is the most often utilized material in materials application. Numerous researchers discovered that Nano clay filler can significantly strengthen and change the mechanical properties of fiber reinforced polymers when Nano clay is effectively dispersed in polyester/epoxy resin composites. Both Nano silica and clay were purchased from Sigma Aldrich, USA and the macroscopic images can be seen in Figure 4.2. Table 4.1 Shows the comparison of the basic properties of Nano silica and Nano clay.

Figure 4.2 Shows the images of a) Nano clay b) Nano silica

4.3. HYBRID COMPOSITE PREPARATION

In this process Nano clay/Nano silica was mixed with Polyester for optimum stacking sequences for both KSSK and GSSG, which forms a hybrid polymer Nanocomposite

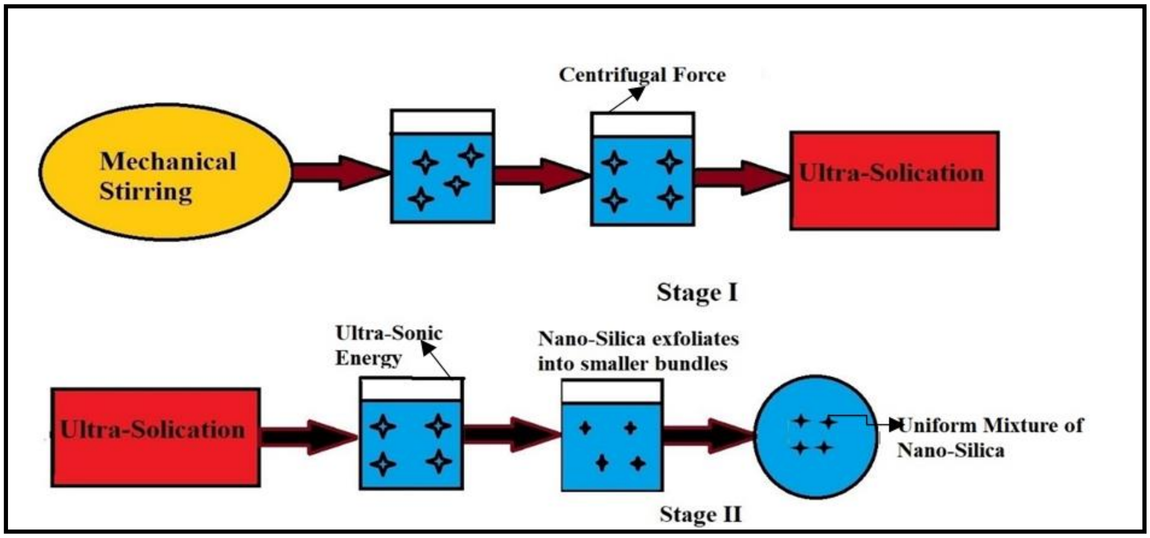


Figure 4.3. Schematic Diagram of particle distribution

In the initial step, the Nano-silica and Polyester were mixed using mechanical stirring process for 10 min to mix the matrix and filler. In the next step, ultrasonic vibrations were used by an ultra-sonicator to distribute filler into the matrix properly. Fig. 4.1 shows the schematic diagram of the mechanical stirring process and Ultra-Sonicating of polyester/Nano-silica. Different weight percentages of Nano-silica filler content, such as 2, 4 & 6 wt.%, were used to fabricate composites.

Nano silica and polyester mixture were placed in a glass beaker, mixed with a mechanical stirrer, and kept at high intensity for 30 min with a pulse mode (15 s on/15 s off) in Ultra-Sonicator. Figure 4.3 shows the sketch of the filler distribution in different steps. Step-1: a mechanical stirring process is performed at room temperature and stirred for 10 min, which mixes the powder and polymer, but due to density differences and centrifugal action, all the particles were distributed in the corner or near glass beaker. In Step-II, by ultra-sonication process, the particles are distributed uniformly due to Ultrasonic vibration. The Sonication process creates high pressure, vibrations, and acoustic wave streaming, which lead to silica nanoparticles, homogeneous distribution in a polymer. Figure 4.4 shows the sample preparation for the present objective. A similar procedure was carried out for Nano-clay also. Table 4.2 shows the Tensile and flexural results of Polyester /Nano-silica/Nano clay/KSSK/GSSG reinforced polyester hybrid nanocomposites after testing the samples as per ASTM standards.

Figure 4.4 Shows the sample preparation step by step procedure

Table 4.2 Tensile and flexural results of Polyester /Nano-silica/Nano clay/KSSK/GSSG reinforced polyester hybrid nanocomposites

wt.% of Filler	**Tensile Strength(MPa)**				**Flexural Strength (MPa)**			
	Nano Silica		**Nano Clay**		**Nano Silica**		**Nano Clay**	
	KSSK	**GSSG**	**KSSK**	**GSSG**	**KSSK**	**GSSG**	**KSSK**	**GSSG**
0 wt.%	110	81	110	81	305	303	305	303
2 wt.%	124	108	113	89	326.33	320	390	377
4 wt.%	135.28	115	123	95	420.45	365	326	326
6 wt.%	127.54	79	98	74	370	301	305	250

4.4.RESULTS AND DISCUSSION

4.4.1. Effect of Nano silica on KSSK reinforced polyester composites

4.4.1.1.Tensile properties

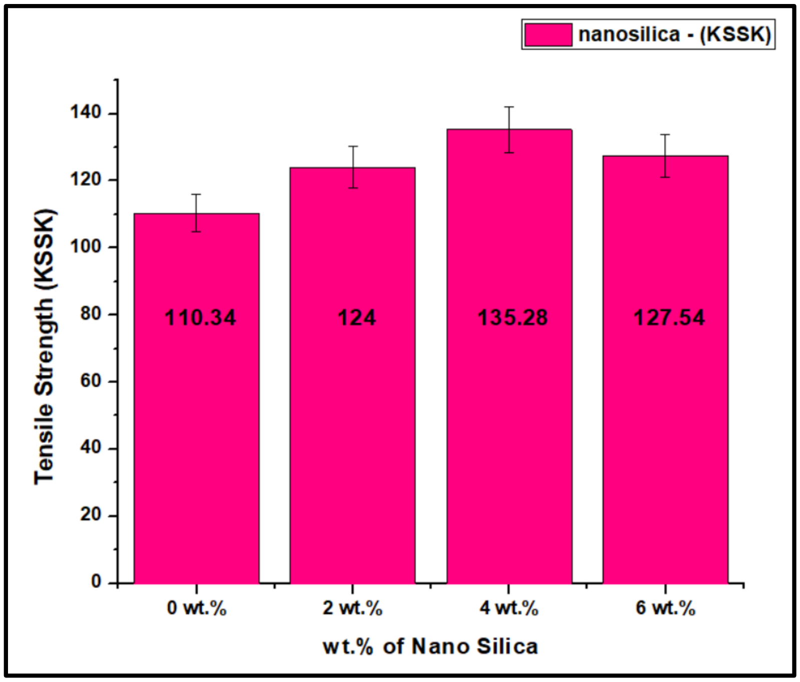


Figure 4.5. Tensile strength with different wt. % of Nano silica-KSSK

The tensile strength of the hybrid nano composites for different wt.% of Nano silica is shown in Figure 4.5. From Figure 4.5., it is clear that the nano-silica by double-stirring process improved the tensile performance of polyester/kevlar/sisal composite because of the better nano-silica dispersion which results in good interfacial interaction with the matrix. Also, upon an increase in Nano silica content, there is an increase in tensile strength, which decreases with further in an increase in Nano silica. I.D.G. Ary Subagia et al. can observed a similar result.[137]

The tensile strength of Nano silica-reinforced hybrid composites increase with an increased wt.% of Nano silica from 0wt.% to 4wt.% and with any further increase in silica content, i.e., 6wt.%, there is a decrease in tensile strength. This is because of agglomeration, which is caused by poor dispersion of nanomaterials, which may cause non-homogeneity and, eventually, uncured resin zones while imposing extra energy into the mixing process. Shu-Xue Zhou et al.[138], in their studies, confirmed that the adding of a small amount of Nano silica enhanced the tensile properties of the polymer. These tensile properties could, however, worsen with higher Nano silica content.

The highest tensile strength was achieved at 4 wt.% of Nano silica- KSSK stacking sequence which is increased by 23% and with a further increase in silica content, there is a reduction in tensile strength this is due to the wettability problem occurred to higher filler percentage as wt.% of silica is increased.[139] This result can be seen in any of the stacking sequences. The addition of 4 wt.% nano-silica reduced the porosity, and the reduction of porosity significantly increased the nanocomposites' resistance. A higher amount of nano-silica concentration caused agglomeration and poor dispersion, which showed an increase in porosity.

4.4.1.2.Flexural properties

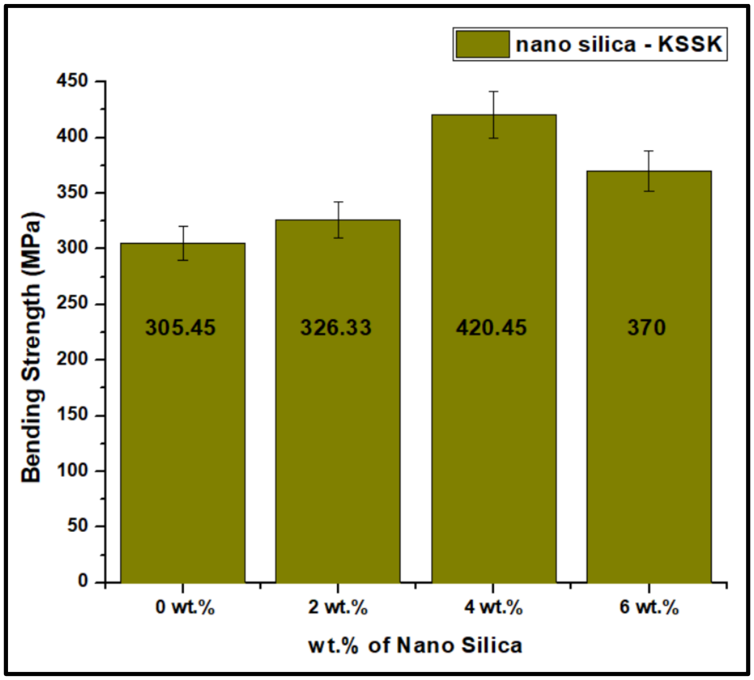


Figure 4.6. Flexural strength with different wt. % of Nano silica-KSSK

Figure 4.6. shows the flexural strength for different wt.% of Nano silica. The maximum flexural strength was obtained at the 4wt.% of Nano Silica. Up to 4 wt.%, there is an increase in the bending strength and any further increase in Nano silica content led to a decrease in strength. A similar trend of flexural strength for nano-filler loading can be observed in N. Merah et al. [36].

It is observed that due to the addition of 4 wt.% nano-silica in KSSK composite, there is a 27% increase in the bending strength in KSSK stacking sequence from 0 wt.% to 4 wt.%. Besides, the decrease in flexural strength of more than 4 wt.% of silica may be due to the agglomeration of silica in the resin, which serves as a stress concentrates and decreases flexural strength.

4.4.1.3.SEM Studies

Figure 4.7. shows SEM images of particulate distribution of tested tensile specimens of KSSK stacking sequence at 4 wt.% of Nano-silica in which there are no voids present in the composites and from which we can conclude that there is an excellent interfacial bond between the fiber and matrix due to the inclusion of Nano-silica. Thus, SEM images also support the results. Figure 4.7 shows the uniform distribution of particles in the composite. This is due to the mixing of silica particles through Ultrasonication, while low porosity can be observed from the images which are similar to results obtained by Pagidi Madhukar et al.[140]

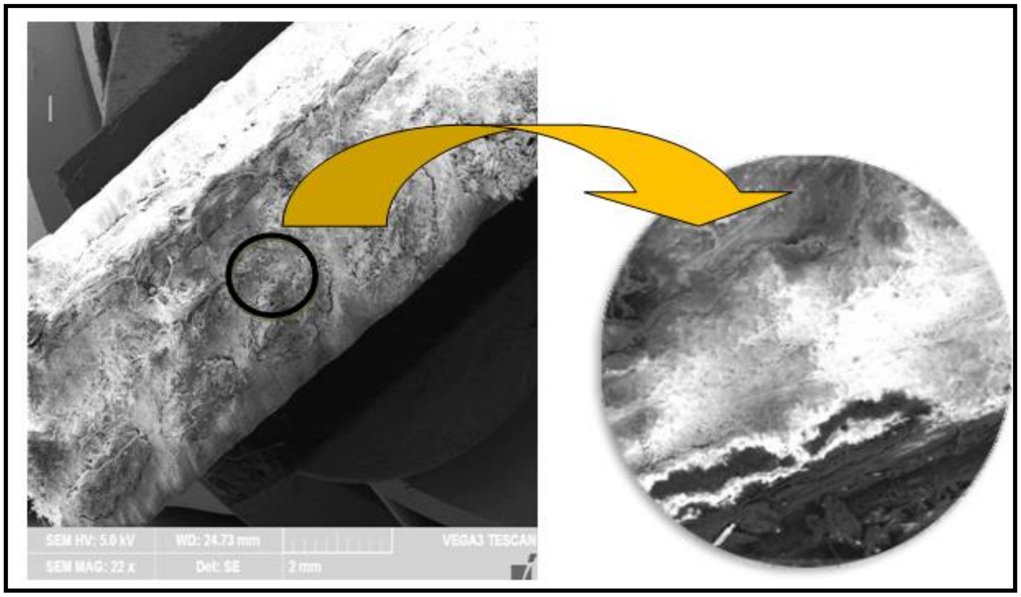


Figure 4.7. Shows the SEM images of the Particulate distribution of tensile specimens of Nano-silica 4 wt.% of KSSK stacking sequence

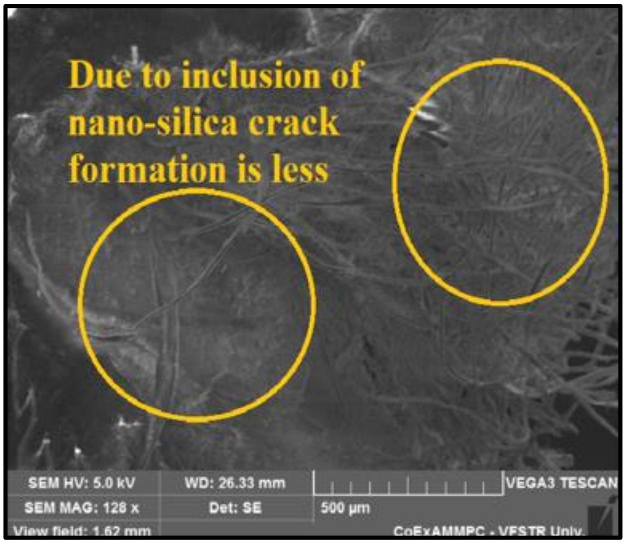


Figure 4.8. Flexural tested specimen of Polyester/KSSK / Nano Silica hybrid composite with 4 wt.% of Nano silica

Figure 4.8 demonstrates the results of the introduction of fillers in hybrid composites. The crack formation before breakage is observed to be lower compared to Figure 3.11 due to flexural load. This shows that the fillers increase the composite's strength [27]. The fracture material fails under stress; the failure planes are always natural to the load. Nevertheless, cross-section failure alone does not affect the composite failure mode. Composite failure mode depends on a variety of variables, including the type of fiber, type of matrix, fiber/matrix communication, reinforcement transfer place of failure, etc.[74]

4.4.2. Effect of Nano silica on GSSG reinforced polyester composites

4.4.2.1.Tensile properties

The effect of Nano silica on the tensile properties of GSSG reinforced polyester composites is shown in figure 4.9. The highest tensile strength was obtained at 4 wt.% NS reinforcement. Similar results can be seen in KSSK reinforcements. There is a 41% increase in the bending strength in GSSG stacking sequence from 0 wt.% to 4 wt.%.

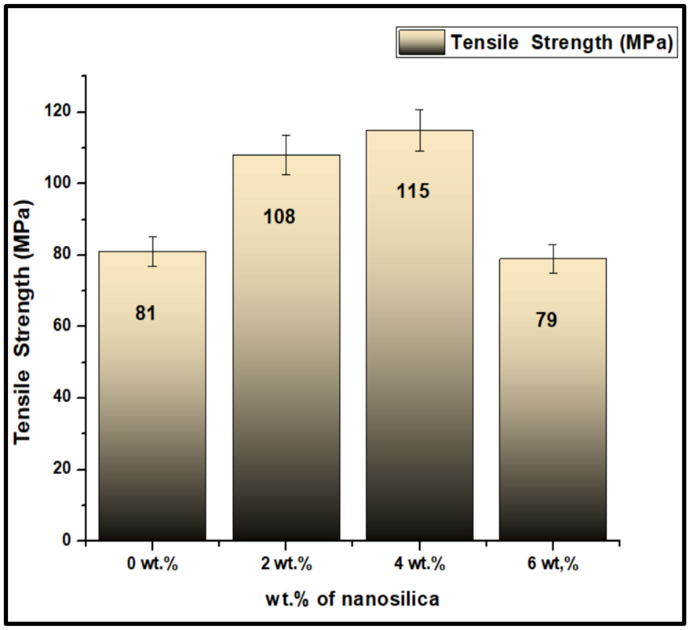


Figure 4.9. Tensile strength with different wt. % of Nano silica-GSSG

4.4.2.2.Flexural properties

Figure 4.10. shows the flexural strength of different wt.% of Nano silica. The maximum flexural strength was obtained at 4wt.% of Nano Silica. Up to 4 wt.%, there is an increase in the bending strength and further increase in Nano silica content leads to decrease in strength. When compared to 0 to 4 wt.% there is 20% increase in strength.

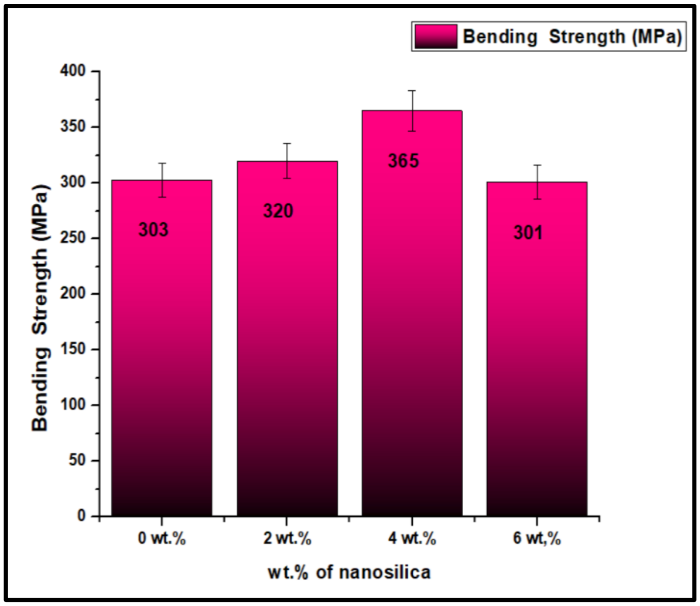


Figure 4.10. Flexural strength with different wt. % of Nano silica-GSSG

4.4.3. Effect of Nano clay on KSSK reinforced polyester composites

4.4.3.1. Tensile properties

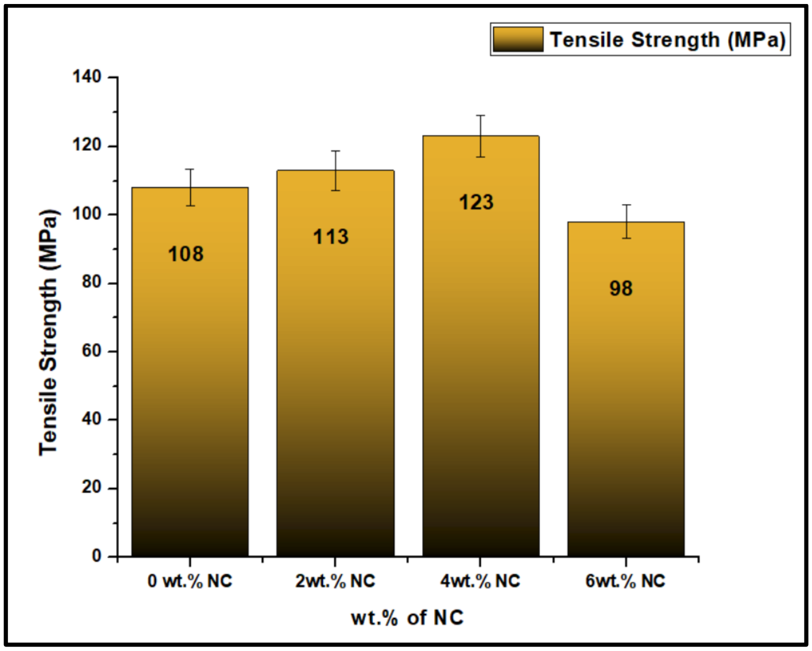


Figure 4.11. Tensile strength with different wt. % of Nano clay-KSSK

ASTM D638 standard was used to investigate the tensile properties of laminates using a UTM machine. Figure 4.11 shows the impact of adding Nano clay (NC) to polyester/KSSK tensile strength at various weight % of NC. The strength of polyester/KSSK increases up to 4 wt.% due to differences in fibre, filler, and matrix ratios, after which it begins to decline. The highest tensile strength achieved for polyester/KSSK is 123Mpa for 4 wt. % filler, and then it reduces at 6 wt. %. Tensile strength of nano clay reinforced hybrid composites improves as the nano clay % grows from 0 to 4 wt.%, then declines as the clay level rises to 6 wt.%. Similar outcomes can be seen in [141, 142]. In comparison to 0–4 wt.% NC reinforcement, the tensile strength increased by 18% for polyester/KSSK composites. The addition of 4 wt.% NC reduced the porosity of nanocomposites, and resistance of nanocomposites was considerably raised due to reduction in porosity. The increased concentration of nano clay generated aggregation and poor dispersion, indicating a rise in porosity. The improvement in tensile strength may be due to the exfoliated structure in polyester/KSSK fibre composite with 4 wt.% clay. In the exfoliated structure, individual nanometer-sized silicate layers are distributed uniformly in a polymer matrix with a high aspect ratio. By increasing the nanofiller surface contact with the polymers, the enhanced aspect ratio of nano clay may increase tensile strength. In nanocomposites, multiple reinforcing nanoclay platelets embedded in the polymer matrix serve as effective stress transfer carriers[143].

4.4.3.2.Flexural properties

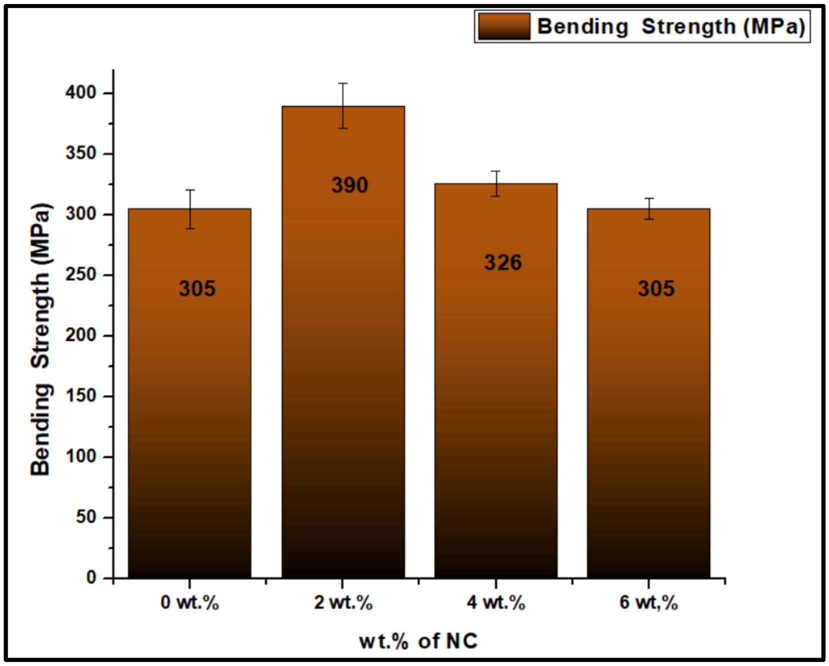


Figure 4.12. Flexural strength with different wt. % of Nano clay-KSSK

Figure 4.12 depicts the flexural strength of hybrid polymer composites. The flexural strength suggested that the fabric–matrix and filler material had better adhesive qualities. The hybrid polymer composite with 2 wt. % NC reinforcement had the highest flexural strength (390 MPa) of all composites. 0 wt. % and 6 wt. % were the lowest results found. Similar results can be observed at [36]. Improved interfacial properties of micro clay particles, which are responsible for stress transfer and elastic distortion, are accountable for higher flexural strength. Nano clay is used to reinforce and stiffen the adjacent matrix. When the proportion of nano clay is increased, the nano clay may clump together, leading to poor resin dispensability. Additionally, as more Nano-fillers were added, the viscosity of the polyester resin increased, leading to an increase in internal porosity and a loss in flexural strength. As a result, as the filler concentration rises, stress is concentrated in the agglomerated nano clay area, allowing cracks to propagate throughout the composite[73].

4.4.3.3.SEM Studies

The Factured surface of 4 wt.% NC/polyester/KSSK composites is shown in Figures 4.13 a, b. Nano clay is evenly dispersed throughout the composites, with no evidence of particle aggregation. A few minor voids can be seen on the surface. No cracks were made due to these voids, indicating that the sample failed due to brittle cracking.[144]. The breakage surface roughness rises from 4 to 6 wt.% as the wt.% of NC increases. Also, the fibre pullouts are plenty as seen in the images, as shown in Figure 4.13b. Additionally, as the quantity of filler loaded rises, the polymer becomes deficient to retain Nano clay, causing Nano clay clusters to form, as seen in Figure 4.13b. The SEM morphologies of 4 wt. % nano clay composites with no voids also show that adding nano clay results in a solid interfacial construction among the fibre and matrix[133]. As a result, SEM backs up the results of mechanical results.

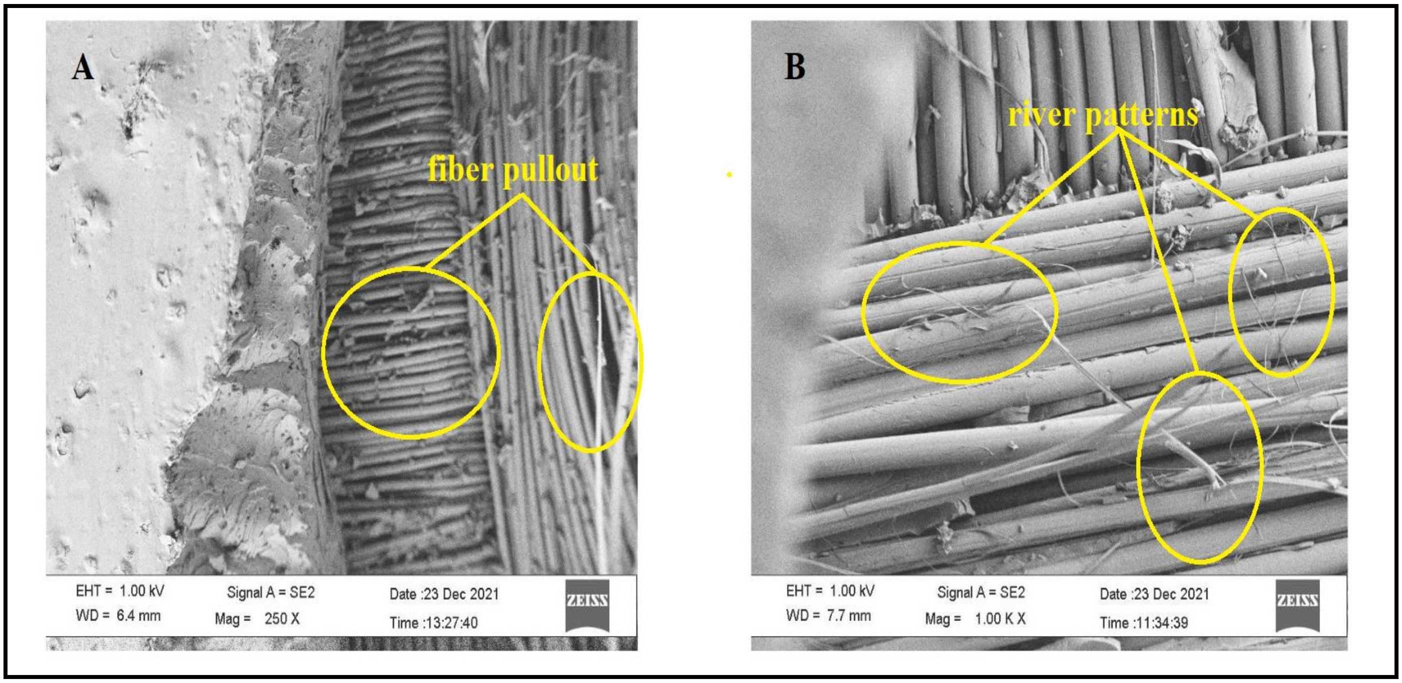


Figure 4.13. a) SEM 4 wt.% NC/polyester/KSSK b) SEM 6 wt.% NC/polyester/KSSK

4.4.4. Effect of Nano clay on GSSG reinforced polyester composites

4.4.4.1.Tensile properties

The effects of Nano clay(NC) addition on Tensile Strength of Polyester/GSSG with different wt.% of NC can be seen in Figure 4.14. Because of the inequality in fibre, filler, and matrix ratios, the strength of Polyester/GSSG increases up to 4 wt.% and then starts to fall after that.The highest tensile strength obtained was 95MPa for Poly/GSSG for the 4wt.% filler which decreased at 6 wt.%. The tensile strength of Nano clay reinforced hybrid composites increases as the wt.% of Nano clay increases from 0 to 4 wt.% and decreases as the clay content increases to 6 wt.%. Agglomeration, produced by inadequate nanoparticle dispersion, can induce non-homogeneity in the resin mixture, resulting in a loss in tensile strength for increased Nano clay content[33, 145, 146]. Similar results were witnessed by Raghavendra G et al. [74]. NC composites compared with 0 wt.% to 4 wt.% tensile strength increased by 16%. The overall conclusion also confirms proposed laminate is fitness for possible use in structural applications in aerospace sector and marine sector.[37]

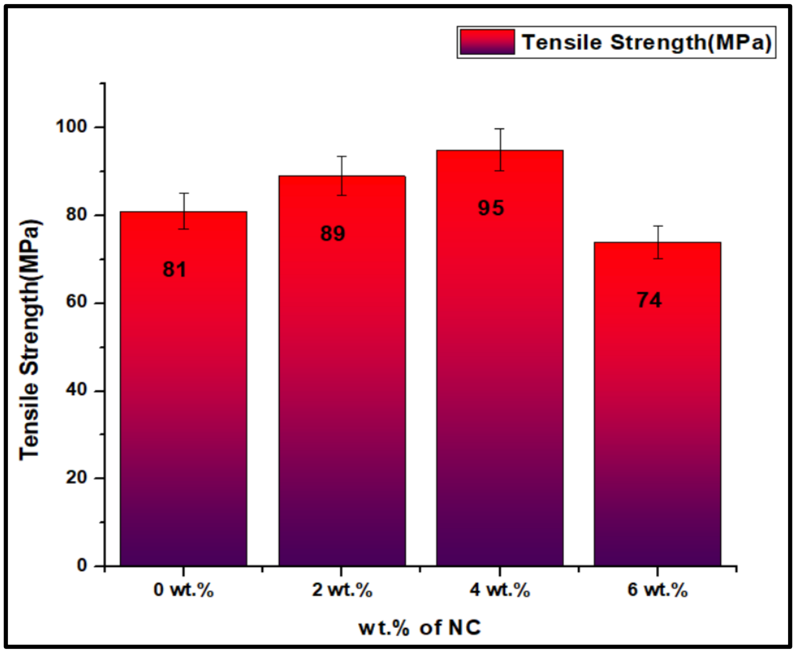


Figure 4.14. Tensile strength with different wt. % of Nano clay-GSSG

4.4.4.2.Flexural properties

The effects of Nano clay(NC) addition on Bending Strength of Polyester/GSSG with different wt.% of NC can be seen in Figure 4.15. The highest bending strength is 377 MPa, and it has increased to 24% compared to 0wt.% NC addition. The highest Bending strength is obtained at 2wt.% of NC addition; after that, the bending strength seems to decrease. The increased flexural strength is attributable to improved interfacial characteristics in Nano clay particles which are, responsible for stress transport and elastic distortion. The nearby matrix is strengthened and stiffened using Nano clay. Increasing the Nano clay concentration can lead the Nano clay to agglomerate resulting in poor polyester resin dispersibility[147].

Furthermore, as more Nano-fillers are applied, the polymer resin's viscosity enhances, resulting in more significant internal porosity and reduced flexural strength. As a result, as the filler content increases, stress is concentrated on the agglomerated nano clay area, making it easier for the crack to propagate through the composite.[148]. In tensile properties, the maximum tensile strength is at 4wt.%, but the flexural strength is found to be maximum at 2wt.%, and similar results can be found in [149, 150].

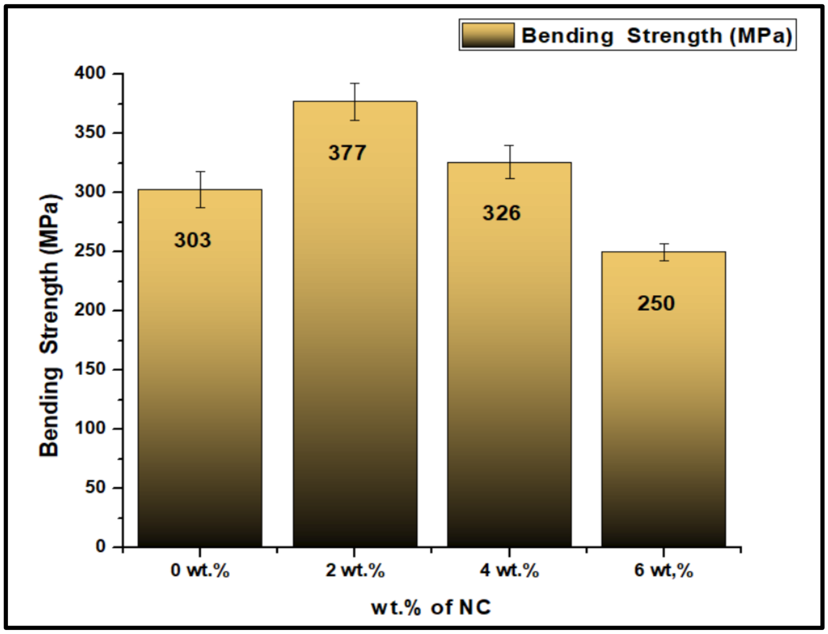


Figure 4.15. Flexural strength with different wt. % of Nano clay-GSSG

4.4.4.3.SEM Studies

Figures 4.16(a) and (b) show the fracture surface of 4 wt. % Nano clay reinforced polyester/GSSG composites and the fracture surface of 4 wt. % Nano clay reinforced polyester/GSSG composites. Nano clay is consistently distributed in both composites and no indication of particulate aggregation has been seen. On the surface, there are a few small voids. However, no cracks formed due to the voids wave-like patterns on the fracture surface of 4wt. % NC reinforced composites, which indicate that the sample failed to owe to brittle cracking[151].

As wt.% of NC increases, the fracture surface roughness increases from 4 to 6 wt.%, as seen in Figure 9(c).

Furthermore, when the amount of filler loaded increases, the polymer matrix becomes insufficient to contain the Nano clay resulting in the creation of nanolcay clusters. Also, the SEM morphologies of 4 wt. % Nano clay composites with no voids, allow us to conclude that the addition of Nano clay results in a great interfacial connection between the fibre and matrix.[133] As a consequence, SEM morphology also support the outcomes of mechanical tests.

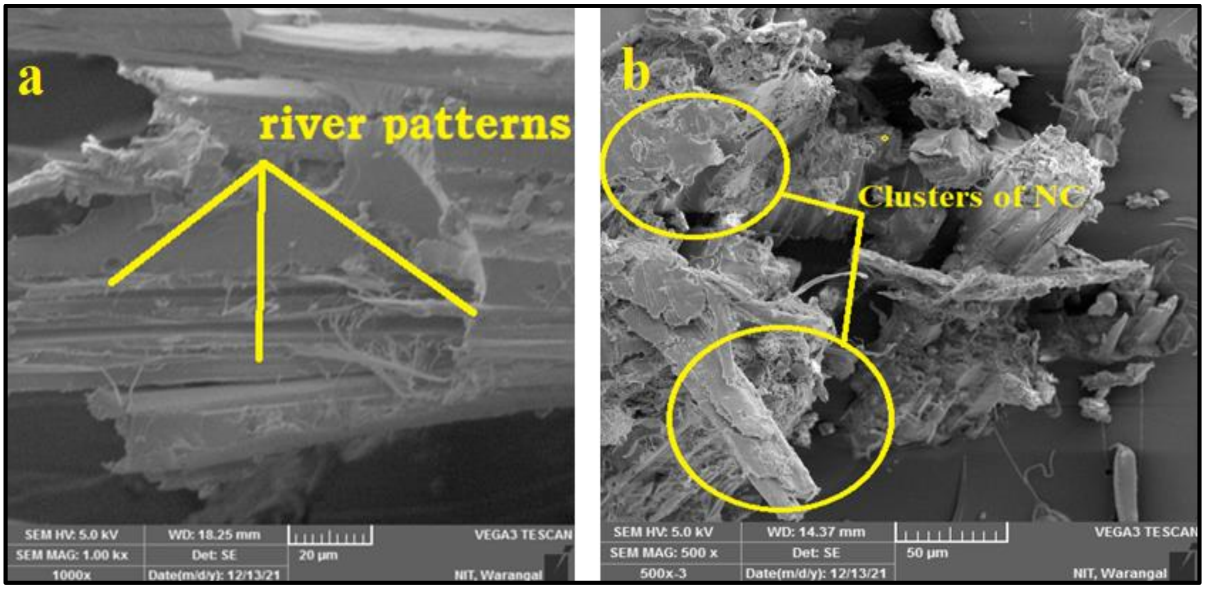


Figure 4. 16. a) SEM images of 4 wt.% of NC reinforced Polyester/GSSG **(b)** 6 wt.% of NC reinforced Polyester/GSSG (Tensile)

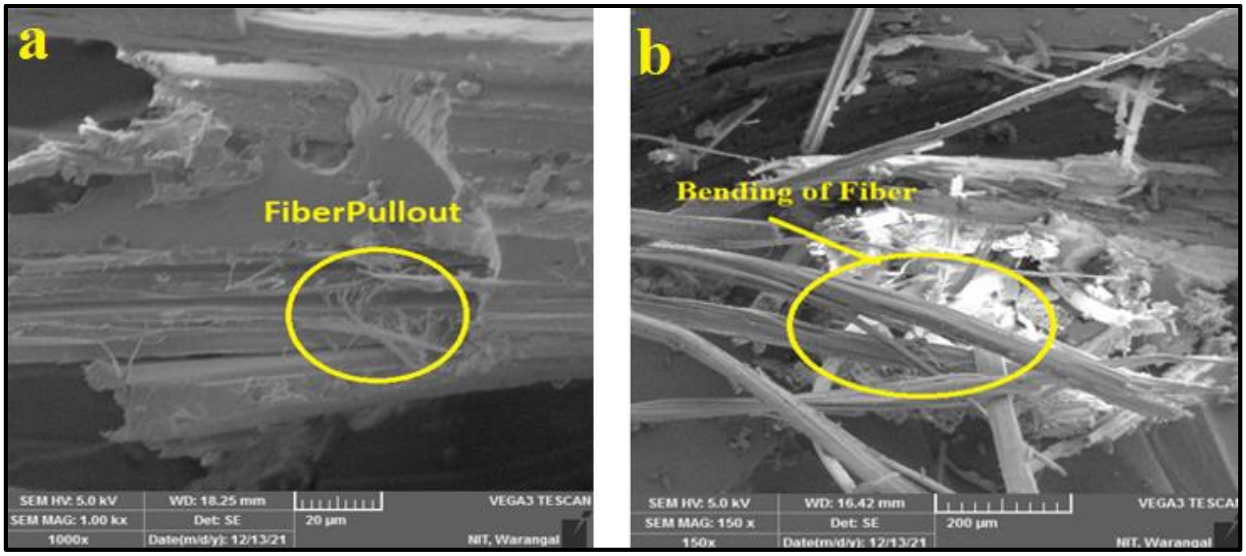


Figure 4.17. a) SEM images of 0 wt.% of NC reinforced Polyester/GSSG composites

(b) 2 wt.% NC reinforced Polyester/GSSG (Flexural)

SEM pictures of tested flexural specimens of polyester/GSSG reinforced composite Figure 4.17 (a) In the studied specimens, fibre pulling is visible. The brittleness of the sisal fibre can be seen here. Also, Fiber pull-out is visible in both images and is caused by the flexural load. The fracture material fails under stress, and the failure planes are always parallel to the load. On the other hand, cross-section failure does not influence the composite failure mode. The composite failure mode is influenced by the type of fibre, matrix, fibre/matrix connection, reinforcement transfer area of failure, and other aspects. Various researchers have reported similar findings. [152–154]. Figure. 4.17 (b) shows the SEM micrographs of 2wt.% of NC, and it can be seen that the inclusion of NC fiber pull-out is less than 0wt.% of NC Fiber bending, which can also be seen in the micrograph, indicating the semi-brittle nature of Glass fiber and this phenomenon was investigated by R. Kaundal [155].

4.5.COMPARISONS OF NANOCLAY AND NANO SILICA

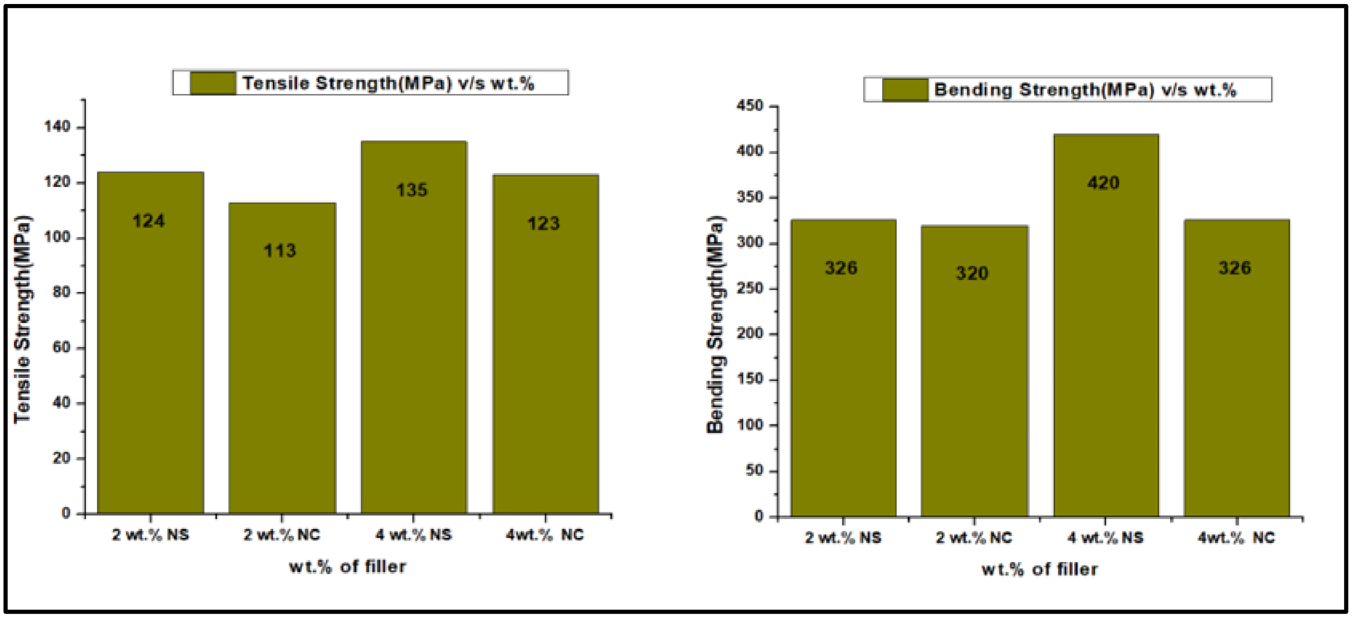


Figure 4.18. Comparison of Nano silica V/S Nano clay (Strengths to wt. %)

The effect of filler addition of NC and NS Hybrid Composites are shown in Fig 4.18. The comparison figure shows that NS-reinforced hybrid composites showed better tensile and flexural strength when compared to NC reinforcements. The density of NS was (2.2 g/cc) and the density of NC is 1.1(g/cc). When we consider this in terms of strength-to-weight ratio, as the density of NC is half the density of NS and NC filler composites gave better results when compared to NS. In the present work, the idea was to develop low-weight to high-strength composites. So, nano-clay was chosen as a potential filler for the development of further hybrid nanocomposites.

4.6.CONCLUSIONS

The effect of Nanoclay and Nanosilcia on the mechanical properties of Polyester reinforced KSSK/GSSG hybrid nano composites was studied. Based on the results the following conclusion were drawn.

1. The highest tensile strength is achieved at 4 wt.% of Nanosilica/ KSSK and GSSG hybrid composites. For a further increase in silica content, there is a reduction in tensile strength which is due to the viscosity of the polymer that increases as wt.% of silica is increased. A higher amount of Nano-silica concentration caused agglomeration and poor dispersion, which showed an increase of porosity.
2. There is an increase in the bending strength in KSSK /GSSG from 0 wt.% to 4 wt.%. The decrease in flexural strength of more than 4 wt.% of silica may be due to the agglomeration of silica in the resin, which serves as stress concentrates and decreases flexural strength.
3. The highest tensile strength is achieved at 4 wt.% of Nano clay/ KSSK and GSSG hybrid composites. Similar results can be observed for Nano silica wt.% reinforcement. Interestingly for flexural results, 2wt.% inclusion of Nano-clay was found to be better.
4. Overall Mechanical results were found to be better for Nano silica reinforcements but when we consider this in terms of strength-to-weight ratio, as the density of NC is half the density of NS, NC filler composites gave better results when compared to NS. In the present work, the idea was to develop low-weight to high-strength composites. So, Nano-clay was chosen as a potential filler for the development of further hybrid nanocomposites.

Chapter – 5

Effect of moisture absorption on mechanical and tribological properties of KSSK & GSSG reinforced Nano-clay Polymer (polyester, epoxy) composites

5.1.DEGRADATION OF PROPERTIES

For hybrid polymer composites, some factors are responsible for influencing the degradation of properties based on the literature i) Aging in the type of liquid ii) Aging time iii) Curing rate of resin iv) Type of polymer v) Type of Reinforcement vi) Treatment of fiber vii) Filler content loading and viii) diffusion coefficients, etc.[156–158]

The mechanical properties of the composite materials remain very much significant in deciding the application of these materials. And the degradation of mechanical properties is evident if they are exposed to liquid media since liquid media acts as plasticizer[31]. Natural and aramid fibers are hydrophilic, while polyalkenes are hydrophobic, and other polymers may be polar with hydrophilic properties [159–161]. In natural fiber reinforcement, moisture absorption is higher compared to synthetic fiber reinforcement [56]. The hybridization of composites shows better resistance to the degradation of properties compared to normal composites[87].

5.2.RECENT TRENDS IN DEGRADATION OF PROPERTIES

Anu Gupta et al.[162] studied water absorption properties of bamboo fiber reinforced epoxy composites and concluded that water absorption rises with fiber content since bamboo fiber is hydrophilic, and epoxy is hydrophobic. Also, the high content of cellulose in bamboo fiber contributes to more water entering the interface through the micro-cracks caused by the swelling of the fibers. This swelling stress additionally contributes to composite failure. Samples were submerged in water for around 60 days; initially, sorption (%) was linear in the start, then it decelerated and approaches saturation after an extended period. (Where U1= Epoxy + 10 wt.% of fiber & for U2, U3, U4 following weight % increase of fiber up to 40 wt%) following the Fickian diffusion cycle.

U. Huner et al. [163] have determined water absorption behavior of hemp fiber reinforced epoxy composites and found that with an increase in fiber content, there was greater absorption. Flax fibers contain plenty of polar hydroxides clusters resulting in a high level of moisture absorption of natural fiber reinforced epoxy composites and an additional reason for increased absorption rate of composites is the nature of flax fiber and voids within composites which lead to microchannel development. Here two temperatures are maintained (25^{o}C and 90^{o}C) out which samples immersed in 25^{o}C tend to absorb more amounts of water compared to samples in 90^{o}C.

G. Das et al. [164] have reported the water absorption properties of coir fiber reinforced epoxy composites for different lengths of fiber and wt.% of fiber. In all cases, in the beginning, the water absorption cycle is severe and it flattens off over a certain amount of time, until it reaches equilibrium. The rate of water absorption is typically significantly impacted by the density and void quality of the composite. The longer the fiber, the higher the intake of water. Water absorption levels are also observed to increase with increased fiber content. Composites with a coir fiber content of 20 wt.% percent display a higher rate of water absorption compared to 5 wt.% percent of fiber. This may be since the coir fibers produce further polar hydroxide groups, resulting in a high degree of absorption of natural fiber-based polymer composites.

A. Devadas et al.[165] studied the water absorption properties of kenaf fiber reinforced epoxy composites and reported that Pure epoxy composites exhibited least water absorption whereas samples with 5% kenaf fiber has least water absorption among other reinforcements. And 20% reinforcement showed maximum water absorption. This is due to the hydrophilic nature of NFREC’s.

J. Gassan et al. [166] studied the effect of moisture absorption on the mechanical properties of jute fiber reinforced epoxy composites. The effects of water absorption on the mechanical properties of epoxy resins containing untreated and silane-treated jute fibers have been discussed in this study. Silane treatment of fibers resulted in improved tensile and flexural strength and an improvement of up to 30 percent in their composites in Young's modulus.

L. Yan et al.[167] analyzed Flax fiber-epoxy reinforced composites under the influence of three environmental conditions i.e. Sea water, water and 5% NaOH Solution. and concluded that weight gain behavior of the flax fabric/epoxy composites was similar in three ageing conditions, i.e. a large increase was observed in the initial two months of immersion which only slightly increased until the stage of saturation. All three aging solutions resulted in significant deterioration of the tensile and flexiural properties of the composites. The largest reduction was in specimen immersed in NaOH solution, followed by the smallest reduction in seawater and the specimen immersed in water.

5.3.EROSION WEAR

Wear is unnecessary damage to the surface of a solid due to its relative motion, which entails partial loss of material from the contacting surfaces. It is a natural reaction of a substance that may either be mechanical or chemical[168]. Both industry and consumers spend a significant amount on wear each year. The majority of this involves replacing or fixing machinery that has become so worn out that it can no longer serve a meaningful purpose. This happens for many machine parts after only a relatively small portion of the entire volume has been worn away. Up to 40% of equipment replacement parts for some industries, like agriculture, have failed due to abrasive wear. Additional significant causes of spending include production losses caused by decreased efficiency and plant downtime, the need to invest in capital equipment more frequently, and higher energy usage as equipment ages. Estimates of the direct cost of abrasive wear to industrialised countries range from 1 to 4% of GDP. One of the principal causes of material failure and damage to equipment is identified as friction and wear [169–171].

Polymer composites have drawn much interest from scientists in current history because of their specific strength and favourable wear characteristics, which are essential for the automobile and aerospace sectors[172].Due to their capacity to self-lubricate, numerous polymer filler/fibre composites are quickly replacing metallic materials for parts, including shafts, gearboxes, gaskets, and bushings. Due to their need for wear-loading situations, polymeric-reinforced composites are a type of material that require specific consideration when examining wear qualities[173]. The equipment's operating condition will degrade due to wear caused by materials with low wear qualities, necessitating ongoing maintenance. Wear is the steady material loss that occurs from interacting surfaces due to their relative movement, which is unwanted because it can harm a solid's surface. It is a substance's reaction to its environment, that may be mechanical or chemical. In the early 1960s, industrialised nations started doing wearing studies. The most frequent types of wear include fatigue, erosion, adhesion, fretting, and abrasion. Abrasion and erosion are the most significant, accounting for 75% of overall wear expense[174]. Erosion wear is commonly described as material loss instigated by the repeated impression of hard and pointed particles. The individual particles strike the object's surfaces at different speeds and positions. Deterioration occurs on the external surface. Erosion wear has been a severe problem in many equipment parts such as hydraulic fluid, jet engines, compressors, aviation parts, impellers, etc.[175, 176]. Because these applications are used in dusty environments, erosion resistance is critical[177]. However, in other cases of erosion, such as sandblasting, erosion is a beneficial phenomenon since it enhances the exterior polish of finished material properties. Non-metallic materials' resilience to rain and erosion was a critical difficulty in radar systems.

Pure thermoplastic polymers generally erode ductilely, whereas thermosetting polymers erode in a brittle fashion [3]. We can change or improve the material's erosion behaviour by incorporating various fillers or fibres reinforced into matrix materials. Pratap Naidu et al.[178]explored the erosive wear for Bidirectional & Multidirectional Oriented Glass Fibre reinforced with Epoxy. They determined that the introduction of fibre helped to improve wear resistance under various impact circumstances based on their experimental observations of erosion wear tests. Researchers evaluated the wear behaviour of composites by introducing stiff conventional fibres and discovered that particle reinforcements improved wear resistance and altered erodent impingement angles. Particulate reinforcements improved wear resistance and altered erodent impingement angles[60, 179–181].

5.4.RECENT TRENDS IN EROSION WEAR

Tewari et al. [182] investigated the erosion wear of solid particles in unidirectional glass and carbon fibre reinforcing filler polymers. These composites' erosive wear was examined at various impact angles (15-90°) and three distinct fibre orientations (0, 45, and 90°). Steel balls with diameters of 300-500 m and impact velocity of 45 m/s were employed for wear studies. The semi-ductile eroding characteristic of unidirectional carbon and glass fibre-reinforced epoxy composites was observed, with a maximal erosion rate at 60° impact angles. They also concluded that directions of the fibres significantly impact erosion. Vigneshwaran et al. [183] studied the erosion durability of red mud-filled and unfilled sisal fibre-reinforced hybrid composites using the ASTM standard G76 solid particle eroding test. When performing the trials, wearing ratio is determined while taking into consideration eroding features including erodent velocity, angle, and wear rate flow velocity. According to Taguchi's examination of the findings of eroding tests, eroding losses in composites is strongly affected by erodent velocity, red mud particles fraction, and erodent discharge. The introduction of red-mud to a polymer composite demonstrated better eroding wear performance as compared to empty composite. The inclusion of red mud alters the composite's ductility where the highest depreciation was seen at a lower impact angle. The erosion rate of the composite rose as the erodent velocity increased. Kaundal[184] studied the erosion wear behaviour of fly ash-filled polyester composites and concluded that Unfilled glass polyester composites have higher wear loss than particle-filled glass polyester composites.

Pun et al. [185] adding micro- and nano-silica (SiO2) particles to glass-fibre/vinyl ester composites. The highest deterioration of all combinations was observed at a 60° impact angle, demonstrating the semi-ductility of the particulates. In all testing conditions, nano composites outperformed micro composites in terms of wear resistance with various weight filler %. Sem micrograph suggests that micron particle composites perform better than filler particle blends at cavity formation. Kuruvilla et al.[186] produced an epoxy composite material strengthened with a predefined wt.% of fibreglass and filled it with a combination of nano and micro inorganic nanoparticles. The use of these hybrid types progressively improves the properties of composites. High-voltage external insulating was suggested for use with the composite materials.

Manoj Panchal et al.[187] reported tribological properties of boiled and unboiled eggshell particulates epoxy composites that were exposed to saline, mineral, sub-zero, and kerosene environments. The maximum erosion rate was observed at 60^o for all the composites, but for sub-zero condition samples, it was 90^o for particle impingement. When the maximum erosion rate occurs at a normal occurrence (90^o), it is categorized as brittle behavior. In contrast, ductile behavior is indexed by the highest erosion wear rate at lower angles, i.e., between 15^o and 30^o angles of impingement. The material is said to exhibit semi-brittle behavior for a maximum erosion at 60^o ranges. The maximum erosion rate is for 12wt.% boiled eggshells of loading. This may occur due to the agglomeration of egg particles. Wear resistance is lower for boiled eggshells compared to un-boiled. Optimum filler loading is at 4wt.% for un-boiled eggshells.

In this chapter, nano-clay was chosen as filler material based on the conclusions arrived at from the previous objective. The effect of moisture absorption on the mechanical and tribological properties of KSSK & GSSG reinforced Nano-clay Polymer (Polyester, epoxy) composites were compared and the results reported.

5.5.RAW MATERIALS

1. Epoxy
2. Polyester
3. Nano clay
4. Kevlar
5. Sisal
6. Glass

5.5.1. Epoxy

The epoxy used in this research is Araldite which is chemically similar to the epoxide group. The existence of a 3 chain comprising two carbons and an oxygen distinguishes epoxy (epoxy group or epoxide or oxirane ring). Epoxy is the initial liquid reactions result of bisphenol-A with an amount of epichlorohydrin, and this resin is known as Bisphenol-A Diglycidyl-Ether (DGEBA). DGEBA is widely utilised in industry due to its high fluidity, processing simplicity, and superior physical qualities of the finished resin. The hardener NNO-bis (2amino ethyl ethane-1,2diamin) was employed in conjunction with the epoxy HY 951. Bindu Agency in Vijaywada supplied both the epoxy and the hardener. The property comparison of epoxy and polyester can be seen in Table 5.1.

Table 5.1. Shows the property comparison of epoxy and polyester

Properties	**Polyester**	**Epoxy**
Phyisical State	Liquid	Liquid
Form	White	White
Density	1.12 g/cm^3	1.2 g/cm^3
Melting point/range	260 ^{o}C	300 ^{o}C

5.6.SAMPLE PREPARATION

The epoxy and filler particles were appropriately combined initially using a magnetic stirrer before being sonicated. The hardener was then added to the nanoparticle/resin dispersion. Hardener was mixed in a ratio of 10:1 with epoxy (resin to hardener weight ratio). The fabrication method was followed as in the previous objective. A similar procedure was followed for polyester as discussed in the above objectives.

5.7.MOISTURE ABSORPTION PROPERTIES

Tests were carried out for investigating the effect of various conditions on GSSG/NC, KSSK/NC with various wt.% such as 0,2,4,6 wt. % reinforced polyester and epoxy composites.

This test aims to study the effect of particle reinforcement and absorption on the characteristics of composites and investigate the kinetics involved. Moisture transport in polymeric composites occurs via a variety of methods. Capillary action is the initial method of liquid transportation into tiny networks among the matrix and reinforcement. Second process is transmission of micro-voids caused by fibre enlargement into the matrix material. The third process is the dispersion of water molecules into the hole among polymer chains[188, 189]. Samples were subjected to various conditions such as seawater, mineral water, groundwater, and sub-zero temperatures for varying time intermissions until the water content in the samples achieved saturation and the weight of the samples was assessed. Moisture absorption was determined using the variation between the samples using the formula.

$$\mathrm{M}(\text{weight gain}) = \frac{W_f - W_i}{W_i}$$

Where W_f is the mass of the composite after it has been treated under various circumstances and W_i is the mass of the composite before it has been exposed to the atmosphere. The simulation approach for different climatic variables for moisture uptake testing is shown below.

i. Ground Water: For a typical water test, tap water with a pH of 6–7 was utilised.
ii. Sea Water: For the experiment, sea water with a pH of 7.95 was taken from the Bay of Bengal.
iii. Mineral Water: For the test, mineral water with a pH of 7.3-7.9 was utilised.
iv. Sub-zero: Samples were kept at approximately -18 ^{o}C.

5.7.1. Wear Properties

Using erosion equipment following ASTM G76 standard, erosion wear characteristics of reinforced hybrid composite materials were examined. The equipment needed to conduct an erosion test included a compressor, sample holder, conveyor for moving dirt particles, and nozzles. The sand particles were transported through the mixing chamber by high-pressure air from the compressor. The mixture then travelled through the convergent nozzle and was launched at high speed onto the specimen surface in the sample holder. Using the corresponding adjustable knobs, you can change the specimen holder's tilt and pressure can be changed. 20 mm x 20 mm x 3.1 mm square cross section samples were used for the tests. The test was conducted using several parameters shown in Table 5.2. The initial sample weight was recorded before each sample underwent an erosion test. Each sample underwent an erosion test for 8 minutes, with readings taken every two minutes. By averaging values from each test, the graphs were created. The erosion test rig for conducting tests is shown in Figure 5.1. The erosion rate is expressed as g/g. The following formula was used to calculate the erosion wear rate[190][191].

$$\text{Wear rate (grams/grams)} = \frac{\mathbf{Wt_1 - Wt_2}}{\mathbf{W}}$$

Where Wt_1= weight of the sample before testing and Wt_2 = weight of the sample after testing and W = weight of the erodent used.

Table 5.2. Shows the Test Parameters

Erodent	Silica sand
Erodent size (µm)	200 ± 50
Erodent shape	Angular
The hardness of silica particles (HV)	1420 ± 50
Impingement angle (θ)	30, 60 and 90
Impact velocity (m/s)	148 m/s
Nozzle to sample distance (mm)	10
Test temperature	ROOM TEMP

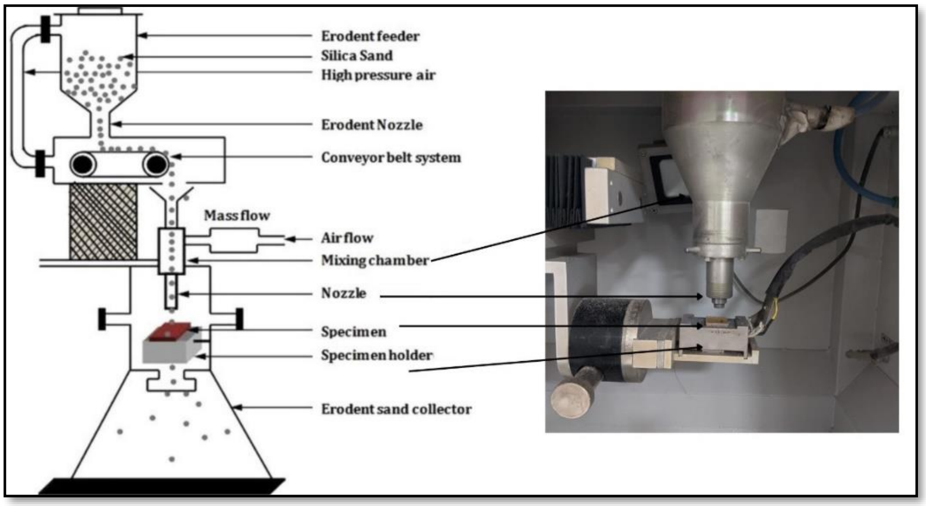


Figure 5.1. Shows the apparatus of erosion testing

5.7.2. Degradation of properties by moisture absorption tests

Mechanical and wear analysis were carried out on normal samples, and the samples were exposed to different environments and a comparison was drawn. The tests were used to determine the degradation of tensile, flexural and erosion wear properties. Figure 5.2 & 5.3 show the samples immersed in various environments. The method below can determine how much weight composite the samples acquired or lost under various environmental conditions [43].

$$\text{Weight gain}(\%) = \frac{\mathbf{M_2 - M_1}}{\mathbf{M_1}} \times 100 \quad (5.2)$$

Where $\mathbf{M_2}$ is the mass of the composite after environmental conditions were applied, and $\mathbf{M_1}$ is the mass of the composite after being exposed to those conditions (gm)

Figure 5.2. Shows the mechanical samples immersed in various environments

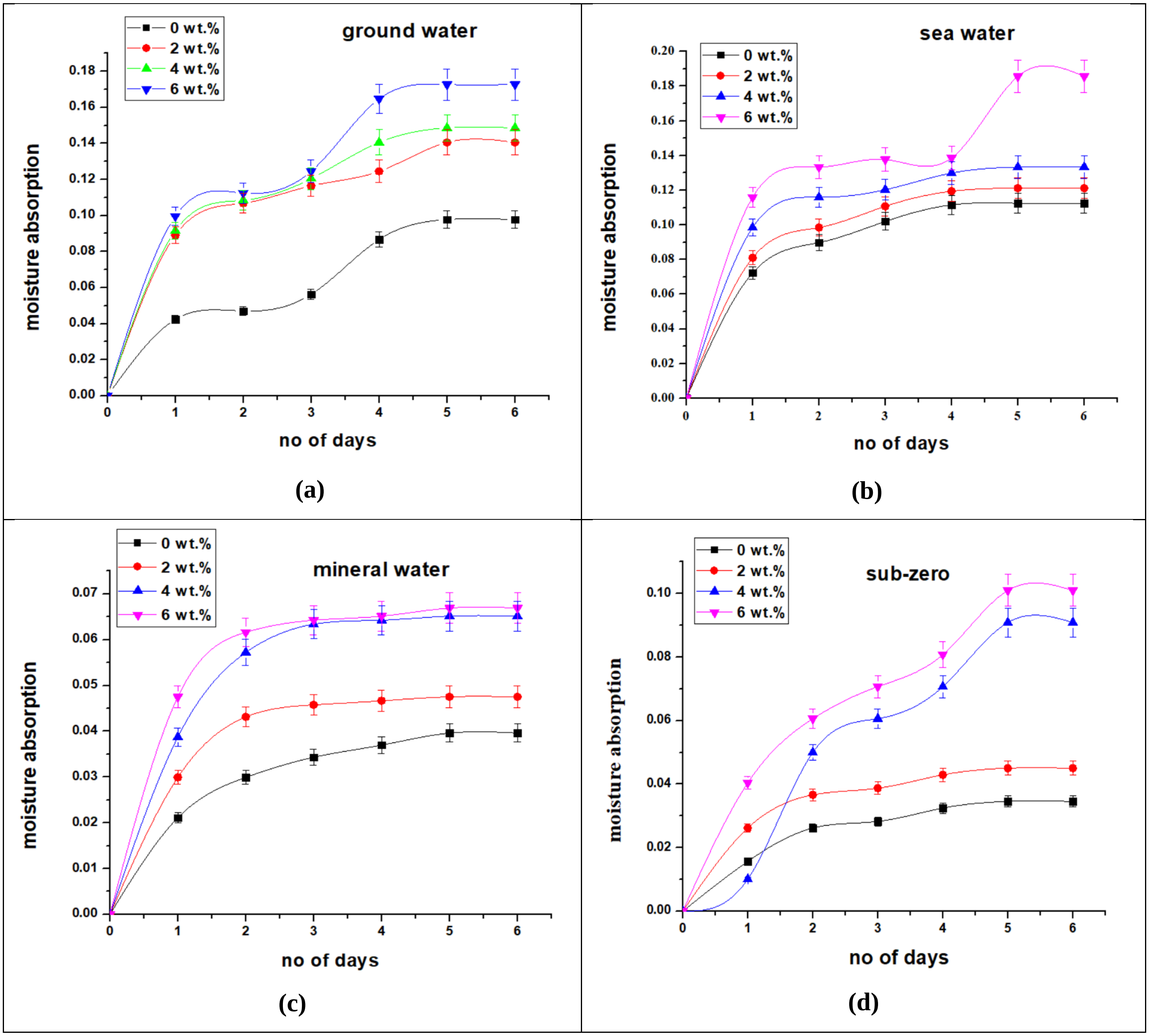
Figure 5.3. Shows the wear samples immersed in various environments

5.8.RESULTS AND DISCUSSION

5.8.1. Moisture absorption properties

Moisture absorption of composite samples was studied in various environments such as mineral water, seawater, groundwater, and sub-zero conditions, and shown in the figures 5.4(a-d)–5.7(a-d) for both, polyester and epoxy reinforcements with both GSSG and KSSK fibers. The composites moisture absorption in different environments were noted up to the saturation period which is 6 days. The results revealed that the samples exhibited typical Fickian diffusion behaviours. According to the principle, water absorption happens fast at the start of the matter's exposure to water, but after some time, the absorption rate slows down until it reaches the point of equilibrium [192]. Because water molecules rapidly diffuse into the micro-voids contained in the composites at the start, the graphs of the initiation of water absorption was shown to be linear for hybrid polymer composites. As the period of immersion time increases, water absorption by composites decreases and eventually approaches saturation. The results showed that the samples exposed to seawater had more moisture absorption than in all other environments. The absorption order was higher in seawater, followed by groundwater, mineral water and sub-zero temperature.

The rapid changes in the curves for all the findings may be due to the presence of NC reinforcement. As NC wt.% seems to be increasing, the curves are rapidly changing. This outcome was considered due to Nano clay’s hydrophilic nature, which causes it to absorb a lot of water based on the conditions. The molecular basis for this is the availability of hydroxyl groups in Nanoclay, which attracts and interact with water molecules via hydrogen bonding. Moisture absorption is more significant in samples with an NC level of 6wt% and less in samples with an NC content of 0%. [193]. It is also found that absorption rises intially, then reduces further until it reaches saturation after a set amount [43, 92, 194, 195].It was also clearly observed that moisture absorption were lower when compared to pure natural fibre composites, based on the results of moisture absorption, the hybrid polymer composites have the potential to be used as storage tanks of mineral water and at sub-zero environments. [196]. Among all the fabricated samples Polyester/KSSK/NC reinforcements tends absorb least amount water among all the environments which can be also be concluded that Kevlar is hydrophobic compared to glass as outer most fiber.



(a) (b) (c) (d)

Figure 5.4 (a-d) Moisture absorption behavior of Polyester/GSSG/NC

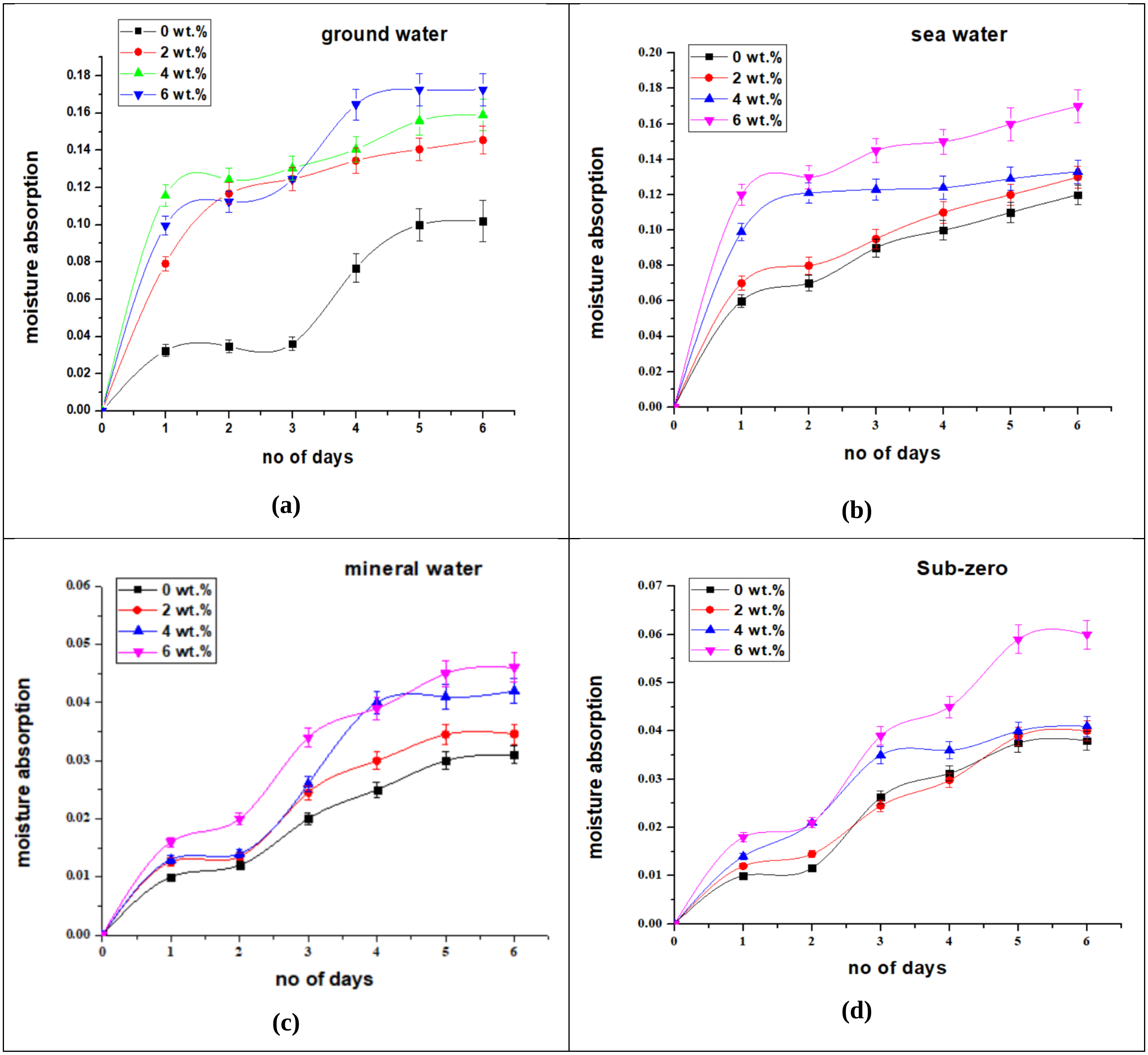


Figure 5.5 (a-d). Moisture absorption behavior of Polyester/KSSK/NC

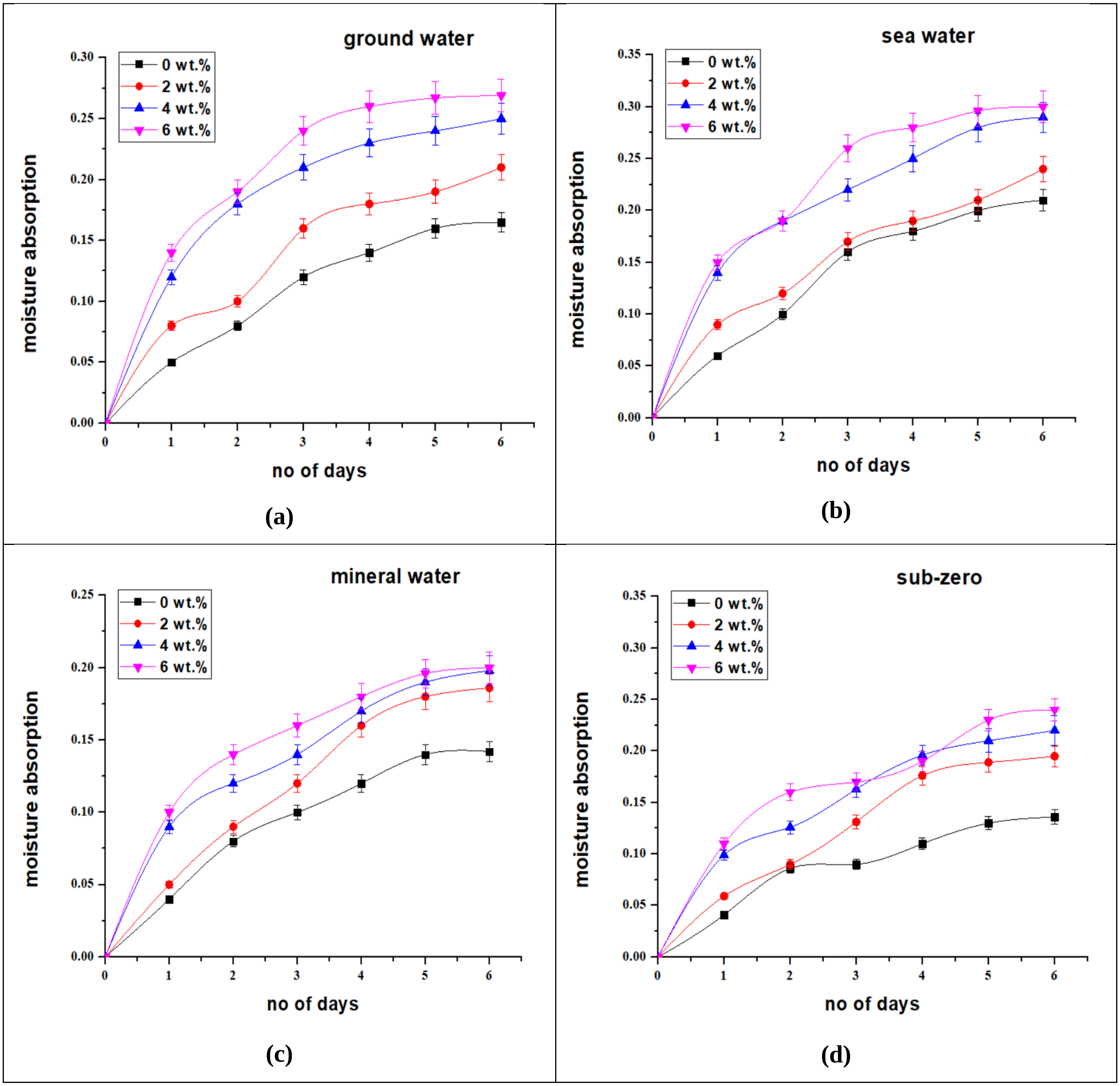
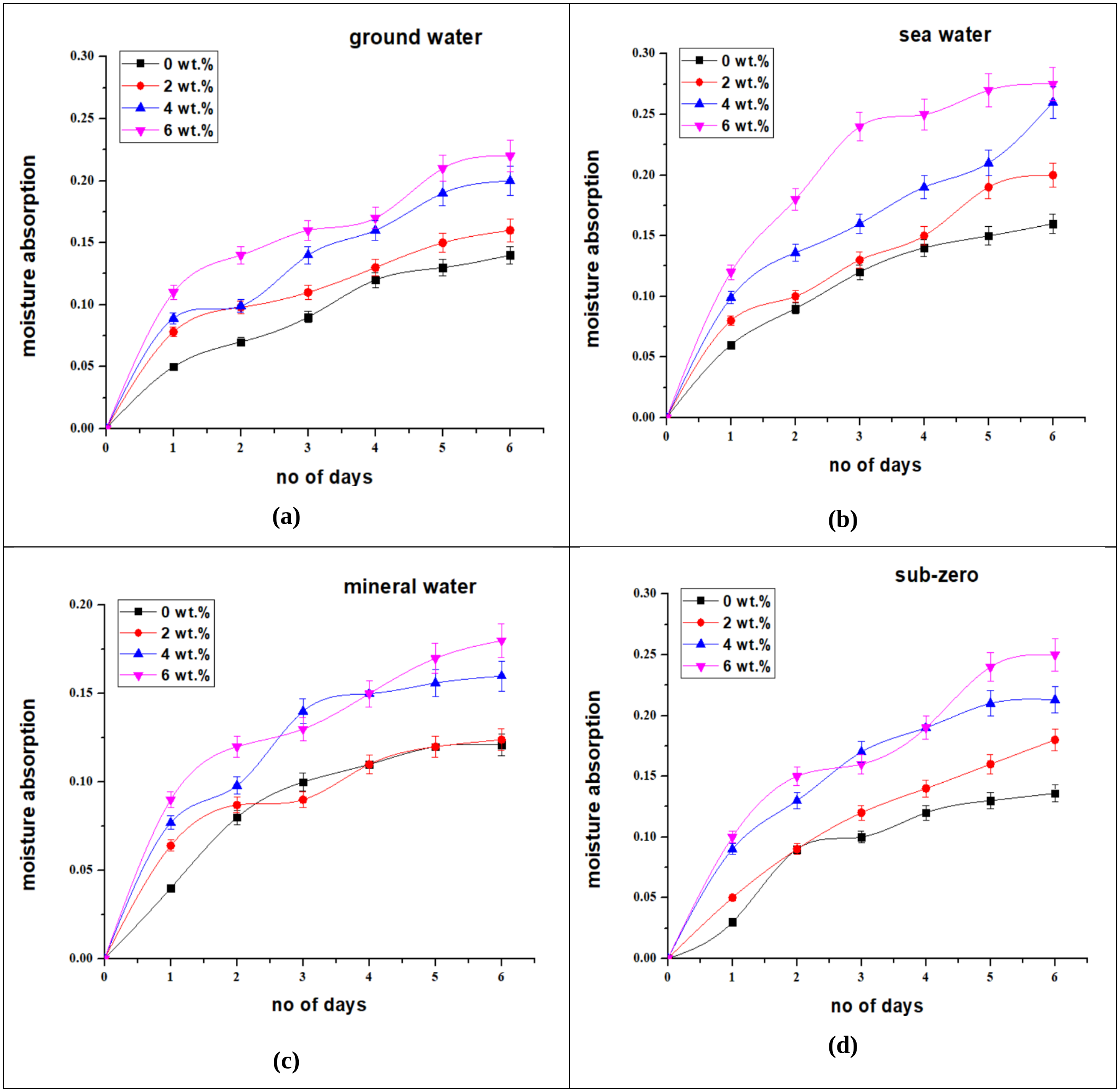


Figure 5.6 (a-d) Moisture absorption behavior of Epoxy/GSSG/NC



(a)

(b)

(c)

(d)

Figure 5.7 (a-d) Moisture absorption behavior of Epoxy/KSSK/NC

5.8.2. Mechanical Properties of different environmental exposed samples

The tensile and flexural strengths of all the composites after exposure to different environmental conditions along with normal conditions are compared in table 5.3.

Table 5.3 Mechanical Properties of different environmental exposed samples

Environments	**Tensile Strength (MPa) (Polyester)**							
	0 wt.% NC		**2 wt.% NC**		**4 wt.% NC**		**6 wt.% NC**	
	KSSK	**GSSG**	**KSSK**	**GSSG**	**KSSK**	**GSSG**	**KSSK**	**GSSG**
Groundwater	64	70	76	71	79	74	61	62
Sea water	67	74	65	78	68	68	60	64
Mineral water	71	80	87	88	80	84	75	74
Sub-zero	75	77	87	82	89	80	72	67
Environments	**Tensile Strength (MPa) (Epoxy)**							
	0 wt.% NC		**2 wt.% NC**		**4 wt.% NC**		**6 wt.% NC**	
	KSSK	**GSSG**	**KSSK**	**GSSG**	**KSSK**	**GSSG**	**KSSK**	**GSSG**
Groundwater	56	56	61	66	72	73	47	58
Sea water	53	66	62	68	71	72	44	65
Mineral water	64	65	69	76	82	79	50	63
Sub-zero	61	63	63	72	80	76	61	61

Environments	**Flexural Strength(MPa) (Polyester)**							
	0 wt.% NC		**2 wt.% NC**		**4 wt.% NC**		**6 wt.% NC**	
	KSSK	**GSSG**	**KSSK**	**GSSG**	**KSSK**	**GSSG**	**KSSK**	**GSSG**
Groundwater	298	266	305	285	301	226	243	210
Sea water	270	271	291	290	269	224	245	210
Mineral water	299	290	316	315	300	299	258	248
Sub-zero	302	295	314	310	269	300	248	240
Environments	**Flexural Strength(MPa) (Epoxy)**							
	0 wt.% NC		**2 wt.% NC**		**4 wt.% NC**		**6 wt.% NC**	
	KSSK	**GSSG**	**KSSK**	**GSSG**	**KSSK**	**GSSG**	**KSSK**	**GSSG**
Groundwater	180	148	210	191	179	166	156	129
Sea water	174	151	191	189	131	136	125	127
Mineral water	210	160	223	210	196	198	166	152
Sub-zero	201	150	244	193	183	173	147	164

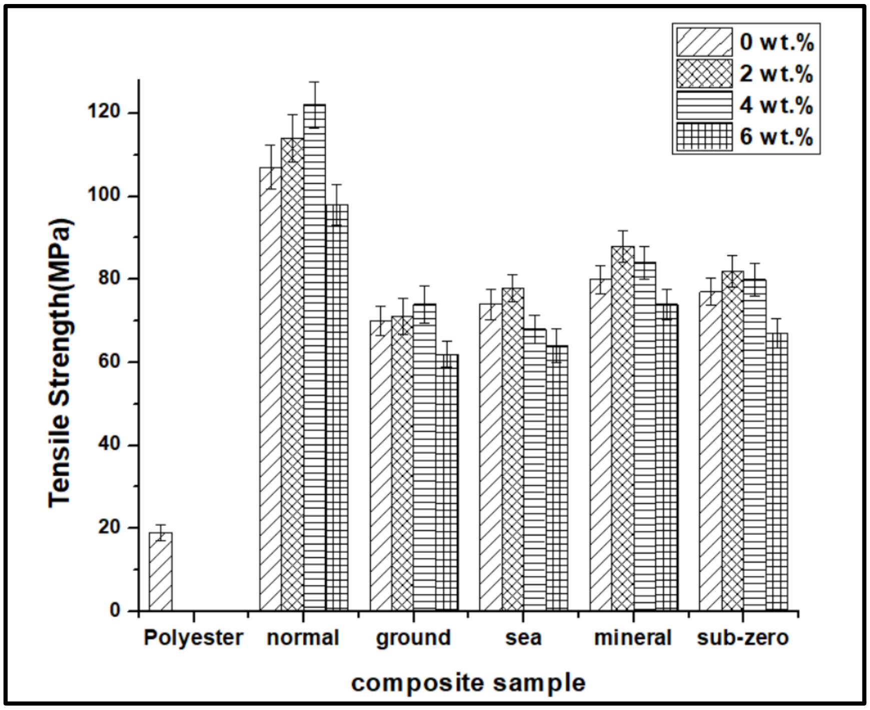


Figure. 5.8 Tensile properties of Polyester/GSSG/NC reinforced composites

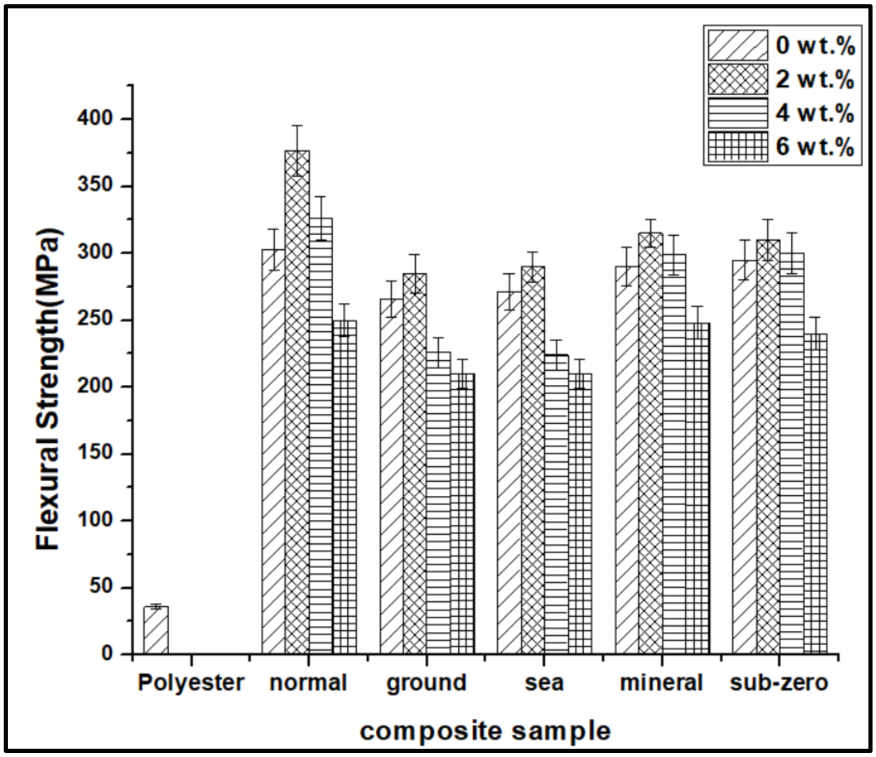


Figure. 5.9 Flexural properties of Polyester/GSSG/NC reinforced composites

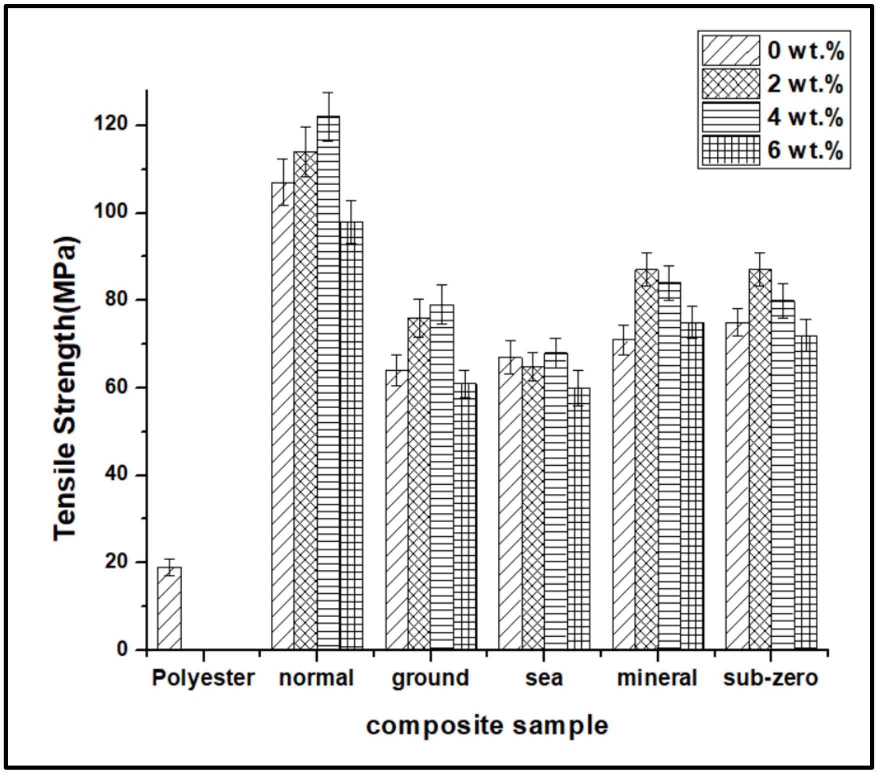


Figure. 5.10 Tensile properties of Polyester/KSSK/NC reinforced composites

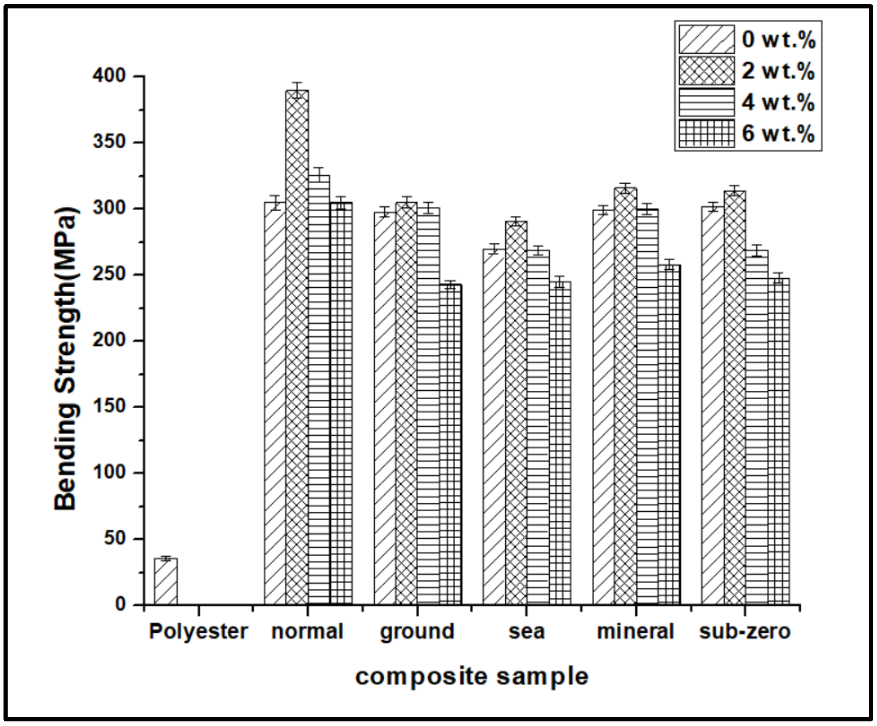


Figure. 5.11 Flexural properties of Polyester/KSSK/NC reinforced composites

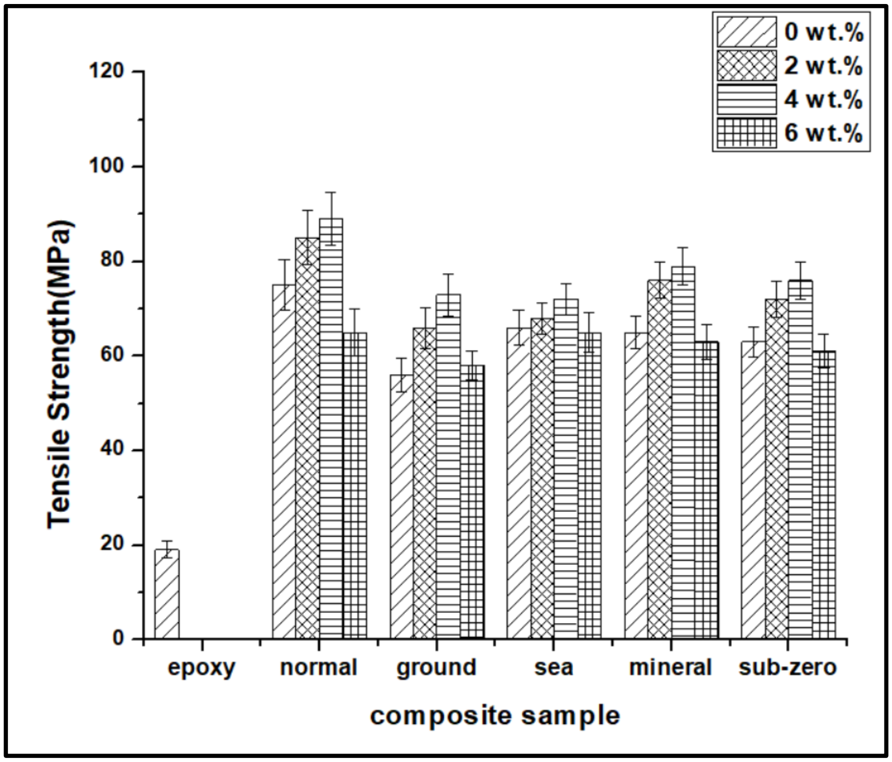


Figure. 5.12 Tensile properties of Epoxy/GSSG/NC reinforced composites

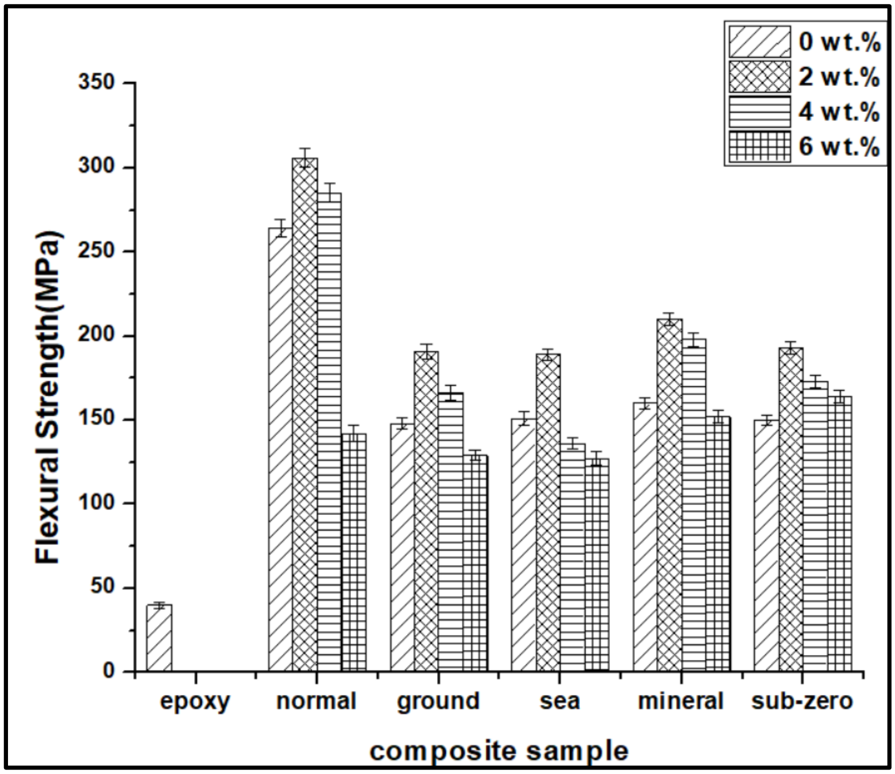


Figure. 5.13 Flexural properties of Epoxy/GSSG/NC reinforced composites

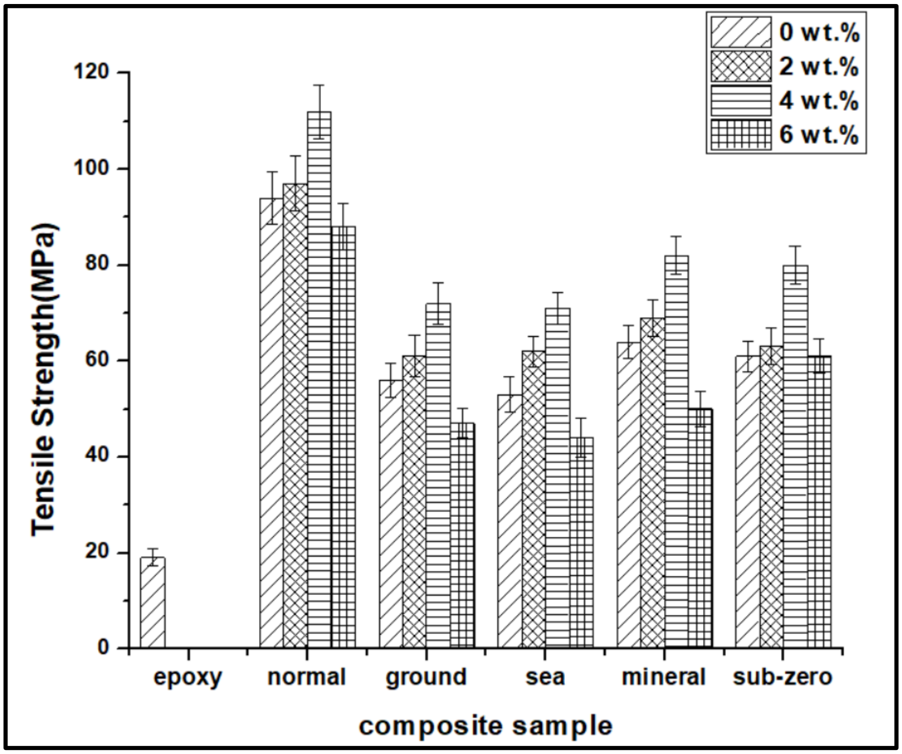


Figure. 5.14 Tensile properties of Epoxy/KSSK/NC reinforced composites

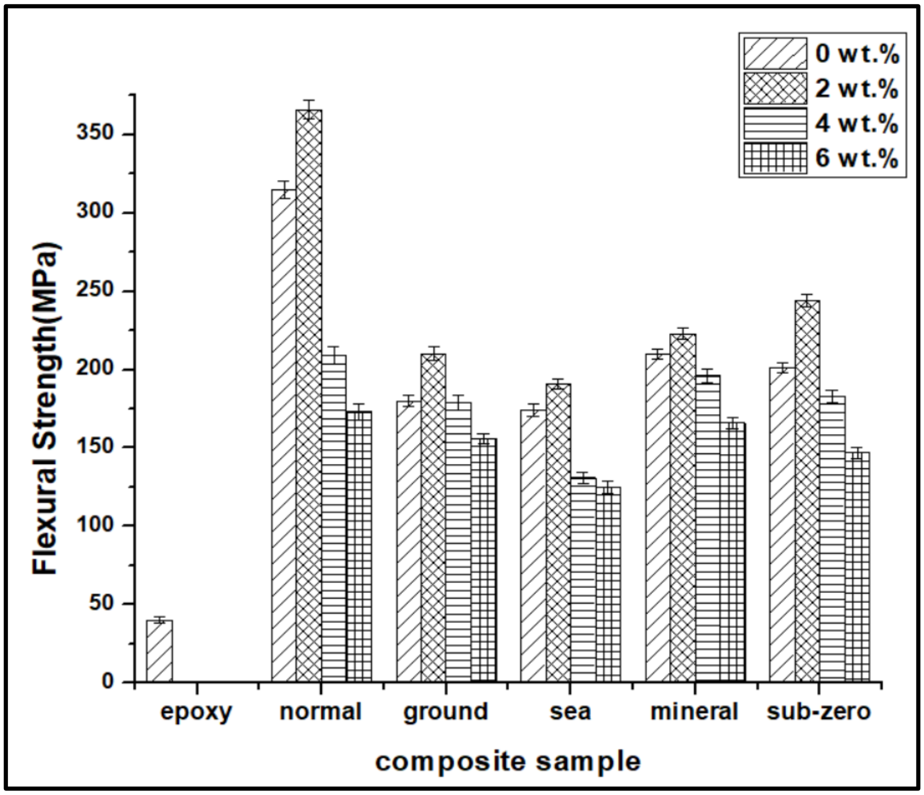


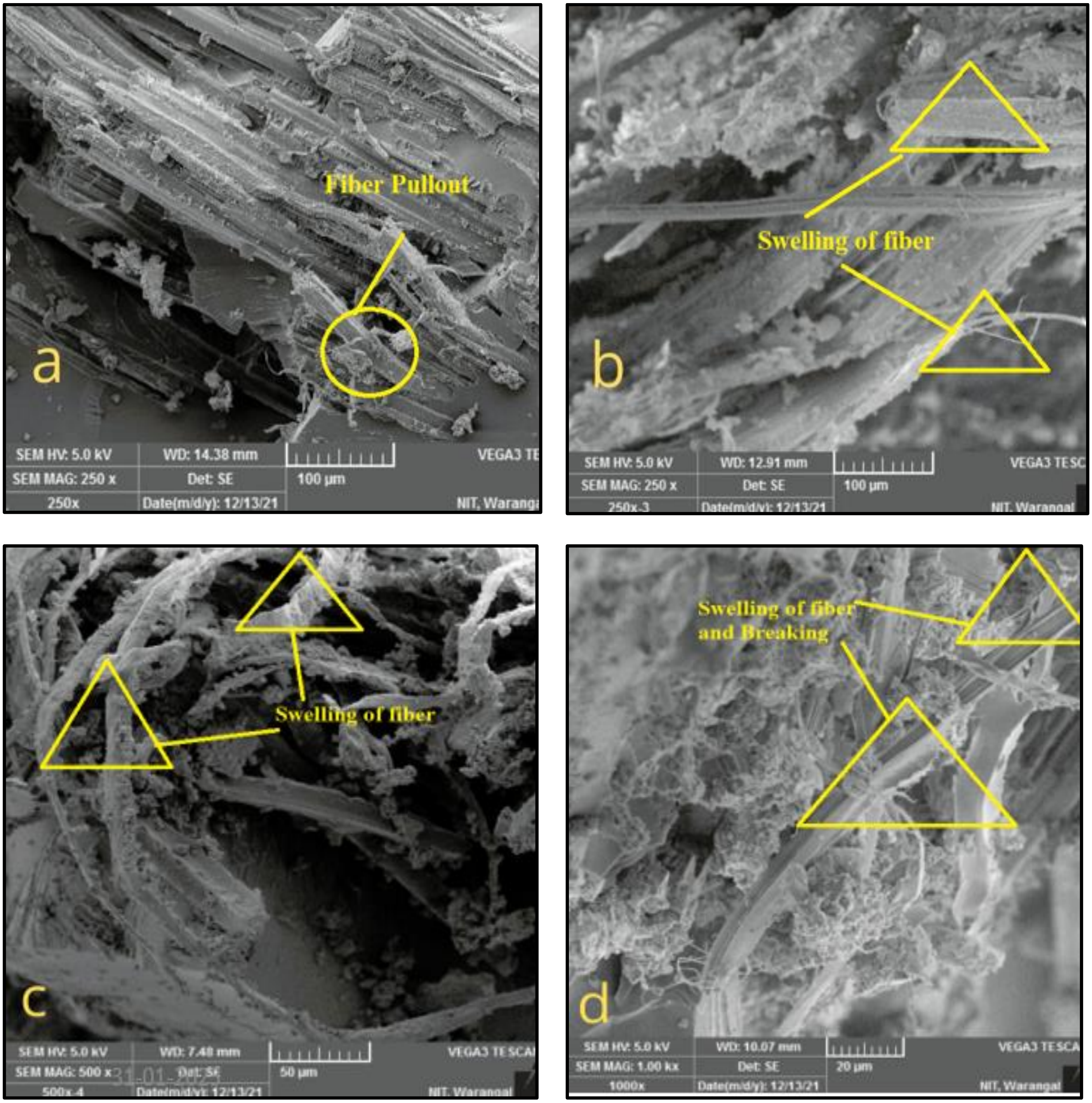
Figure. 5.15 Flexural properties of Epoxy/KSSK/NC reinforced composites

Figure. 5.8 – 5.15 depicts differences in tensile strength and flexural strength of different weight % of NC reinforced Polyester/GSSG, Polyester/KSSK, Epoxy/GSSG, Epoxy/ KSSK under various environmental conditions. Both the Tensile & Flexural strength of the polyester and epoxy composites increased upon reinforcement of the NC, as seen in the figures. The maximum tensile strength was found to be at 4 wt.% NC reinforcement and interestingly for bending 2wt.% NC reinforcement was found to be better among various reinforcements. The higher flexural strength at 2wt% is due to enhanced interface characteristics of Nano clay particles, particularly control load distribution and elasticity deformation. Furthermore, the flexibility of the polymer matrices improved as further Nano particles were introduced leading to expanded interior pores and decreased flexural strength. As a result, stress was centred on the area of agglomerated nano clay as filler concentration rose, which makes it simpler for the crack to spread through the composite. The most significant drop was found under seawater conditions for all conditions. This may be due to seawater acting as an acidic environment by which the materials lose their strength. The most significant depreciation of results is seen in 6 wt. % NC reinforcement. Similar results can be found at [36, 68, 197, 198].

In a comparison of tensile and flexural strengths, the effect of environmental behaviour was found to be the same as that of the tensile graphs. Including NC improves polymer load-bearing capacity, which is among the most apparent advantages of composites, while also lowering polymer content in the materials, resulting in more sustainable and environmentally friendly polymer composites. Similar outcomes were obtained by [199–201].

Mineral water and sub-zero environments tend to be better environments. Based on the findings, hybrid polymer composites can be potentially used for storing mineral water or soft water, or these can also be used in sub-zero temperatures. When compared to thermoset, Polyester tends to be better and when compared to synthetic fibers, Kevlar tends to be better in terms of determination in properties when exposed to harsh environments.

5.8.3. SEM Studies



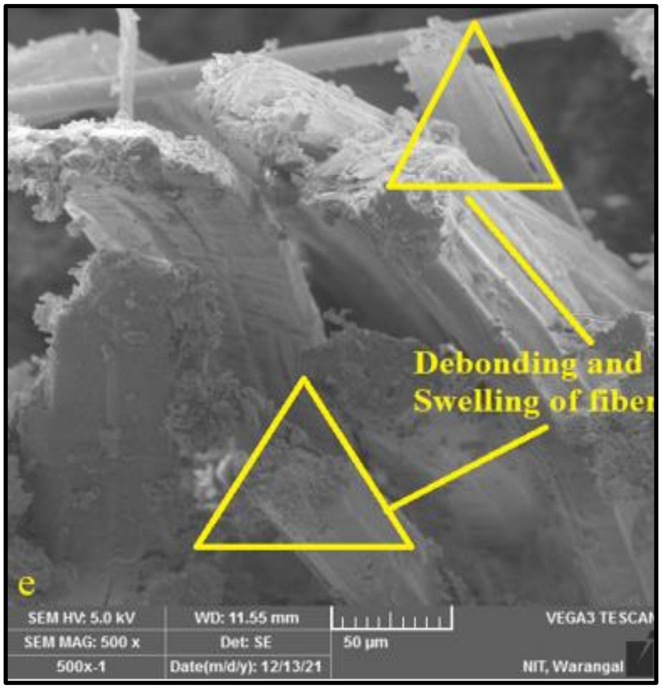
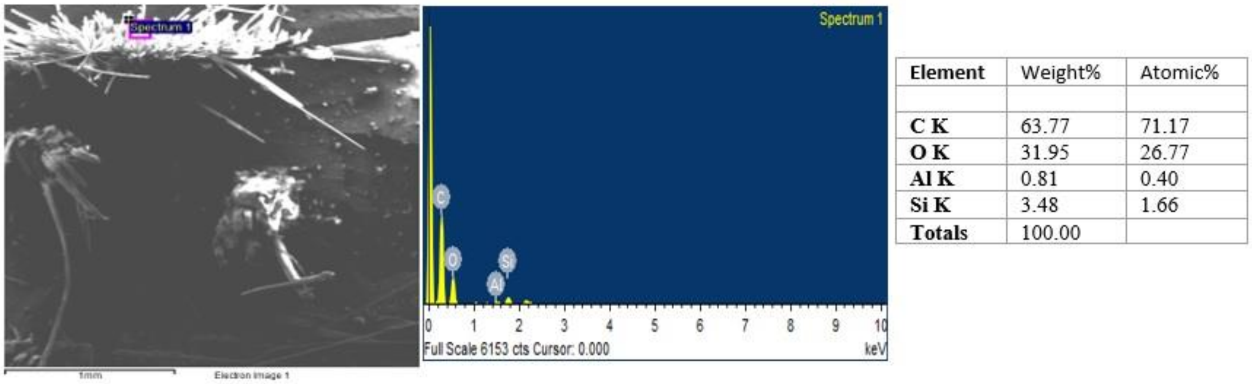


Figure 5.16. SEM micrographs of 4 wt.% NC reinforced Polyester/GSSG. Under different environmental conditions a) Normal b) Ground c) Sea d) Mineral e) Sub-zero

SEM micrographs of 4 wt. % NC reinforced Polyester/G.S.S.G. under various environmental conditions are shown in Fig 5.16. a–e. i.e. a) Normal b) Ground c) Sea d) Mineral, and e) Sub-zero. Figure. 5.16 a shows the sample with 4 wt.% of composites under normal conditions. The illustration clearly shows that tensile loading causes fibre breakage and splits, illustrating fragility. Figure. 5.16 b subjected to groundwater, offers fibre swelling when a composite is exposed to liquid media. A similar effect may be seen in all exposed specimens. Figure 5.16 c, shows the composite which has been subjected to a seawater environment. Compared to other composites, seawater reduces fibre strength and increases swelling; breaking of fibre is also noted, as is fibre pullout due to tensile stress. Figure. 5.16 d, displays the same phenomenon as the sample exposed in Figure 5.16 e. Figure 5.16 e shows the sample under sub-zero conditions where fibre pullout is detected due to reduced temperature and moisture absorption, as well as a minor degree of thickness swelling in the fibre. The swelling of fibre is more in samples exposed to ground and seawater. In contrast, swelling of fibre and breaking is less in samples exposed to mineral water and sub-zero condition, potentially making them be used in such situations.

When comparing the SEM micrographs of the normal and liquid-exposed samples, normal composites have rougher fracture surface than wet composites. Fibre breakage is visible in dry composites but challenging to discern. However, the presence of continuous fibres in damp composite after tensile testing shows that fibres are easily dragged away from the matrix, revealing a weak link between the fibre and matrix[197]. This fibre de-bonding, or the creation of a gap between both the fiber and matrix, is compelling proof that the composition of moist composite has weak fiber-matrix interfacial bonding. The discovers is similar to what Mohan found[202]. Water particles enter these composites via microscopic fissures and diffuse through the fiber-matrix integrations, causing delamination between the reinforcement and resin by replacing the matrix-fibre covalent bond in such a moist climate with weakened hydroxyl group.[203].



Element	Weight%	Atomic%
C K	63.77	71.17
O K	31.95	26.77
Al K	0.81	0.40
Si K	3.48	1.66
Totals	100.00	

Figure 5.17. EDX of the 4 wt.% NC reinforced Polyester/GSSG composite after tensile testing.

Figure 5.17 indicates the EDX analysis of 4 wt.% Nanoclay reinforced Polyester/GSSG hybrid polymer composite under normal conditions. It suggests that after tensile testing, the failure of composites and fibre tends to delaminate, leading to the composite's failure. The elemental constituents show the presence of carbon, oxygen, aluminium and silica, which indicates their presence by fibres and Nano-clay, which is reinforced.

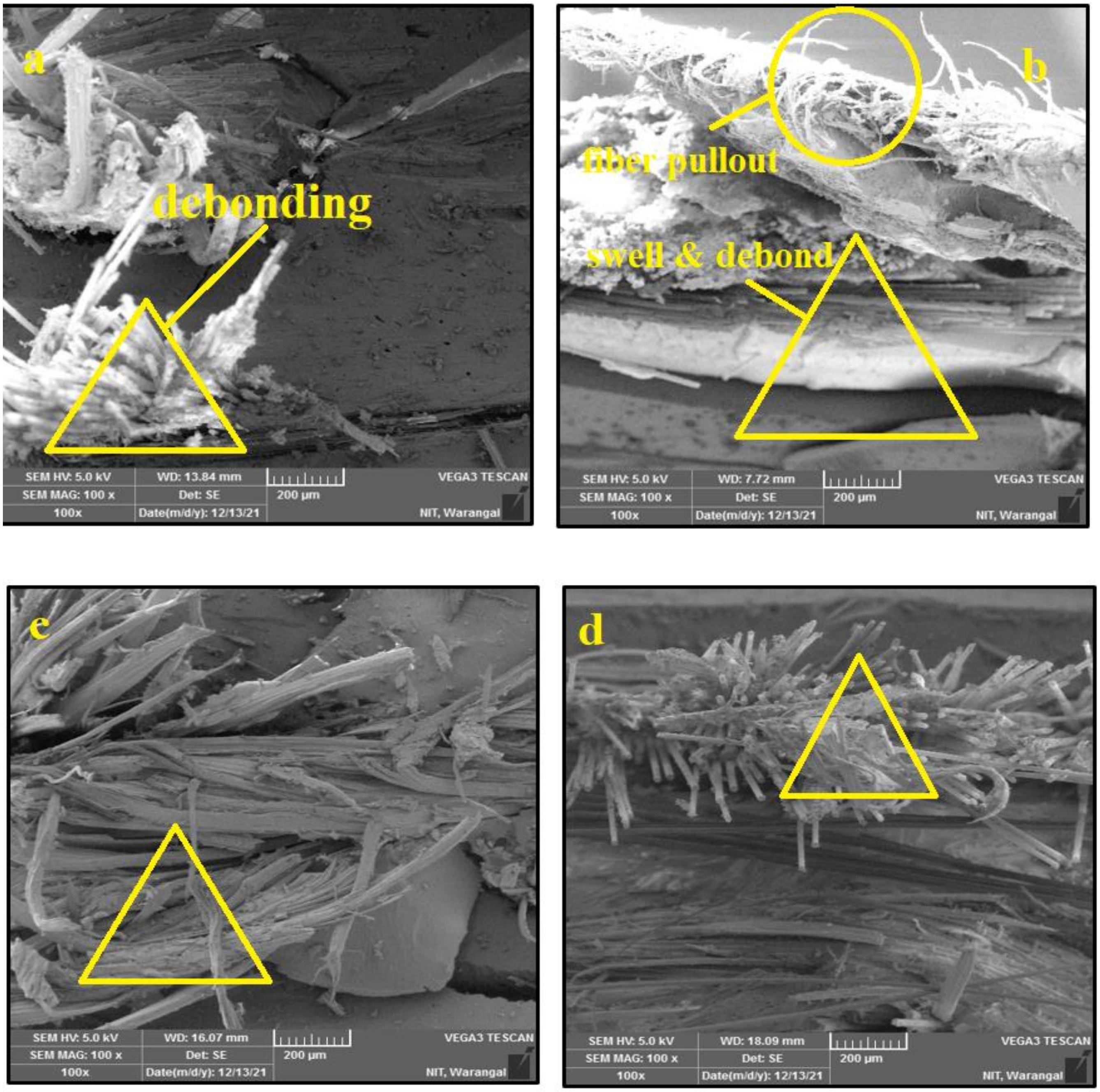


Figure 5.18. SEM micrographs of 4 wt.% NC reinforced Polyester/KSSK. under different environmental conditions a) Ground b) Sea c) Mineral d) Sub-zero

The samples immersed in various conditions of 4 wt.% NC reinforced Polyester/KSSK samples are shown in Figure 5.18. From the figures it can be seen that Fibers tend to absorb water in all environments and fibers tend to swell and due to that, debonding of fiber takes place. The same phenomenon can seen in samples for Polyester/GSSG/4 wt.% NC. When comparing Kevlar and Glass fiber swelling of fiber is lower in Kevlar compared to glass. The SEM images also validate the moisture absorption results.

5.8.4. Wear Properties

Figure 5.19. Samples for erosion wear

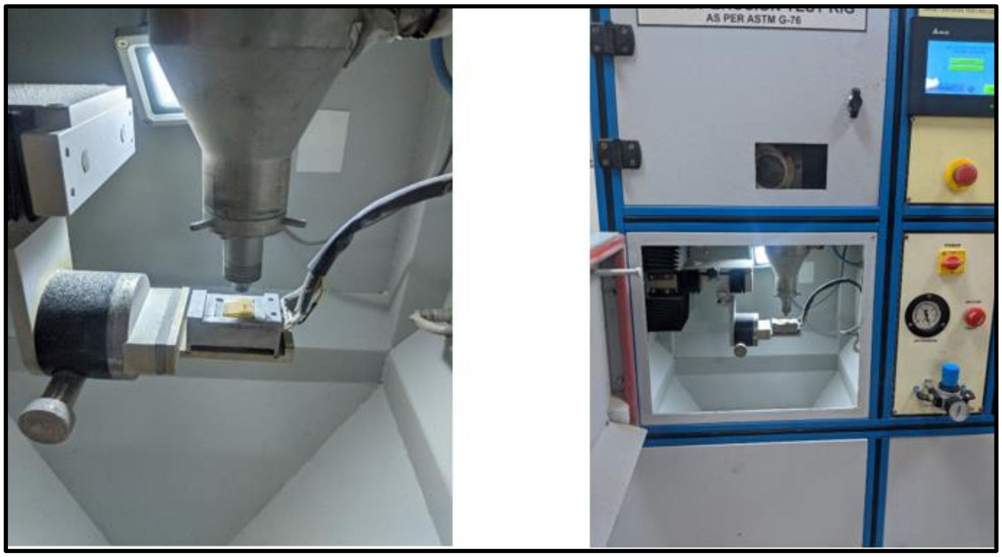


Figure 5.20. Samples under erosion testing

Figure 5.19 and Figure 5.20 shows the samples at the time of testing in air jet test rig erosion wear apparatus.

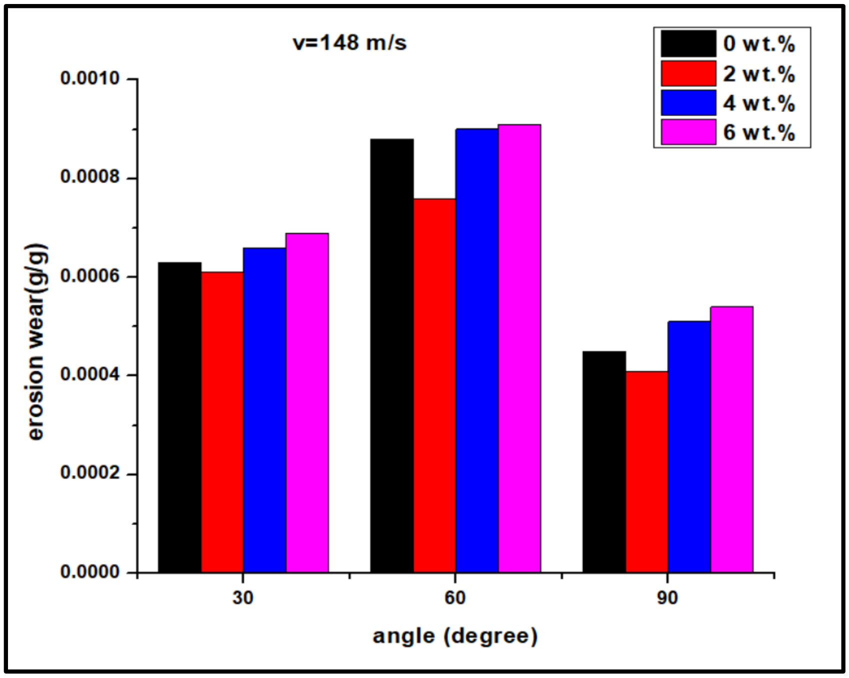


Figure 5.21. Erosion wear studied of polyester/GSSG/NC (0,2,4,6 wt.%)

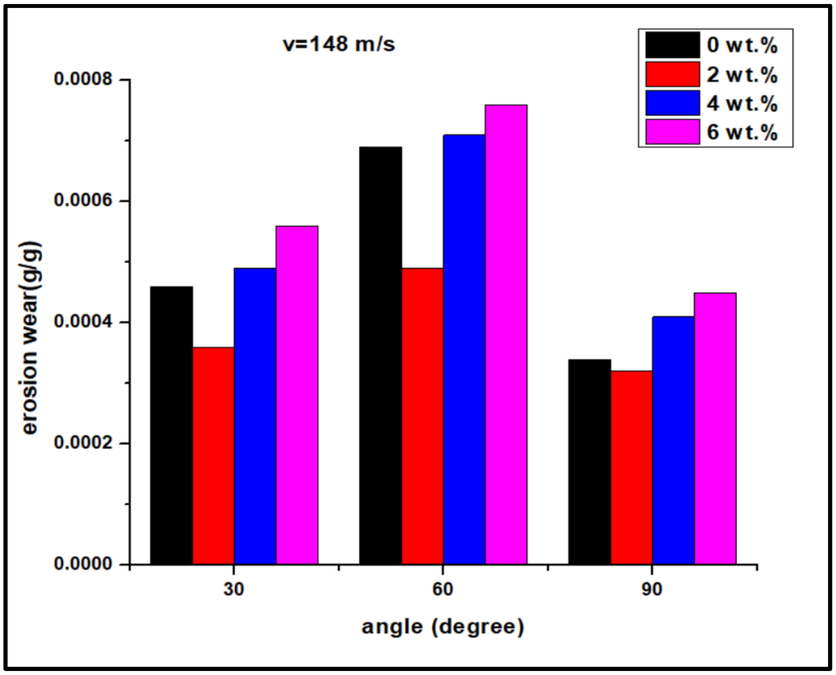


Figure 5.22. Erosion wear studied of polyester/KSSK/NC (0,2,4,6 wt.%)

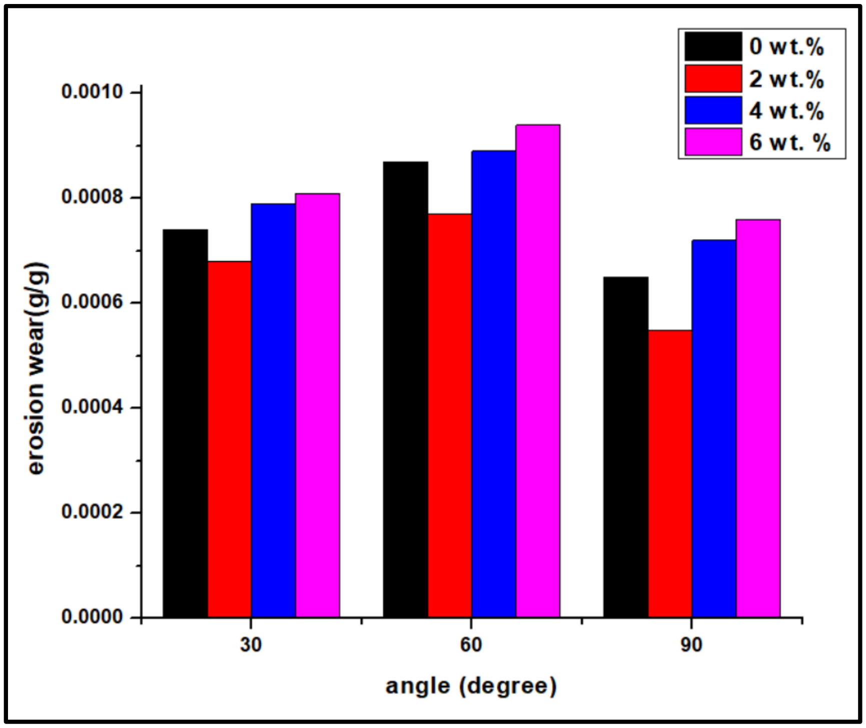


Figure 5.23. Erosion wear studied of Epoxy/GSSG/NC (0,2,4,6 wt.%)

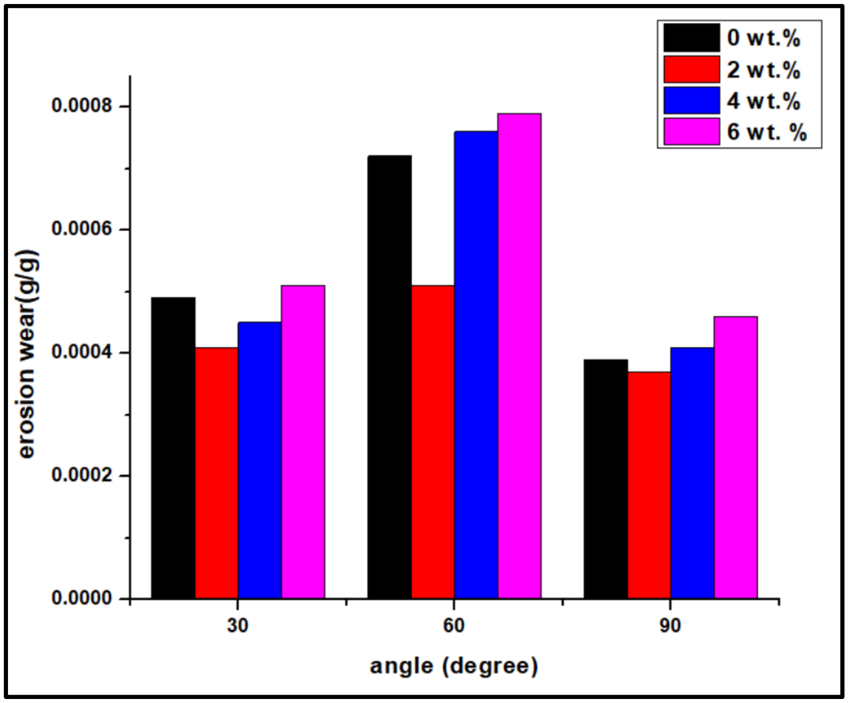


Figure 5.24. Erosion wear studied of Epoxy/KSSK/NC (0,2,4,6 wt.%)

The erosion wear resistance of NC-reinforced GSSG and KSSK composites with both polyester and epoxy was tested at different impact angles. Figure 5.21 shows the erosion wear behaviour of 0,2,4,6 wt% NC of GSSG/Polyester composites, Figure 5.22 shows the wear behaviour of 0,2,4,6 wt% NC of KSSK/polyester composites. Figure 5.23 shows the erosion wear behaviour of 0,2,4,6 wt% NC of GSSG/epoxy composites and , Figure 5.23 shows the erosion wear behaviour of 0,2,4,6 wt% NC of KSSK/epoxy composites. According to the data from all the proportions, composite materials' wear performance significantly improved at 2 wt.% of NC loading compared to composites at other NC loadings[204][205]. With the addition of 2 wt.% of NC reinforcement, material loss was reduced and wear resistance increased, which may be attributed to the filler's efficient dispersion and smooth bonding with the polyester/epoxy resin. At 60 degree impingement angle, the erosion wear was high, followed by 30^o and 90^o, indicating the semi-ductile nature of hybrid polymer nanocomposites[206]. Polyester reinforcement tends to be improved compared to epoxy. When comparing both thermosets, and Kevlar fiber as outermost reinforcement tends to be better than glass.

The wear behaviour for the samples produced at different impingements was also studied, and it is shown in Figures 5.21-5.24. The characteristic of polymeric erosion was recognised by those who had worked with polymers based on maximum and least erosion rates at altered impact angles. It was discovered that when the most significant erosion rate happens at 90^o impact angle, the materials' erosion wear behaviour is brittle. The erosion wear behaviour is ductile when severe wear rate occurs at a 30^o impact angle. Maximum erosion wear was observed in all combinations of composites at a 60^o impact angle, exhibiting semi-ductile erosion[207][208]. When added to brittle polyester/epoxy resin, these particles boost the surface's hardness, providing strong erosion resistance in the perpendicular direction and minor wear at 90 degrees. Composites come into close contact with particulate/Fiber when erodent strikes them in the usual order. Because reinforcments offer resistance to erodent contact power and are stiffer than silica sand, NC particles and Glass fibres have lower MRR. It is envisaged that the composites created in this work would mainly be used as lubricants to increase erosion and wear resistance[209].

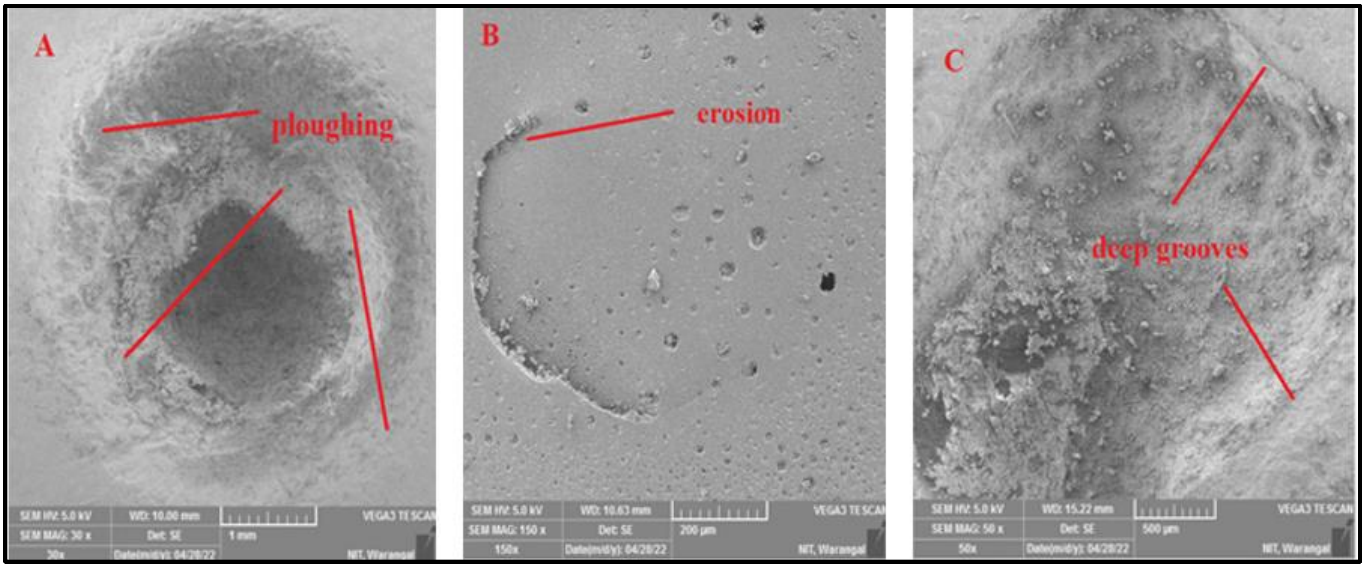


Figure 5.25. Erosion Behavior of polyester/KSSK/NC reinforced hybrid composite a)2 wt.% at 60^o b)2 wt.% at $90^{\,o}$ c) 4 wt.% at $60^{\,o}$

After the erosion wear test on polyester/KSSK/NC, the eroded surfaces were studied by SEM. Figures 5.25 a & c illustrate the degraded surface of 2 and 4 wt.% NC reinforced hybrid polymer samples, respectively. Both surfaces have parallel micro-cuts and channels, indicating the plastic flow of materials induced by erodent particles striking them. When erodent particles of hard silica sand collide with the composite at a reduced impact angle, the erodent particles puncture the composite, causing materials to be removed. Parallel forces effect cutting and ploughing at lower impact angles, but vertical forces have low impact. As a result of the high influence of similar strength, plastic-deformation micro-grooves/cuts and cracks are noticed at 60^0 impact angle, resulting in considerable material loss. The fractures enlarged and ploughed the surface due to constant influence of erodent on the composite, resulting in material removal. Compared to 2 wt.% filler composites, the eroding surface of 4 wt.% filler composites has more extensive and deeper grooves. Agglomeration and weak interfacial bonding are to be responsible for this. When erodent collides with the target, the substance chips away at the surface due to low binding strength and accumulation. Figure 5.25 b shows the eroded surface of a 2 wt.% sample at 90^0. There are no fractures or micro-cutting on the surface. Due to the lack of parallel force, the impact of eroded sand particles in the normal direction could not form fractures, micro grooves, or ploughs. The erosion wear of composites at a 90^0 impact angle is negligible owing to the combination of complex nanoparticles.

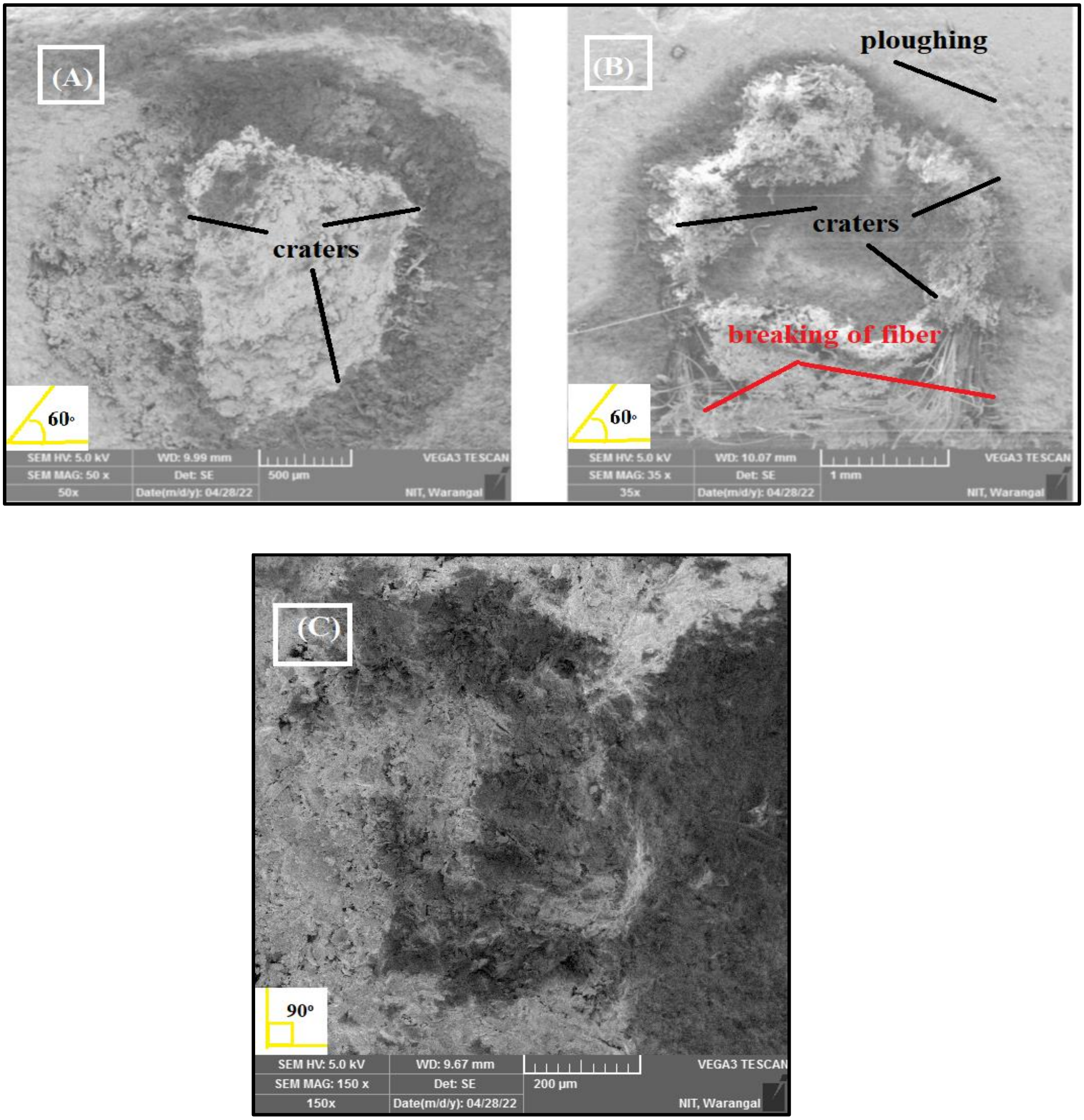


Figure 5.26. Shows the eroded samples (a)Polyester/GSSG/6 wt.% NC at 60^0 (b) Epoxy/GSSG/6 wt.% NC at 60^0 (c) Polyester/GSSG/6 wt.% 90^0.

Figure 5.26 shows erosion surfaces of 6 wt.% and 6 wt.% of NC-reinforced Polyester/GSSG and Epoxy/GSS, respectively, at a 60-degree striking angle and a velocity of 148 m/s. When compared to the surface that has been eroded in a 90-degree orientation, as shown in Figure 5.26 c, it can be understood that the surfaces of both composites have critically broken from the increasing impact of silica particles. Sand particles striking a composite surface at a 60-degree angle cause severe material loss because the impact forces cut and plough away the material, leaving grooves on the surface. Vertical force (perpendicular to the surface) and inclined force (parallel/inclined to the surface) were two types of impact forces that contributed to sand erosion wear[210]. Based on a study by Acharya et al.[211], the influence of erodents at lower angles significantly affects wear and is the cause of the most significant amount of material loss due to micro-cutting and ploughing. Due to slanted forces, cracks formed when erodent particles struck the composite surfaces. The materials become cracked and fractured when erodent particles continue to strike them over time. Continuous contact with hard sand silica particles results in plastic deformation, which leads to chipping off of material and significant wear rates. The high filler loading that results in inadequate interfacial bonding strength can be blamed for 6 wt.% NC reinforcement's poor resistance to erosion wear. There is no trace of cracks or tiny cuttings on the surfaces. The impact of eroding sand grains in the typical orientation also couldn't produce fractures, micro-grooves, or plough due to the absence of simultaneous force. Because of hard NC reinforcements, wear of composites at 90 ^{o} impact is little. From the figures, it can also be concluded that most of the fibres are still with the matrix[207].

5.8.5. Degradation of wear properties

Liquids, as a common solvent, come into touch with machine elements and might operate as a lubricant or a pollutant[212]. The wear behaviours of composites following contact with normal, groundwater, seawater, mineral water, and sub-zero temperatures are depicted in Figures 5.27-5.30. Maximum erosion wear was recorded in both composite combinations at a 60^{o} impact angle, demonstrating semi-ductile erosion in all environmental circumstance. From the figures 5.27-5.30, it can be observed that mineral water and sub-zero temperatures perform the best of all environments since they are the least influenced and have the least amount of property degradation. The most substantial drop is noticed in saltwater circumstances. This could be because seawater acts as an acidic environment, causing the materials to lose strength. Also, seawater absorbs sodium and chlorine ions, resulting in a chemical reaction with the fibre that results in degradation[213][214]. Water disseminates into formless portions of NC-reinforced hybrid composites, producing plasticisation, enlargement, and softening. This reduces rigidity and strength and allows fibres/polymers to be separated more quickly, making the composite less wear-resistant.

Plasticization of polymers, carefully connected to solubility, entails disabling heat and entropy considerations involved with crystallisation and intermolecular connections in the polymer's formless regions[215]. Plasticization reduces the properties and is limited to the polymer's undeveloped portions. Water particles convey segmented gestures in the polymers by swiftly diffusing into the surface area of the phases of the polymer/amorphous fibre. Water particles entering the polymer's underdeveloped regions cause swelling, which causes interactions among polymer molecules to weaken. Because intermolecular forces are reduced, the material is easily removed during erosion, increasing the wear rate. From the above results, it can be concluded that hybrid composites can be employed wherever erosion takes place in environments like mineral water and sub-zero temperatures.

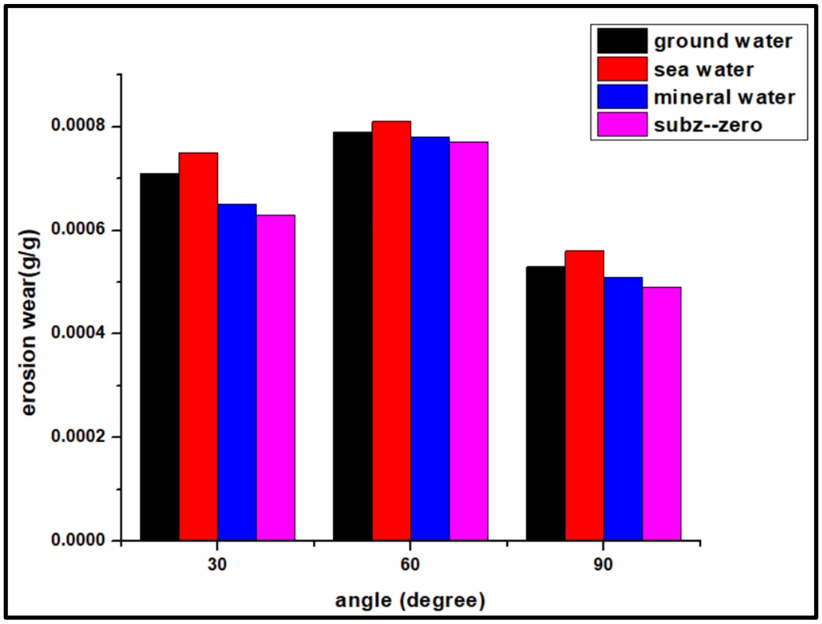


Figure 5.27. Degradation of wear properties of Polyester/GSSG/2wt.% NC under different conditions

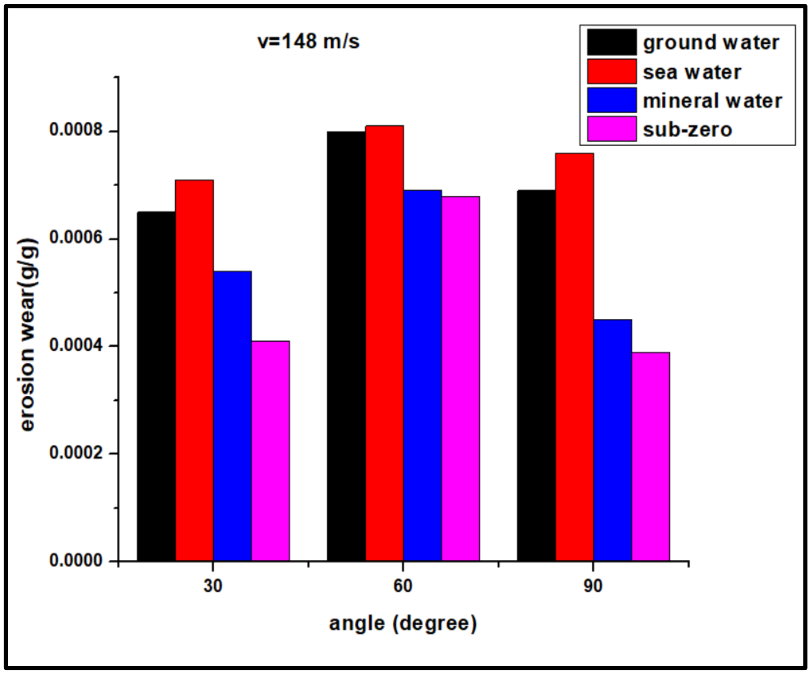


Figure 5.28. Degradation of wear properties of Polyester/KSSK/2wt.% NC under different conditions

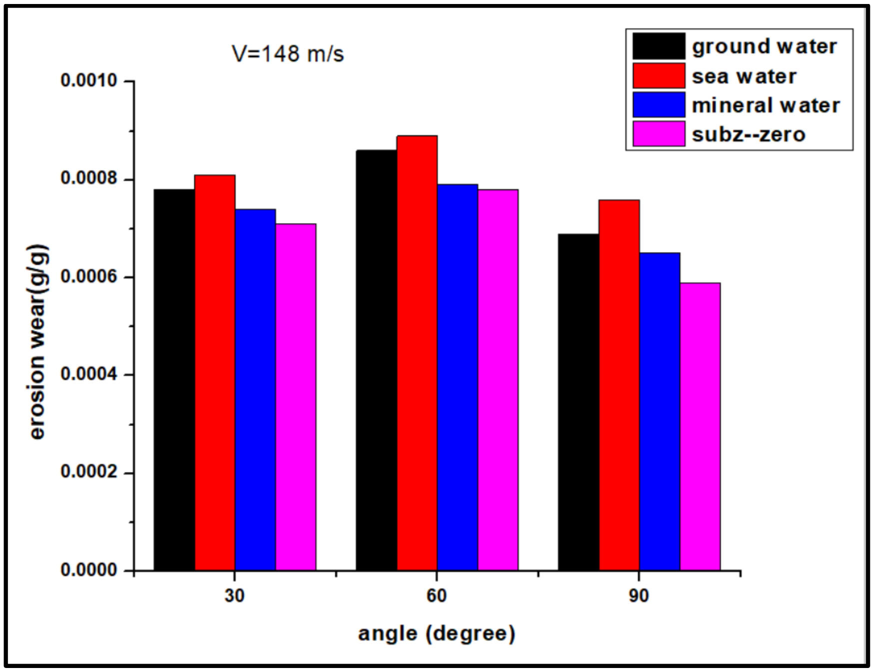


Figure 5.29. Degradation of wear properties of Epoxy/GSSG/2wt.% NC under different conditions

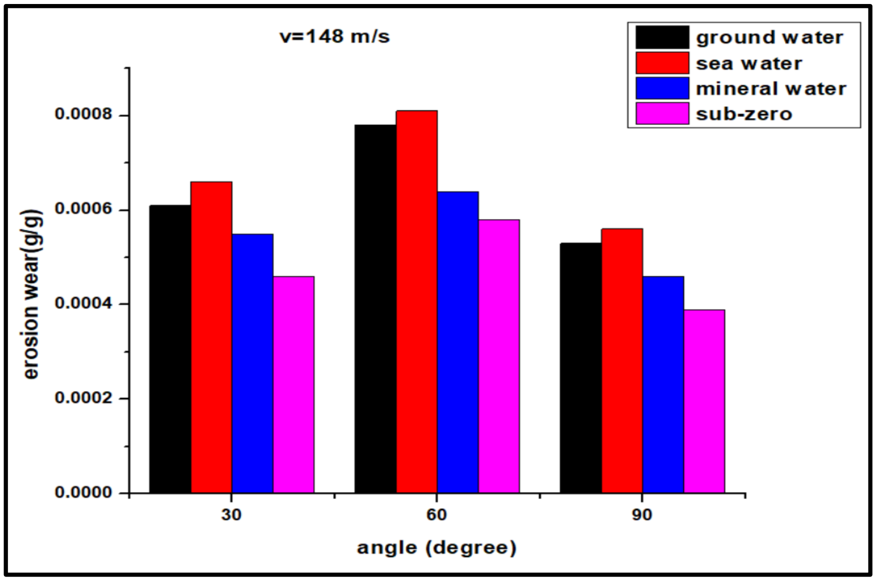


Figure 5.30. Degradation of wear properties of Epoxy/KSSK/2 wt.% NC under different conditions

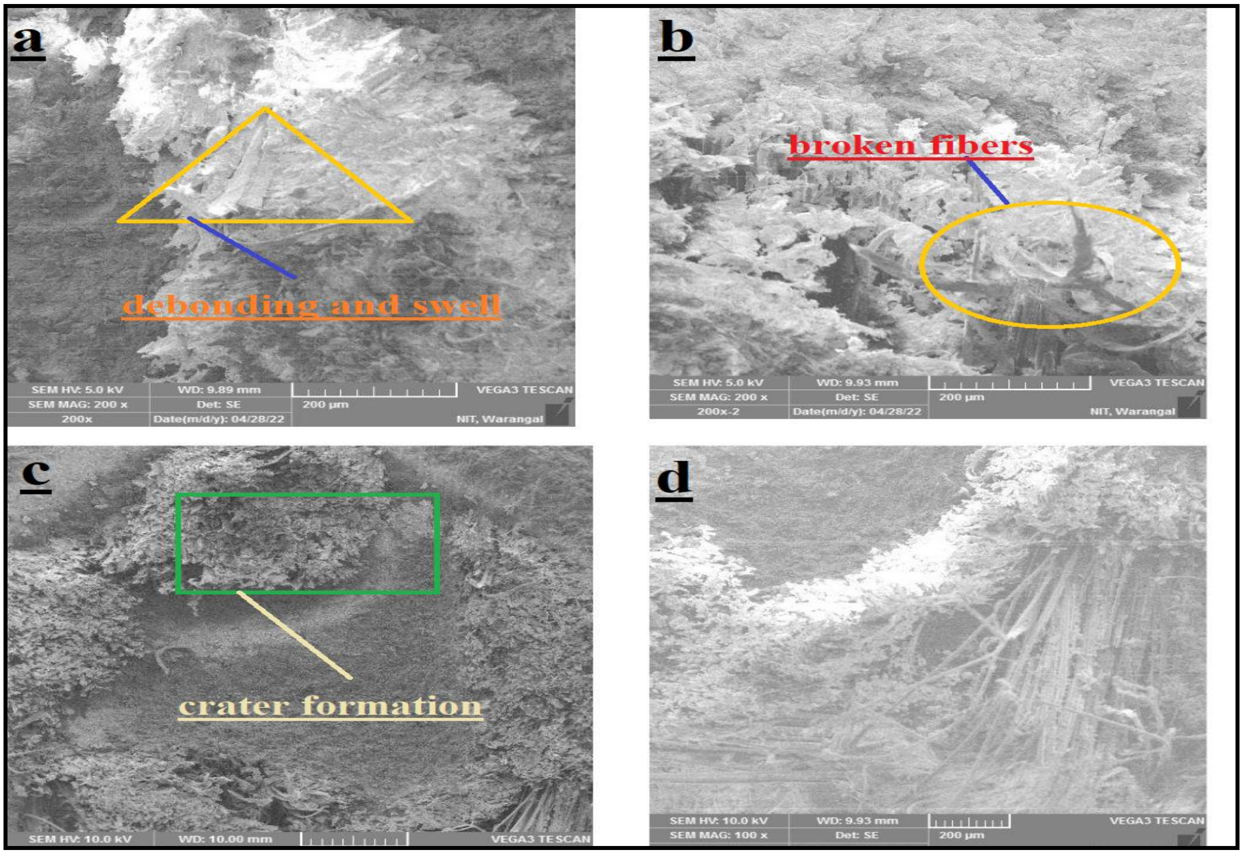


Figure 5.31. SEM micrographs of 2 wt.% NC reinforced Polyester/GSSG under different environmental conditions a) Ground b) Sea c) Mineral d) Sub-zero (at 60 degree)

There was increased amount of erosion wear when compared to dry condition, which are shown in Figure 5.31 a-d. When compared to a normal environment, it was noticed that eroding wear was enhanced. When comparing dents on a surface to a normal environment using SEM image, the area and volume of the craters appear to be larger, which is indicative of moisture absorption. From Figures 5.31a and 5.31b, it can be seen that de-bonding and swelling of fibre is more in seawater and groundwater conditions, which can be compared to wear analysis, as higher wear rate was found among samples immersed in seawater and groundwater. As seen from SEM images, more cavities and wider channels were observed in seawater conditions, leading to increased water absorption and erosion rates. From figure 5.31c and 5.31d, crater formation can be seen but are these fewer compared to seawater and groundwater conditions.

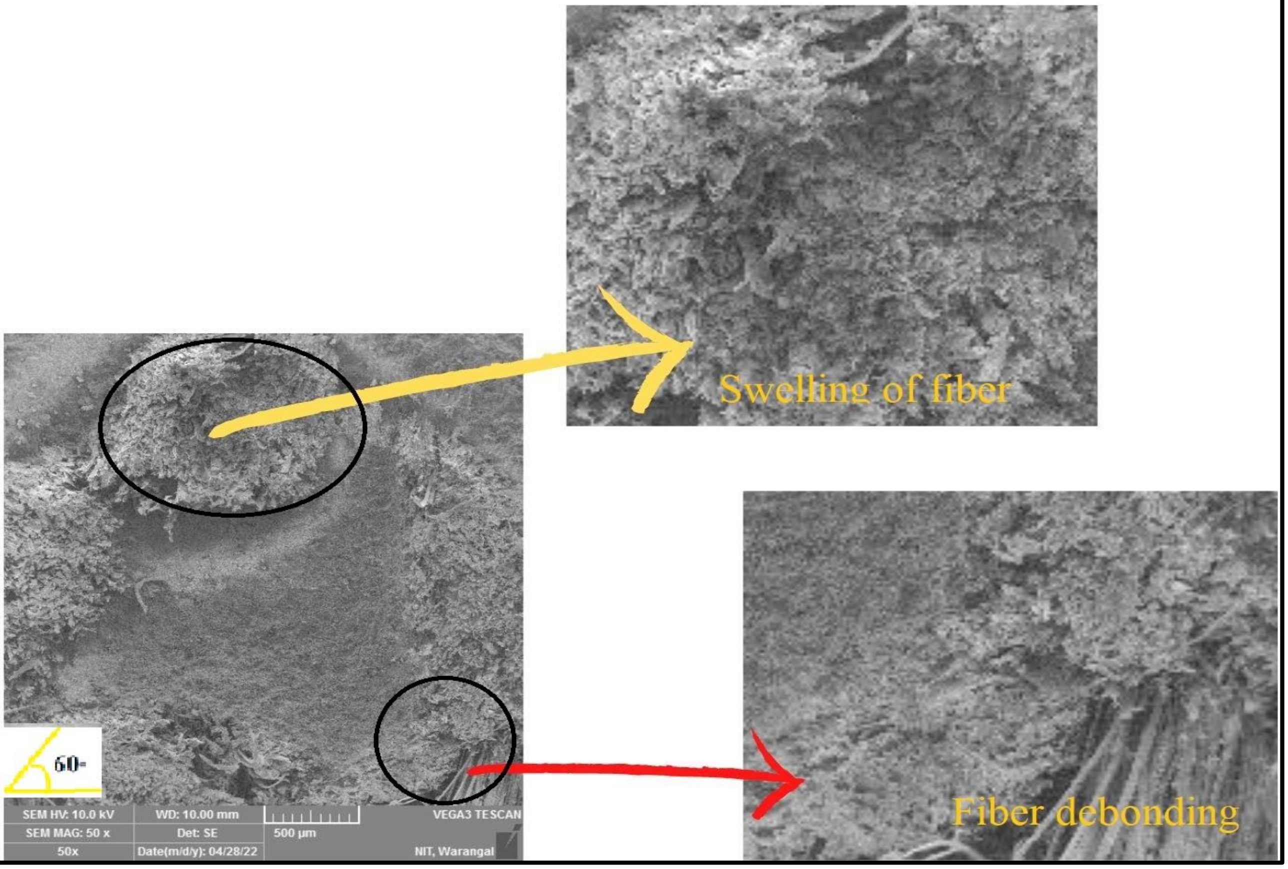
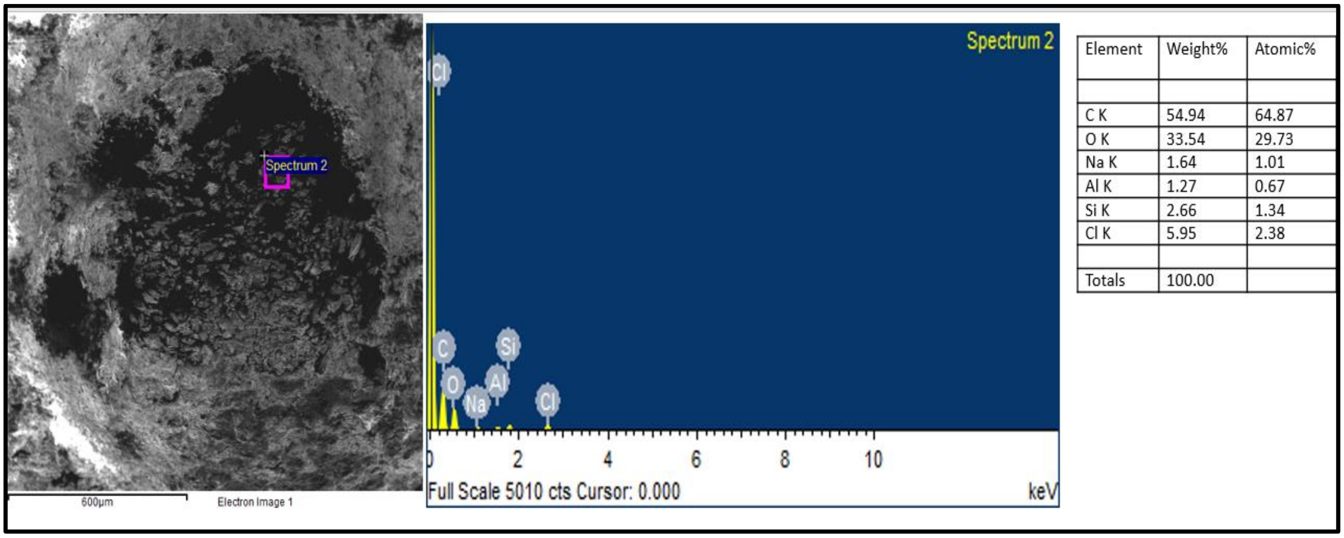


Figure 5.32. Shows the eroded samples Polyester/GSSG/6 wt.% NC in sea water conditions

Figure 5.32 displays the degraded specimens after being submerged in sea water. When comparing the SEM micrographs in Figures 5.26 to the number of impacts that are apparent on the surface, the size and density of the impacts appear to be on the upper side, which is indicative of water penetration. One can see how many craters and other features have increased from the SEM image in Figure 5.32, Deep grooves were caused because seawater conditions result in greater moisture content, that in return speeds up erosion. When compared to image Figures 5.26, one can also see the fibre swelling and deboning. By quickly diffusing into the surface area of the polymer's phases and amorphous fibres, water particles quickly diffuse into polymers to transmit segmentation movements. Water particles causing swelling in the polymer's undeveloped regions weaken the attraction between polymerization processes.



Element	Weight%	Atomic%
C K	54.94	64.87
O K	33.54	29.73
Na K	1.64	1.01
Al K	1.27	0.67
Si K	2.66	1.34
Cl K	5.95	2.38
Totals	100.00	

Figure 5.33. Shows the EDX analysis in sea water conditions Polyetser/GSSG/2 wt.%

EDX analysis of 2 wt.% NC reinforced Polyester/GSSG hybrid polymer composite under sea water conditions is shown in Figure 5.33. The presence of Cl and Na indicates the presence of salts dissolved in the sea water.

5.10. CONCLUSIONS

1. The samples were fabricated with both polyester and epoxy as matrix materials and GSSG and KSSK as reinforcements and Nano clay as the filler material.
2. The mechanical and wear analysis of fabricated samples were done followed by the degradation of the properties under various conditions such as ground water, sea water, mineral water and sub-zero conditions.

3. The results showed that the samples exposed to seawater had more moisture absorption than in all other environments. The absorption order was higher in seawater, followed by groundwater, mineral water and sub-zero temperature.

4. Moisture absorption is more significant in samples with an NC level of 6wt% and less in samples with an NC content of 0%. This outcome was considered due to Nano clay's hydrophilic nature, which causes it to absorb a lot of water based on the conditions. The molecular basis for this is the availability of hydroxyl groups in Nanoclay, which attracts and interact with water molecules via hydrogen bonding.

5. The degradation of mechanical properties was most significant in seawater conditions for all the conditions. This may be due to seawater acting as an acidic environment by which the materials lose their strength. The most significant depreciation of results is seen in 6 wt. % NC reinforcement. The same trend was observed in glass fibers and kevlar fiber hybrid composites. Also the SEM results validated the mechanical results as in sea water fiber swelling and fiber debonding is high in sea water conditions.

6. The 2 wt.% NC hybrid polymer composite showed maximum erosion wear resistance and the composites showed semi ductile behavior. With the addition of the 2 wt.% of NC reinforcement, the material loss was reduced and wear resistance was increased, which may be attributed to the filler's efficient dispersion and bonding with the polyester/epoxy resin.

7. The degradation of wear properties also had substantial drop is noticed in seawater circumstances same as the mechanical results. This could be because seawater acts as an acidic environment, causing the materials to lose strength. Also, seawater absorbs sodium and chlorine ions, resulting in a chemical reaction with the fibre that results in degradation. SEM results validated the wear results.

8. Polyester/Kevlar/NC 2 wt.% hybrid composites showed better mechanical and tribological properties among fabricated composites. These composites with Kevlar as outer most fiber and Polyester/2 wt.% NC reinforcement are well suited for marine applications which absorbs less amount of water and have better properties compared to all other reinforcements.

Chapter -6

Conclusions and Future Scope

6.1.CONCLUSIONS

The overall observations with regard to various fabricated samples are as follows.

1. A noval hybrid nano composites are successfully fabricated by hand layup technique with the following materials.
   i. Kevlar/Glass as synthetic fibers and Sisal as natural fiber as fiber reinforcements,
   ii. Thermosets Polyester/Epoxy as matrices &
   iii. Nano fillers Nanoclay/Nano silica as filler reinforcements.
2. Both the Nano fillers Nanoclay/Nano silica are uniformly mixed to thermosets by a novel technique by the Sonication process called Ultra-sonication which created high pressure, vibrations, and acoustic wave streaming, which lead to homogeneous distribution of nanoparticles in thermoset.
3. Hybridization of fiber composites with synthetic fiber in the outside layer led to have improved mechanical properties. Synthetic fibers are more durable, stiffer, and inter-laminar shear strength is better than natural fibers. The load resisting capacity is also better compared to natural fiber. So it does not break easily after applying load.

4. From the results, it is also observed that the outer layer is sisal fiber; the strength is lower compared to Glass/Kevlar. This may be due to the presence of higher hemicellulose and lignin content in the sisal fiber, does not make a suitable bond with the matrix. Hence it cannot resist the load and breaks easily after applying load. The decrease in strength is due to fiber breakage and delaminating of the composites.

5. The highest tensile strength is achieved at 4 wt.% of Nanosilica/ KSSK and GSSG hybrid composites. For a further increase in silica content, there is a reduction in tensile strength which is due to the viscosity of the polymer that increases as wt.% of silica is increased. A higher amount of Nano-silica concentration caused agglomeration and poor dispersion, which showed an increase of porosity.
6. There is an increase in the bending strength in KSSK /GSSG from 0 wt.% to 4 wt.%. The decrease in flexural strength of more than 4 wt.% of silica may be due to the agglomeration of silica in the resin, which serves as stress concentrates and decreases flexural strength.

7. The highest tensile strength is achieved at 4 wt.% of Nano clay/ KSSK and GSSG hybrid composites. Similar results can be observed for Nano silica wt.% reinforement. Interestingly for flexural results, 2wt.% inclusion of Nano-clay was found to be better.
8. Overall Mechanical results were found to be better for Nano silica reinforcements but when we consider this in terms of strength-to-weight ratio, as the density of NC is half the density of NS, NC filler composites gave better results when compared to NS.
9. When comparing Glass and Kevlar as outer surface reinforcements, Kevlar had better properties than glass and when compared to thermosets Polyester had better properties compared to Epoxy.
10. Moisture absorption is more significant in samples with an NC level of 6wt% and less in samples with an NC content of 0%. This outcome was considered due to Nano clay's hydrophilic nature, which causes it to absorb a lot of water based on the conditions. The molecular basis for this is the availability of hydroxyl groups in Nanoclay, which attracts and interact with water molecules via hydrogen bonding. All the samples showed fickian behaviour. The results revealed more moisture absorption in seawater than in other samples.
11. Polyester composites tend to absorb low amounts of moisture when compared to epoxy composites and Low moisture absorption was observed in Kevlar based hybrid composites when compared to glass fiber hybrid composites.
12. The major degradation of mechanical properties was observed in samples exposed to sea water. The same trend was observed in glass fibers and Kevlar fiber hybrid composites. This may be due to the seawater acting as an acidic environment by which the materials lose their strength.
13. The 2 wt.% NC hybrid polymer composite showed maximum erosion wear resistance and the composites showed semi ductile behavior. With the addition of the 2 wt.% of NC reinforcement, the material loss was reduced and wear resistance was increased, which may be attributed to the filler's efficient dispersion and bonding with the polyester/epoxy resin.
14. Polyester/Kevlar/NC 2 w.% hybrid composites showed better mechanical and tribological properties among fabricated composites. These composites are well suited for marine applications.

6.2.SCOPE AND SUGGESTIONS FOR FURTHER RESEARCH

1. The present investigation deals with the Development of Glass/Kevlar/Sisal Hybrid Polymer Nanocomposite for Mechanical and Tribological applications. Likewise, many synthetic fibres such as carbon and baron can be taken as an alternative and natural fibres such as jute, bamboo, coconut can also be chosen as alternatives.
2. A comparison has been between Polyester and Epoxy, which are two thermosets and conclusions are drawn. However, thermoplastics can also be chosen as matrix and the results can be analysed.
3. One can fabricate samples with advanced techniques such as additive manufacturing and RTM and the results can be compared and analysed from the existing literature i.e. From the above results.
4. Mechanical and tribological behaviour of Hybrid nano composites were studied in the current study whereas thermal and electrical properties were ignored. As a result, the study can be expanded by taking the factors into account.

REFERENCES

1. Vigneswaran C, Ananthasubramanian M, Kandhavadivu P (2014) Bioprocessing of synthetic fibres. Bioprocess Text 189–250. https://doi.org/10.1016/B978-93-80308-42-5.50004-4

2. Kilinç AÇ, Durmuşkahya C, Seydibeyoğlu MÖ (2017) Natural fibers. Fiber Technol Fiber-Reinforced Compos 209–235. https://doi.org/10.1016/B978-0-08-101871-2.00010-2

3. Saba N, Tahir PM, Jawaid M (2014) A review on potentiality of nano filler/natural fiber filled polymer hybrid composites. Polymers (Basel) 6:2247–2273. https://doi.org/10.3390/polym6082247

4. Mohammed L, Ansari MNM, Pua G, et al (2015) A Review on Natural Fiber Reinforced Polymer Composite and Its Applications. Int J Polym Sci 2015:. https://doi.org/10.1155/2015/243947

5. Amir SMM, Sultan MTH, Jawaid M, et al (2018) Nondestructive testing method for Kevlar and natural fiber and their hybrid composites. Durab Life Predict Biocomposites, Fibre-Reinforced Compos Hybrid Compos 367–388. https://doi.org/10.1016/B978-0-08-102290-0.00016-7

6. Yashas Gowda TG, Sanjay MR, Subrahmanya Bhat K, et al (2018) Polymer matrix-natural fiber composites: An overview. Cogent Eng 5:. https://doi.org/10.1080/23311916.2018.1446667

7. H Ku, H Wang NP and MT (1384) A review on the tensile properties of natural fibre reinforced polymer composites. 300

8. Bharath KN, Basavarajappa S (2016) Applications of biocomposite materials based on natural fibers from renewable resources: A review. Sci Eng Compos Mater 23:123–133. https://doi.org/10.1515/secm-2014-0088

9. Chandgude S, Salunkhe S (2021) In state of art: Mechanical behavior of natural fiber-based hybrid polymeric composites for application of automobile components. Polym Compos 42:2678–2703. https://doi.org/10.1002/pc.26045

10. Jagadeesh P, Puttegowda M, Oladijo OP, et al (2022) A comprehensive review on polymer composites in railway applications. Polym Compos 43:1238–1251. https://doi.org/10.1002/PC.26478

11. Saba N, Jawaid M, Sultan MTH (2017) Thermal properties of oil palm biomass based composites. Elsevier Ltd.

12. Bilyeu B, Brostow W, Menard K (2001) Epoxy thermosets and their applications. III. Kinetic equations and models. J Mater Educ 23:189–204

13. Dogan A, Arikan V (2017) Low-velocity impact response of E-glass reinforced thermoset and thermoplastic based sandwich composites. Compos Part B Eng 127:63–69. https://doi.org/10.1016/j.compositesb.2017.06.027

14. Khalid MY, Al Rashid A, Arif ZU, et al (2021) Natural fiber reinforced composites: Sustainable materials for emerging applications. Results Eng 11:100263. https://doi.org/10.1016/J.RINENG.2021.100263

15. Lotfi A, Li H, Dao DV, Prusty G (2019) Natural fiber–reinforced composites: A review on material, manufacturing, and machinability. J Thermoplast Compos Mater. https://doi.org/10.1177/0892705719844546

16. Puttegowda M, Rangappa SM, Jawaid M, et al (2018) Potential of natural/synthetic hybrid composites for aerospace applications. Elsevier Ltd

17. Chand N (2008) Natural fibers and their composites. Tribol Nat Fiber Polym Compos 1–58. https://doi.org/10.1533/9781845695057.1

18. Derradji M, Wang J, Liu W (2018) Fiber-Reinforced Phthalonitrile Composites. Phthalonitrile Resins Compos 241–294. https://doi.org/10.1016/B978-0-12-812966-1.00005-6

19. Amir SMM, Sultan MTH, Jawaid M, et al (2019) Nondestructive testing method for Kevlar and natural fiber and their hybrid composites. Durab Life Predict Biocomposites, Fibre-Reinforced Compos Hybrid Compos 367–388. https://doi.org/10.1016/B978-0-08-102290-0.00016-7

20. Govarthanam KK, Anand SC, Rajendran S (2016) Technical textiles for knife and slash resistance. Handb Tech Text Tech Text Appl 193–236. https://doi.org/10.1016/B978-1-78242-465-9.00007-0

21. Hasan Z (2020) Composite materials. Tool Compos Aerosp Struct 21–48. https://doi.org/10.1016/B978-0-12-819957-2.00002-X

22. Kotal M, Bhowmick AK (2015) Polymer nanocomposites from modified clays: Recent advances and challenges. Prog Polym Sci 51:127–187. https://doi.org/10.1016/j.progpolymsci.2015.10.001

23. Rafiee R, Shahzadi R (2019) Mechanical Properties of Nanoclay and Nanoclay Reinforced Polymers: A Review. Polym Compos 40:431–445. https://doi.org/10.1002/pc.24725

24. Singh P, Srivastava S, Singh SK (2019) Nanosilica: Recent Progress in Synthesis, Functionalization, Biocompatibility, and Biomedical Applications. ACS Biomater Sci Eng 5:4882–4898. https://doi.org/10.1021/acsbiomaterials.9b00464

25. Plummer CJG, Bourban P-E, Månson J-A (2016) Polymer Matrix Composites: Matrices and Processing. Ref Modul Mater Sci Mater Eng 1–9. https://doi.org/10.1016/b978-0-12-803581-8.02386-9

26. Mostafa NH, Ismarrubie ZN, Sapuan SM, Sultan MTH (2016) Effect of fabric biaxial prestress on the fatigue of woven E-glass / polyester composites. JMADE 92:579–589. https://doi.org/10.1016/j.matdes.2015.12.109

27. Sanjay MR, Siengchin S, Parameswaranpillai J, et al (2019) A comprehensive review of techniques for natural fibers as reinforcement in composites: Preparation, processing and characterization. Carbohydr Polym 207:108–121. https://doi.org/10.1016/j.carbpol.2018.11.083

28. Jawaid M, Khalil HPSA, Bakar AA, Khanam PN (2011) Chemical resistance, void content and tensile properties of oil palm/jute fibre reinforced polymer hybrid composites. Mater Des 32:1014–1019. https://doi.org/10.1016/j.matdes.2010.07.033

29. M. Xanthos (2005) Functional Fillers for Plastics. Wiley-VCH Verlag GmbH & Co. KGaA, germany

30. Singh K, Ohlan A, Saini P, Dhawan SK (2008) composite – super paramagnetic behavior and variable range hopping 1D conduction mechanism – synthesis and characterization. Polym Adv Technol 229–236. https://doi.org/10.1002/pat

31. Saharudin MS, Atif R, Shyha I, Inam F (2016) The degradation of mechanical properties in polymer nano-composites exposed to liquid media - A review. RSC Adv 6:1076–1089. https://doi.org/10.1039/c5ra22620a

32. Seo S-JPM-K (2011) Element and processing

33. Alsagayar ZS, Rahmat AR, Arsad A, binti Mustaph SNH (2015) Tensile and Flexural Properties of Montmorillonite Nanoclay Reinforced Epoxy Resin Composites. Adv Mater Res 1112:373–376. https://doi.org/10.4028/www.scientific.net/amr.1112.373

34. Saharudin MS, Atif R, Shyha I, Inam F (2017) The degradation of mechanical properties in halloysite nanoclay–polyester nanocomposites exposed to diluted methanol. J Compos Mater 51:1653–1664. https://doi.org/10.1177/0021998316660178

35. Suresha B, Varun CA, Indushekhara NM, et al (2019) Effect of Nano Filler Reinforcement on Mechanical Properties of Epoxy Composites. IOP Conf Ser Mater Sci Eng 574:. https://doi.org/10.1088/1757-899X/574/1/012010

36. Merah N, Mohamed O (2019) Nanoclay and water uptake effects on mechanical properties of unsaturated polyester. J Nanomater. https://doi.org/10.1155/2019/8130419

37. Alrobei H (2021) Mechanical properties of natural screw pine fiber reinforced polyester nanocomposites. J Mech Sci Technol 35:1969–1975. https://doi.org/10.1007/s12206-021-0414-6

38. Ferreira DP, Cruz J, Fangueiro R (2019) Surface modification of natural fibers in polymer composites. Elsevier Ltd

39. Ojha S, Raghavendra G, Acharya SK (2016) Utilization of Waste Carbon as Reinforcement in Thermoset Composites. Spherical Fibrous Fill Compos 203–229. https://doi.org/10.1002/9783527670222.ch8

40. Thakur VK, Thakur MK (2014) Processing and characterization of natural cellulose

fibers/thermoset polymer composites. Carbohydr Polym 109:102–117. https://doi.org/10.1016/j.carbpol.2014.03.039

41. Mittal V, Sinha S (2017) Study the effect of fiber loading and alkali treatment on the mechanical and water absorption properties of wheat straw fiber-reinforced epoxy composites. Sci Eng Compos Mater 24:731–738. https://doi.org/10.1515/secm-2015-0441

42. Raghavendra G, Ojha S, Acharya SK (2013) Jute fiber reinforced epoxy composites and comparison with the glass and neat epoxy composites. https://doi.org/10.1177/0021998313499955

43. G, Raghavendra KAK (2015) Moisture Absorption Behavior and Its Effect on the Mechanical Properties of Jute-Reinforced Epoxy Composite. Polym Polym Compos 16:101–113. https://doi.org/10.1002/pc

44. Muñoz E, García-Manrique JA (2015) Water absorption behaviour and its effect on the mechanical properties of flax fibre reinforced bioepoxy composites. Int J Polym Sci 2015:16–18. https://doi.org/10.1155/2015/390275

45. Hamdan MHM, Siregar JP, Cionita T, et al (2019) Water absorption behaviour on the mechanical properties of woven hybrid reinforced polyester composites. Int J Adv Manuf Technol 104:1075–1086. https://doi.org/10.1007/s00170-019-03976-9

46. Jamir MRM, Majid MSA, Khasri A (2018) Natural lightweight hybrid composites for aircraft structural applications. Sustain Compos Aerosp Appl 155–170. https://doi.org/10.1016/B978-0-08-102131-6.00008-6

47. Atmakuri A, Palevicius A, Vilkauskas A, Janusas G (2022) Numerical and Experimental Analysis of Mechanical Properties of Natural-Fiber-Reinforced Hybrid Polymer Composites and the Effect on Matrix Material. Polymers (Basel) 14:. https://doi.org/10.3390/polym14132612

48. Thwe MM, Liao K (2003) Durability of bamboo-glass fiber reinforced polymer matrix hybrid composites. Compos Sci Technol 63:375–387. https://doi.org/10.1016/S0266-3538(02)00225-7

49. Fu SY, Xu G, Mai YW (2002) On the elastic modulus of hybrid particle/short-fiber/polymer

composites. Compos Part BEngineering 33:291–299. https://doi.org/10.1016/S1359-8368(02)00013-6

50. Joshi S V., Drzal LT, Mohanty AK, Arora S (2004) Are natural fiber composites environmentally superior to glass fiber reinforced composites? Compos Part A Appl Sci Manuf 35:371–376. https://doi.org/10.1016/j.compositesa.2003.09.016

51. Assarar M, Zouari W, Sabhi H, et al (2015) Evaluation of the damping of hybrid carbon-flax reinforced composites. Compos Struct 132:148–154. https://doi.org/10.1016/j.compstruct.2015.05.016

52. Jawaid M, Abdul Khalil HPS (2011) Cellulosic/synthetic fibre reinforced polymer hybrid composites: A review. Carbohydr Polym 86:1–18. https://doi.org/10.1016/j.carbpol.2011.04.043

53. John MJ, Thomas S (2008) Biofibres and biocomposites. Carbohydr Polym 71:343–364. https://doi.org/10.1016/j.carbpol.2007.05.040

54. Venkateshwaran N, Elayaperumal A, Sathiya GK (2012) Prediction of tensile properties of hybrid-natural fiber composites. Compos Part B Eng 43:793–796. https://doi.org/10.1016/J.COMPOSITESB.2011.08.023

55. Panneerdhass R, Gnanavelbabu A, Rajkumar K (2014) Mechanical Properties of Luffa Fiber and Ground nut Reinforced Epoxy Polymer Hybrid Composites. Procedia Eng 97:2042–2051. https://doi.org/10.1016/j.proeng.2014.12.447

56. Yahaya R, Sapuan SM, Jawaid M, et al (2016) Water absorption behaviour and impact strength of Kenaf-Kevlar reinforced epoxy hybrid composites. Adv Compos Lett 25:98–102. https://doi.org/10.1177/096369351602500403

57. Vijay R, Lenin Singaravelu D (2018) Influence of stacking sequence on mechanical characteristics of Cyperus pangorei fibres based natural fibre composites. Mater Today Proc 5:8504–8513. https://doi.org/10.1016/j.matpr.2017.11.547

58. Daniel D Jafrey, G.SaiKrishnan, VelmuruganP. (2019) Investigation on the characteristics of bamboo/jute reinforced hybrid epoxy polymer composites. Mater Res Express. https://doi.org/https://doi.org/10.1088/2053-1591/ab3ae7

59. Biswas B, Hazra B, Sarkar A, et al (2019) In fl uence of ZrO 2 Incorporation on Sisal Fiber Reinforced Unsaturated Polyester Composites. https://doi.org/10.1002/pc.25087

60. Tejyan S (2022) Effect of erosive parameters on solid particle erosion of cotton fiber–based nonwoven mat/wooden dust reinforced hybrid polymer composites. J Ind Text 51:2514S-2532S. https://doi.org/10.1177/15280837211064241/ASSET/IMAGES/LARGE/10.1177_15280837211064241-FIG2.JPEG

61. Ravikumar P, Suresh AR, Rajeshkumar G (2022) An Investigation into the Tribological Properties of Bidirectional Jute/Carbon Fiber Reinforced Polyester Hybrid Composites. J Nat Fibers 19:943–953. https://doi.org/10.1080/15440478.2020.1764444

62. Palanisamy P, Chavali M, Kumar EM, Etika KC (2020) Hybrid nanocomposites and their potential applications in the field of nanosensors/gas and biosensors. Elsevier Inc.

63. Karthicksundar R, Rajendran B, Dinesh Kumar PK, Devaganesh S (2019) Thermal characterization of carbon nanoparticle infused GFRP using dynamic mechanical analyzer. Mater Res Express 6:0–6. https://doi.org/10.1088/2053-1591/ab374b

64. Wong WC, Teh PL, Osman AF, Yeoh CK (2017) The Properties of Epoxy / Graphene Conductive Materials Using High Speed Mechanical Stirrer and Bath Sonicator. 888:222–227. https://doi.org/10.4028/www.scientific.net/MSF.888.222

65. Asadi A, Pourfattah F, Miklós Szilágyi I, et al (2019) Effect of sonication characteristics on stability, thermophysical properties, and heat transfer of nanofluids: A comprehensive review. Ultrason Sonochem 58:. https://doi.org/10.1016/j.ultsonch.2019.104701

66. Vikash, Kumar V (2020) Ultrasonic-assisted de-agglomeration and power draw characterization of silica nanoparticles. Ultrason Sonochem 65:105061. https://doi.org/10.1016/j.ultsonch.2020.105061

67. Akpan EI, Shen X, Wetzel B, Friedrich K (2019) Design and Synthesis of Polymer Nanocomposites. Elsevier Inc.

68. Ramesh PK, Prasad BD, Narayana KL (2021) Influence of Montmorillonite Clay Content on Thermal, Mechanical, Water Absorption and Biodegradability Properties of Treated

Fiber/ PLA-Hybrid Biocomposites. Silicon 13:109–118. https://doi.org/10.1007/s12633-020-00401-9

69. Chee SS, Jawaid M, Alothman OY, Fouad H (2021) Effects of nanoclay on mechanical and dynamic mechanical properties of bamboo/kenaf reinforced epoxy hybrid composites. Polymers (Basel) 13:1–17. https://doi.org/10.3390/polym13030395

70. Raju P, Raja K, Lingadurai K, et al (2021) Mechanical, wear, and drop load impact behavior of glass/Caryota urens hybridized fiber-reinforced nanoclay/SiC toughened epoxy multihybrid composite. Polym Compos 42:1486–1496. https://doi.org/10.1002/pc.25918

71. Prajapati JK, Gupta MK (2019) Development of hybrid glass fibre / nano silica composite for sustainable product : mechanical , dynamic mechanical and optical properties Development of hybrid glass fi bre / nano silica composite for sustainable product : mechanical , dynamic mechanical. Mater Res Express

72. Mohammed RA (2018) Some Mechanical Properties of Polymer Matrix Composites Reinforced by Nano Silica Particles and Glass Fibers. Eng Technol J 36:. https://doi.org/10.30684/etj.36.12a.10

73. Mortazavi V, Atai M, Fathi M, et al (2012) The effect of nanoclay filler loading on the flexural strength of fiber-reinforced composites. Dent Res J (Isfahan) 9:273

74. Raghavendra G, Ojha S, Acharya SK, Pal SK (2015) Influence of micro/nanofiller alumina on the mechanical behavior of novel hybrid epoxy nanocomposites. High Perform Polym 27:342–351. https://doi.org/10.1177/0954008314550889

75. Naidu PP, Raghavendra G, Ojha S, Paplal B (2020) Effect of g-C3N4 nanofiller as filler on mechanical properties of multidirectional glass fiber epoxy hybrid composites. J Appl Polym Sci 137:1–9. https://doi.org/10.1002/app.48413

76. Tay CH, Mazlan N, Hameed Sultan MT, et al (2021) Mechanical performance of hybrid glass/kenaf epoxy composite filled with organomodified nanoclay. J Mater Res Technol 15:4415–4426. https://doi.org/10.1016/j.jmrt.2021.10.062

77. Sathishkumar TP, Rajeshkumar L, Rajeshkumar G, et al (2022) Improving the mechanical properties of jute fiber woven mat reinforced epoxy composites with addition of zinc oxide

filler. 02006:1–5

78. Gapsari F, Purnowidodo A, Setyarini PH, et al (2022) Properties of organic and inorganic filler hybridization on Timoho Fiber-reinforced polyester polymer composites. Polym Compos 43:1147–1156. https://doi.org/10.1002/PC.26443

79. Bouhfid N, Raji M, Boujmal R, et al (2018) Numerical modeling of hybrid composite materials

80. Ngo T-D (2018) Natural Fibers for Sustainable Bio-Composites. Nat Artif Fiber-Reinforced Compos as Renew Sources. https://doi.org/10.5772/intechopen.71012

81. Gujjala R, Ojha S, Acharya SK, Pal SK (2014) Mechanical properties of woven jute-glass hybrid-reinforced epoxy composite. J Compos Mater 48:3445–3455. https://doi.org/10.1177/0021998313501924

82. Sanjay MR, Madhu P, Jawaid M, et al (2018) Characterization and properties of natural fiber polymer composites: A comprehensive review. Elsevier B.V.

83. Ojha S, Raghavendra G, Acharya SK (2014) A Comparative Investigation of Bio Waste Filler (Wood Apple-Coconut) Reinforced Polymer Composites. https://doi.org/10.1002/pc

84. Fuqua MA, Huo S, Ulven CA (2016) Natural Fiber Reinforced Composites. 3724:. https://doi.org/10.1080/15583724.2012.705409

85. Ali A, Shaker K, Nawab Y, et al (2016) Hydrophobic treatment of natural fibers and their composites — A review. 0:1–31. https://doi.org/10.1177/1528083716654468

86. Dhakal HN, Zhang ZY, Richardson MOW (2007) Effect of water absorption on the mechanical properties of hemp fibre reinforced unsaturated polyester composites. Compos Sci Technol 67:1674–1683. https://doi.org/10.1016/j.compscitech.2006.06.019

87. Al-Maharma A, Al-Huniti N (2019) Critical Review of the Parameters Affecting the Effectiveness of Moisture Absorption Treatments Used for Natural Composites. J Compos Sci 3:27. https://doi.org/10.3390/jcs3010027

88. Azwa ZN, Yousif BF, Manalo AC, Karunasena W (2013) A review on the degradability of polymeric composites based on natural fibres. Mater Des 47:424–442.

https://doi.org/10.1016/j.matdes.2012.11.025

89. Sgriccia N, Hawley MC, Misra M (2008) Composites : Part A Characterization of natural fiber surfaces and natural fiber composites. 39:1632–1637. https://doi.org/10.1016/j.compositesa.2008.07.007

90. Alamri H, Low IM (2012) Mechanical properties and water absorption behaviour of recycled cellulose fibre reinforced epoxy composites. Polym Test 31:620–628. https://doi.org/10.1016/j.polymertesting.2012.04.002

91. Gupta MK, Srivastava RK (2016) Properties of sisal fibre reinforced epoxy composite. Indian J Fibre Text Res 41:235–241

92. Panchal M, Raghavendra G, Prakash MO, et al (2018) Moisture Absorption Behavior of Treated and Untreated Eggshell Particulate Epoxy Composites. Silicon 10:859–867. https://doi.org/10.1007/s12633-016-9541-6

93. Prakash MO, Raghavendra G, Panchal M, et al (2017) Effects of Environmental Exposure on Tribological Properties of Arhar Particulate / Epoxy Composites. Polym Compos 3102–3109. https://doi.org/10.1002/pc

94. Leman Z, Sapuan SM, Azwan M, et al (2008) The effect of environmental treatments on fiber surface properties and tensile strength of sugar palm fiber-reinforced epoxy composites. Polym - Plast Technol Eng 47:606–612. https://doi.org/10.1080/03602550802059451

95. Saharudin MS, Wei J, Shyha I, Inam F (2016) The Degradation of Mechanical Properties in Halloysite Nanoclay-Polyester Nanocomposites Exposed in Seawater Environment. J Nanomater 2016:. https://doi.org/10.1155/2016/2604631

96. Sood M, Dwivedi G (2018) Effect of fiber treatment on flexural properties of natural fiber reinforced composites: A review. Egypt J Pet 27:775–783. https://doi.org/10.1016/j.ejpe.2017.11.005

97. Masoodi R, Pillai KM (2012) A study on moisture absorption and swelling in bio-based jute-epoxy composites. J Reinf Plast Compos 31:285–294. https://doi.org/10.1177/0731684411434654

98. Boopalan M, Niranjanaa M, Umapathy MJ (2013) Study on the mechanical properties and thermal properties of jute and banana fiber reinforced epoxy hybrid composites. Compos Part B Eng 51:54–57. https://doi.org/10.1016/j.compositesb.2013.02.033

99. Venkateshwaran N, ElayaPerumal A, Alavudeen A, Thiruchitrambalam M (2011) Mechanical and water absorption behaviour of banana/sisal reinforced hybrid composites. Mater Des 32:4017–4021. https://doi.org/10.1016/j.matdes.2011.03.002

100. Maslinda AB, Majid MSA, Ridzuan MJM, et al (2017) Effect of water absorption on the mechanical properties of hybrid interwoven cellulosic-cellulosic fibre reinforced epoxy composites. Compos Struct 167:227–237. https://doi.org/10.1016/j.compstruct.2017.02.023

101. Venkateshwaran N, Elayaperumal A (2012) Mechanical and Water Absorption Properties of Woven Jute / Banana Hybrid Composites. 13:907–914. https://doi.org/10.1007/s12221-012-0907-0

102. Saw SK, Sarkhel G, Choudhury A (2012) Preparation and Characterization of Chemically Modified Jute – Coir Hybrid Fiber Reinforced Epoxy Novolac Composites. https://doi.org/10.1002/app

103. S.Sathish K.Kumaresan, L.Prabhu N.Vigneshkumar (2017) Experimental Investigation on Volume Fraction of Mechanical and Physical Properties of Flax and Bamboo Fibers Reinforced Hybrid Epoxy Composites. 25:229–236. https://doi.org/10.1177/096739111702500309

104. Shahzad A (2018) Investigation into fatigue strength of natural/synthetic fiber-based composite materials. Elsevier Ltd

105. Rubino F, Nisticò A, Tucci F, Carlone P (2020) Marine Application of Fiber Reinforced Composites: A Review. J Mar Sci Eng 8:26. https://doi.org/10.3390/jmse8010026

106. Thyavihalli Girijappa YG, Mavinkere Rangappa S, Parameswaranpillai J, Siengchin S (2019) Natural Fibers as Sustainable and Renewable Resource for Development of Eco-Friendly Composites: A Comprehensive Review. Front Mater 6:1–14. https://doi.org/10.3389/fmats.2019.00226

107. Shahinur S, Hasan M (2020) Natural Fiber and Synthetic Fiber Composites: Comparison of Properties, Performance, Cost and Environmental Benefits. Elsevier Ltd.

108. Sapuan SM (2017) Materials Selection for Composites: Concurrent Engineering Perspective

109. Varghese AM, Mittal V (2017) Polymer composites with functionalized natural fibers. Elsevier Ltd

110. J. Shesan O, C. Stephen A, G. Chioma A, et al (2019) Fiber-Matrix Relationship for Composites Preparation. Renew Sustain Compos 13–15. https://doi.org/10.5772/intechopen.84753

111. Song B, Wang T, Wang L, et al (2019) Interfacially reinforced carbon fiber/epoxy composite laminates via in-situ synthesized graphitic carbon nitride (g-C3N4). Compos Part B Eng 158:259–268. https://doi.org/10.1016/j.compositesb.2018.09.081

112. Bhattacharyya D, Subasinghe A, Kim NK (2015) Natural fibers: Their composites and flammability characterizations. Multifunct Polym Compos Challenges New Solut 102–143. https://doi.org/10.1016/B978-0-323-26434-1.00004-0

113. Jarukumjorn K, Suppakarn N (2009) Effect of glass fiber hybridization on properties of sisal fiber-polypropylene composites. Compos Part B Eng 40:623–627. https://doi.org/10.1016/j.compositesb.2009.04.007

114. Arthanarieswaran VP, Kumaravel A, Kathirselvam M (2014) Evaluation of mechanical properties of banana and sisal fiber reinforced epoxy composites: Influence of glass fiber hybridization. Mater Des 64:194–202. https://doi.org/10.1016/j.matdes.2014.07.058

115. Zweben CH (2005) Composites: Overview. Encycl Condens Matter Phys 192–208. https://doi.org/10.1016/B0-12-369401-9/00545-3

116. Chawla KK (2016) Glass Fibers. Ref Modul Mater Sci Mater Eng. https://doi.org/10.1016/B978-0-12-803581-8.02325-0

117. Shrivastava A (2018) Additives for Plastics. Introd to Plast Eng 111–141. https://doi.org/10.1016/B978-0-323-39500-7.00004-6

118. Ramesh M, Palanikumar K, Reddy KH (2013) Mechanical property evaluation of sisal–jute–glass fiber reinforced polyester composites. Compos Part B Eng 48:1–9. https://doi.org/10.1016/J.COMPOSITESB.2012.12.004

119. Dalbehera S, Acharya SK (2016) Effect of cenosphere addition on the mechanical properties of jute-glass fiber hybrid epoxy composites. J Ind Text 46:177–188. https://doi.org/10.1177/1528083715577936

120. Alavudeen A, Rajini N, Karthikeyan S, et al (2015) Mechanical properties of banana/kenaf fiber-reinforced hybrid polyester composites: Effect of woven fabric and random orientation. Mater Des 66:246–257. https://doi.org/10.1016/j.matdes.2014.10.067

121. Ojha S, Acharya SK, Raghavendra G (2014) Mechanical properties of natural carbon black reinforced polymer composites. J Appl Polym Sci 132:1–7. https://doi.org/10.1002/app.41211

122. Negi AS, Katiyar JK, Kumar S, et al (2019) Physicomechanical and abrasive wear properties of hemp/Kevlar/carbon reinforced hybrid epoxy composites. Mater Res Express 6:. https://doi.org/10.1088/2053-1591/ab438d

123. Salman, S. D., Leman, Z., Sultan, M. T. H., Ishak, M. R. and C (2015) Kenaf/Synthetic and Kevlar®/Cellulosic Fiber-Reinforced Hybrid Composites: A Review. BioResources 10:8580–8603

124. Rothon R (2017) Fillers for Polymer Applications. Springer 489. https://doi.org/10.1007/978-3-319-28117-9

125. Wetzel B, Haupert F, Zhang MQ (2003) Epoxy nanocomposites with high mechanical and tribological performance. Compos Sci Technol 63:2055–2067. https://doi.org/10.1016/S0266-3538(03)00115-5

126. Cho J, Joshi MS, Sun CT (2006) Effect of inclusion size on mechanical properties of polymeric composites with micro and nano particles. Compos Sci Technol 66:1941–1952. https://doi.org/10.1016/j.compscitech.2005.12.028

127. Rodgers RM, Mahfuz H, Rangari VK, et al (2005) Infusion of SiC nanoparticles into SC-15 epoxy: An investigation of thermal and mechanical response. Macromol Mater Eng

290:423–429. https://doi.org/10.1002/mame.200400202

128. Xu LR, Bhamidipati V, Zhong WH, et al (2004) Mechanical property characterization of a polymeric nanocomposite reinforced by graphitic nanofibers with reactive linkers. J Compos Mater 38:1563–1582. https://doi.org/10.1177/0021998304043758

129. Richard D. West VMM (2006) Rupture of Nanoparticle Agglomerates and Formulation of Al2O3-Epoxy Nanocomposites Using Ultrasonic Cavitation Approach: Effects on the Structural and Mechanical Properties Richard. Polym Eng Sci 426–430. https://doi.org/10.1002/pen

130. Yasmin A, Luo JJ, Daniel IM (2006) Processing of expanded graphite reinforced polymer nanocomposites. Compos Sci Technol 66:1182–1189. https://doi.org/10.1016/j.compscitech.2005.10.014

131. Sandler J, Shaffer MSP, Prasse T, et al (1999) Development of a dispersion process for carbon nanotubes in an epoxy matrix and the resulting electrical properties. Polymer (Guildf) 40:5967–5971. https://doi.org/10.1016/S0032-3861(99)00166-4

132. Shakuntala O, Raghavendra G, Samir Kumar A (2014) Effect of filler loading on mechanical and tribological properties of wood apple shell reinforced epoxy composite. Adv Mater Sci Eng. https://doi.org/10.1155/2014/538651

133. Chee SS, Jawaid M, Alothman OY, Fouad H (2021) Effects of Nanoclay on Mechanical and Dynamic Mechanical Properties of Bamboo/Kenaf Reinforced Epoxy Hybrid Composites. Polym 2021, Vol 13, Page 395 13:395. https://doi.org/10.3390/POLYM13030395

134. Karnati SR, Agbo P, Zhang L (2020) Applications of silica nanoparticles in glass/carbon fiber-reinforced epoxy nanocomposite. Compos Commun 17:32–41. https://doi.org/10.1016/j.coco.2019.11.003

135. Nazari A, Riahi S (2011) The effects of SiO2 nanoparticles on physical and mechanical properties of high strength compacting concrete. Compos Part B Eng 42:570–578. https://doi.org/10.1016/j.compositesb.2010.09.025

136. Rahman IA, Padavettan V (2012) Synthesis of Silica nanoparticles by Sol-Gel: Size-

dependent properties, surface modification, and applications in silica-polymer nanocompositesa review. J Nanomater 2012:. https://doi.org/10.1155/2012/132424

137. Ary Subagia IDG, Kim Y, Tijing LD, et al (2014) Effect of stacking sequence on the flexural properties of hybrid composites reinforced with carbon and basalt fibers. Compos Part B Eng 58:251–258. https://doi.org/10.1016/j.compositesb.2013.10.027

138. Shu-Xue Zhou, Li-Min Wu, Jian Sun W-DS (2003) Effect of Nanosilica on the Properties of Polyester-Based Polyurethane. J Appl Polym Sci 8:189–193

139. Alsaadi M, Bulut M, Erkliğ A, Jabbar A (2018) Nano-silica inclusion effects on mechanical and dynamic behavior of fiber reinforced carbon/Kevlar with epoxy resin hybrid composites. Compos Part B Eng 152:169–179. https://doi.org/10.1016/j.compositesb.2018.07.015

140. Madhukar P, Selvaraj N, Gujjala R, Rao CSP (2019) Production of high performance AA7150-1% SiC nanocomposite by novel fabrication process of ultrasonication assisted stir casting. Ultrason Sonochem 58:104665. https://doi.org/10.1016/j.ultsonch.2019.104665

141. Ramakrishnan S, Krishnamurthy K, Rajasekar R, Rajeshkumar G (2019) An experimental study on the effect of nano-clay addition on mechanical and water absorption behaviour of jute fibre reinforced epoxy composites. J Ind Text 49:597–620. https://doi.org/10.1177/1528083718792915

142. Alamri H, Low IM (2012) Effect of water absorption on the mechanical properties of nano-filler reinforced epoxy nanocomposites. Mater Des 42:214–222. https://doi.org/10.1016/J.MATDES.2012.05.060

143. Arifin Z, Ishak M (2013) Effect of Clay Addition on Mechanical Properties of Unsaturated Polyester / Glass Fiber Composites. Int J Polym Sci 2013:10–17. https://doi.org/https://doi.org/10.1155/2013/797109

144. Khan NI, Halder S, Das S, Wang J (2019) Exfoliation level of aggregated graphitic nanoplatelets by oxidation followed by silanization on controlling mechanical and nanomechanical performance of hybrid CFRP composites. Compos Part B Eng 173:106855.

https://doi.org/10.1016/j.compositesb.2019.05.066

145. Manickam S, Kannan TK, Simon BL, et al (2021) Influence of nanoclay on the technical properties of glass-abaca hybrid epoxy composite. Polimeros 30:1–7. https://doi.org/10.1590/0104-1428.08520

146. Shettar M, Kowshik CSS, Manjunath M, Hiremath P (2020) Experimental investigation on mechanical and wear properties of nanoclay–epoxy composites. J Mater Res Technol 9:9108–9116. https://doi.org/10.1016/J.JMRT.2020.06.058

147. Xu HHK (2016) Whisker-reinforced Heat-cured Dental Resin Composites: Effects of Filler Level and Heat-cure Temperature and Time: J Dent Res 79:1392–1397. https://doi.org/10.1177/00220345000790060701

148. Mortazavi V, Atai M, Fathi M, et al (2012) The effect of nanoclay filler loading on the flexural strength of fiber-reinforced composites. Dent Res J (Isfahan) 9:273

149. Shettar M, Kowshik CSS, Manjunath M, Hiremath P (2020) Experimental investigation on mechanical and wear properties of nanoclay-epoxy composites. J Mater Res Technol 9:9108–9116. https://doi.org/10.1016/j.jmrt.2020.06.058

150. Kini UA, Shettar M, Sharma S, et al (2018) Investigation on effect of cold soaking on the properties of nanoclay-GFRP composite. Mater Res Express 6:015206. https://doi.org/10.1088/2053-1591/aae967

151. Khan NI, Halder S, Wang J (2019) Diels-Alder based epoxy matrix and interfacial healing of bismaleimide grafted GNP infused hybrid nanocomposites. Polym Test 74:138–151. https://doi.org/10.1016/j.polymertesting.2018.12.021

152. Rafiq A, Merah N (2019) Nanoclay enhancement of flexural properties and water uptake resistance of glass fiber-reinforced epoxy composites at different temperatures. J Compos Mater 53:143–154. https://doi.org/10.1177/0021998318781220

153. Yasmin A, Luo JJ, Abot JL, Daniel IM (2006) Mechanical and thermal behavior of clay/epoxy nanocomposites. Compos Sci Technol 66:2415–2422. https://doi.org/10.1016/j.compscitech.2006.03.011

154. Puttegowda M, Ahmed S, Al AA, et al (2020) Preparation and characterization of new hybrid polymer composites from Phoenix pusilla fibers / E-glass / carbon fabrics on potential engineering applications : Effect of stacking sequence. 1–11. https://doi.org/10.1002/pc.25734

155. Kaundal R, Patnaik A, Satapathy A (2012) Solid Particle Erosion of Short Glass Fiber Reinforced Polyester Composite. Am J Mater Sci 2:22–27. https://doi.org/10.5923/j.materials.20120202.05

156. Nacher LS, Amoros JEC, Moya MDS, Martinez JL (2007) Mechanical properties of polyester resins in saline water environments. Int J Polym Anal Charact 12:373–390. https://doi.org/10.1080/10236660701516557

157. Akil HM, Cheng LW, Mohd Ishak ZA, et al (2009) Water absorption study on pultruded jute fibre reinforced unsaturated polyester composites. Compos Sci Technol 69:1942–1948. https://doi.org/10.1016/j.compscitech.2009.04.014

158. Sindhu K, Joseph K, Joseph JM, Mathew T V. (2007) Degradation studies of coir fiber/polyester and glass fiber/polyester composites under different conditions. J Reinf Plast Compos 26:1571–1585. https://doi.org/10.1177/0731684407079665

159. Zamri MH, Akil HM, Bakar AA, et al (2012) Effect of water absorption on pultruded jute/glass fiber-reinforced unsaturated polyester hybrid composites. J Compos Mater 46:51–61. https://doi.org/10.1177/0021998311410488

160. Moudood A, Rahman A, Ochsner A, et al (2018) Flax fiber and its composites : An overview of water and moisture absorption impact on their performance. https://doi.org/10.1177/0731684418818893

161. Colin X, Verdu J (2014) Humid ageing of organic matrix composites. Springer

162. Anu Gupta (2014) Synthesis, Chemical Resistance, and Water Absorption of Bamboo Fiber Reinforced Epoxy Composites. Polym Compos. https://doi.org/10.1002/pc.23164

163. Huner U (2015) Effect of Water Absorption on the Mechanical Properties \of Flax Fiber Reinforced Epoxy Composites. Adv Sci Technol Res J 9:1–6. https://doi.org/10.12913/22998624/2357

164. Das G, Biswas S (2016) Effect of fiber parameters on physical, mechanical and water absorption behaviour of coir fiber-epoxy composites. J Reinf Plast Compos 35:628–637. https://doi.org/10.1177/0731684415626594

165. Devadas A, Nirmal U, Hossen J, Mcnally T (2018) Investigation into mechanical & tribological performance of kenaf fibre particle reinforced composite. Cogent Eng 5:1–23. https://doi.org/10.1080/23311916.2018.1479210

166. Gassan J, Bledzki AK (1999) Effect of cyclic moisture absorption desorption on the mechanical properties of silanized jute-epoxy composites. Polym Compos 20:604–611. https://doi.org/10.1002/pc.10383

167. Yan L, Chouw N (2015) Effect of water , seawater and alkaline solution ageing on mechanical properties of flax fabric / epoxy composites used for civil engineering applications. Constr Build Mater 99:118–127. https://doi.org/10.1016/j.conbuildmat.2015.09.025

168. Boggarapu V, Gujjala R, Ojha S (2020) A critical review on erosion wear characteristics of polymer matrix composites. Mater Res Express 7:. https://doi.org/10.1088/2053-1591/ab6e7b

169. Milosevic M, Valášek P, Ruggiero A (2020) Tribology of Natural Fibers Composite Materials: An Overview. Lubricants 8:42. https://doi.org/10.3390/lubricants8040042

170. Nusrat Z, Srivastava A (2019) Study on tribology of natural fiber reinforced polymer composites : A review. 4–10

171. Sumithra H, Sidda Reddy B (2018) A review on tribological behaviour of natural reinforced composites. J Reinf Plast Compos 37:349–353. https://doi.org/10.1177/0731684417747742

172. Prakash MO, Raghavendra G, Ojha S, et al (2021) Investigation of tribological properties of biomass developed porous nano activated carbon composites. Wear 466–467:203523. https://doi.org/10.1016/J.WEAR.2020.203523

173. Zhang SW (1998) State-of-the-art of polymer tribology. Tribol Int 31:49–60. https://doi.org/10.1016/S0301-679X(98)00007-3

174. Sundström A, Rendón J, Olsson M (2001) Wear behaviour of some low alloyed steels under combined impact/abrasion contact conditions. Wear 250:744–754. https://doi.org/10.1016/S0043-1648(01)00712-8

175. Bagci M (2016) Influence of fiber orientation on solid particle erosion of uni/multidirectional carbon fiber/glass fiber reinforced epoxy composites. http://dx.doi.org/101177/1350650116666739 231:594–603. https://doi.org/10.1177/1350650116666739

176. Harsha AP, Tewari US, Venkatraman B (2003) Solid particle erosion behaviour of various polyaryletherketone composites. Wear 254:693–712. https://doi.org/10.1016/S0043-1648(03)00143-1

177. Padmaraj NH, Vijaya KM, Dayananda P (2019) Experimental investigation on solid particle erosion behaviour of glass/epoxy Quasi-isotropic laminates. Mater Res Express 6:085339. https://doi.org/10.1088/2053-1591/AB2326

178. Pratap Naidu P, Raghavendra G, Ojha S (2019) Comparison of Erosion Wear of Bidirectional and Multidirectional Oriented Glass Fibre Epoxy Composites. Mater Sci Forum 969:157–162. https://doi.org/10.4028/WWW.SCIENTIFIC.NET/MSF.969.157

179. Khare JM, Dahiya S, Gangil B, et al (2021) Comparative Analysis of Erosive Wear Behaviour of Epoxy, Polyester and Vinyl Esters Based Thermosetting Polymer Composites for Human Prosthetic Applications Using Taguchi Design. Polym 2021, Vol 13, Page 3607 13:3607. https://doi.org/10.3390/POLYM13203607

180. Mahapatra SS, Patnaik A (2009) Study on mechanical and erosion wear behavior of hybrid composites using Taguchi experimental design. Mater Des 30:2791–2801. https://doi.org/10.1016/J.MATDES.2009.01.037

181. Rajkumar K, Nambiraj KM, Ramraji K, Khan BSH (2022) Influence of silicon filler size and concentration on thermal stability and erosion wear resistance of polymer composite. Silicon 2022 1–14. https://doi.org/10.1007/S12633-022-01711-W

182. Tewari US, Harsha AP, Häger AM, Friedrich K (2003) Solid particle erosion of carbon fibre– and glass fibre–epoxy composites. Compos Sci Technol 63:549–557.

https://doi.org/10.1016/S0266-3538(02)00210-5

183. Vigneshwaran S, Uthayakumar M, Arumugaprabu V (2019) Solid particle erosion study on redmud - an industrial waste reinforced sisal/polyester hybrid composite. Mater Res Express 6:065307. https://doi.org/10.1088/2053-1591/AB0A44

184. Kaundal R (2018) Utilization of Flyash as Filler Material in Hybrid Polyester Composites for Improved Thermo-Mechanical and Erosion Wear Behavior. Silicon 10:2439–2452. https://doi.org/10.1007/S12633-018-9776-5

185. Pun AK, Siddhartha, Singh AK (2018) Thermo-mechanical and Erosion Wear Peculiarity of Hybrid Composites Filled with Micro and Nano Silicon Dioxide Fillers – A Comparative Study. Silicon 2018 114 11:1885–1901. https://doi.org/10.1007/S12633-018-0007-X

186. Kuruvilla SP, Renukappa NM, Sundara Rajan J (2019) Development of epoxy with nano and micro fillers for core insulation of composite insulators. Proc 2019 Int Conf High Volt Eng Technol ICHVET 2019 14:. https://doi.org/10.1109/ICHVET.2019.8724139

187. Manoj Panchal,G. Raghavendra, M. Om Prakash SO (2017) Effects of Environmental Conditions on Erosion Wear of Eggshell Particulate Epoxy Composites. Silicon 10:627–634. https://doi.org/10.1007/s12633-016-9505-x

188. Somaiah Chowdary M., Raghavendra G., Niranjan Kumar M.S.R., et al. (2020) A review on the degradation of properties under the influence of liquid medium of hybrid polymer composites. SN Appl Sci. https://doi.org/10.1007/s42452-020-03502-7

189. Fan X (2008) Mechanics of moisture for polymers: Fundamental concepts and model study. EuroSimE 2008 - Int Conf Therm Mech Multi-Physics Simul Exp Microelectron Micro-Systems 1–14. https://doi.org/10.1109/ESIME.2008.4525043

190. Panchal M, Raghavendra G, Reddy AR (2020) Experimental investigation of mechanical and erosion behavior of eggshell nanoparticulate epoxy biocomposite. Polym Polym Compos 29:1–12. https://doi.org/10.1177/0967391120943454

191. Tejyan S (2022) Effect of erosive parameters on solid particle erosion of cotton fiber–based nonwoven mat/wooden dust reinforced hybrid polymer composites. J Ind Text 51:2514S-2532S. https://doi.org/10.1177/15280837211064241

192. Alhuthali A, Low IM, Dong C (2012) Characterisation of the water absorption, mechanical and thermal properties of recycled cellulose fibre reinforced vinyl-ester eco-nanocomposites. Compos Part B Eng 43:2772–2781. https://doi.org/10.1016/j.compositesb.2012.04.038

193. Prakash MO, Raghavendra G, Panchal M, et al (2018) Influence of Distinct Environment on the Mechanical Characteristics of Arhar Fiber Polymer Composites. Silicon 10:825–830. https://doi.org/10.1007/s12633-016-9536-3

194. Najafi M, Darvizeh A, Ansari R (2018) Effect of Nanoclay Addition on the Hygrothermal Durability of Glass/Epoxy and Fiber Metal Laminates. Fibers Polym 19:1956–1969. https://doi.org/10.1007/s12221-018-8235-7

195. Megahed AAEW, Megahed M (2017) Fabrication and characterization of functionally graded nanoclay/glass fiber/epoxy hybrid nanocomposite laminates. Iran Polym J (English Ed 26:673–680. https://doi.org/10.1007/s13726-017-0552-y

196. Rull N, Ollier RP, Francucci G, et al (2015) Effect of the addition of nanoclays on the water absorption and mechanical properties of glass fiber/up resin composites. J Compos Mater 49:1629–1637. https://doi.org/10.1177/0021998314538869

197. Alamri H, Low IM (2013) Effect of water absorption on the mechanical properties of nanoclay filled recycled cellulose fibre reinforced epoxy hybrid nanocomposites. Compos Part A Appl Sci Manuf 44:23–31. https://doi.org/10.1016/j.compositesa.2012.08.026

198. Chee SS, Jawaid M, Sultan MTH, et al (2020) Effects of nanoclay on physical and dimensional stability of Bamboo/Kenaf/nanoclay reinforced epoxy hybrid nanocomposites. J Mater Res Technol 9:5871–5880. https://doi.org/10.1016/j.jmrt.2020.03.114

199. Nemati Giv A, Rastegar S, Özcan M (2020) Influence of nanoclays on water uptake and flexural strength of glass–polyester composites. J Appl Biomater Funct Mater 18:. https://doi.org/10.1177/2280800020930180

200. Samariha A, Hemmasi AH, Ghasemi I (2015) EFFECT OF NANOCLAY CONTENTS ON PROPERTIES , OF BAGASSE FLOUR / REPROCESSED HIGH DENSITY POLYETHYLENE / NANOCLAY COMPOSITES. 17:637–646.

https://doi.org/10.4067/S0718-221X2015005000056

201. Ojha S, Pranay V, Raghavendra G, Gara D (2021) Experimental evaluation and comparison of silica/biocarbon particulate-epoxy composites for high-strength applications: https://doi.org/101177/14644207211043506 236:190–199. https://doi.org/10.1177/14644207211043506

202. Mohan TP, Kanny K (2011) Water barrier properties of nanoclay filled sisal fibre reinforced epoxy composites. Compos Part A Appl Sci Manuf 42:385–393. https://doi.org/10.1016/j.compositesa.2010.12.010

203. Kim HJ, Seo DW (2006) Effect of water absorption fatigue on mechanical properties of sisal textile-reinforced composites. Int J Fatigue 28:1307–1314. https://doi.org/10.1016/j.ijfatigue.2006.02.018

204. Chauhan SR, Kumar A, Singh I (2010) Sliding friction and wear behaviour of vinylester and its composites under dry and water lubricated sliding conditions. Mater Des 31:2745–2751. https://doi.org/10.1016/J.MATDES.2010.01.020

205. Pradhan S, Acharya SK (2020) Solid particle erosive wear behaviour of Eulaliopsis binata fiber reinforced epoxy composite. https://doi.org/101177/1350650120931645 235:830–841. https://doi.org/10.1177/1350650120931645

206. Prakash MO, Raghavendra G, Ojha S, et al (2021) Investigation of tribological properties of biomass developed porous nano activated carbon composites. Wear 466–467:203523. https://doi.org/10.1016/j.wear.2020.203523

207. Papadopoulos A, Gkikas G, Paipetis AS, Barkoula NM (2016) Effect of CNTs addition on the erosive wear response of epoxy resin and carbon fibre composites. Compos Part A Appl Sci Manuf 84:299–307. https://doi.org/10.1016/J.COMPOSITESA.2016.02.012

208. Babu BG, Karthikeyan PN, Siva K, Sabarinathan C (2016) Study of erosion characteristics of MWCNT’s-alumina hybrid epoxy nanocomposites under the influence of solid particles. Dig J Nanomater Biostructures 11:1367–1373

209. Abenojar J, Tutor J, Ballesteros Y, et al (2017) Erosion-wear, mechanical and thermal properties of silica filled epoxy nanocomposites. Compos Part B Eng 120:42–53.

https://doi.org/10.1016/J.COMPOSITESB.2017.03.047

210. Wellman RG, Nicholls JR (2007) A review of the erosion of thermal barrier coatings. J Phys D Appl Phys 40:R293. https://doi.org/10.1088/0022-3727/40/16/R01

211. Acharya SK, Dikshit V, Mishra P (2007) Erosive Wear Behaviour of Redmud Filled Metal Matrix Composite. J Reinf Plast Compos 27:145–152. https://doi.org/10.1177/0731684407082543

212. Srinath G, Gnanamoorthy R (2007) Sliding wear performance of polyamide 6–clay nanocomposites in water. Compos Sci Technol 67:399–405. https://doi.org/10.1016/J.COMPSCITECH.2006.09.004

213. Mohammed AS, Bin Ali A (2016) Investigating the Effect of Water Uptake on the Tribological Properties of Organoclay Reinforced UHMWPE Nanocomposites. Tribol Lett 2016 621 62:1–9. https://doi.org/10.1007/S11249-016-0652-4

214. Om Prakash M, Raghavendra G, Panchal M, et al (2018) Effects of environmental exposure on tribological properties of Arhar particulate/epoxy composites. Polym Compos 39:3102–3109. https://doi.org/10.1002/PC.24316

215. Jia JH, Zhou HD, Gao SQ, Chen JM (2003) A comparative investigation of the friction and wear behavior of polyimide composites under dry sliding and water-lubricated condition. Mater Sci Eng A 356:48–53. https://doi.org/10.1016/S0921-5093(03)00052-2

PUBLICATIONS

JOURNALS

1. **M. Somaiah Chowdary**, Raghavendra, G., Niranjan Kumar, M. S. R., et al. Evaluation of mechanical and tribological properties of nano clay reinforced Kevlar/Sisal polyester composites. *Polymer Composites*, 43(12), 8860 (2022) . https://doi.org/10.1002/pc.27067
2. **M. Somaiah Chowdary**, Raghavendra, G., Niranjan Kumar, M. S. R., et al. A comparison of the effect of nano clay addition on microstructures and mechanical properties of epoxy and polyester reinforced glass/sisal hybrid polymer composite. *Polymer Composites*, 43(6), 3871 (2022) . https://doi.org/10.1002/pc.26662
3. **M. Somaiah Chowdary**, Raghavendra, G., Niranjan Kumar, M.S.R., et al. Influence of Nano-Silica on Enhancing the Mechanical Properties of Sisal/Kevlar Fiber Reinforced Polyester Hybrid Composites. *Silicon*, 14,539–546(2020). https://doi.org/10.1007/s12633-020-00846-y.
4. **M. Somaiah Chowdary**, Raghavendra, G., Niranjan Kumar, M.S.R. et al. A review on the degradation of properties under the influence of liquid medium of hybrid polymer composites. *SN Applied Sciences*, 2, 1708 (2020). https://doi.org/10.1007/s42452-020-03502-7.
5. **M. Somaiah Chowdary**, Raghavendra, G., Niranjan Kumar, M.S.R. et al. A study on the effect of Nano clay addition on the erosion wear characteristics of S-Glass/Sisal reinforced hybrid polymer composites (Polymer Composites-UNDER REVIEW)
6. **M. Somaiah Chowdary**, Raghavendra, G., Niranjan Kumar, M.S.R. et al. Effect of different environments on mechanical properties of Nano clay reinforced Hybrid Polymer Composites (Sage part E- UNDER REVIEW)

INTERNATIONAL CONFERENCES

1. **M. Somaiah Chowdary**,**G. Raghavendra, M.S.R.NiranjanKumar**,Shakuntala Ojha,M.Anupama Ammulu, V.Suresh, P. Phani Prasanthi , "Study of the Mechanical Properties of Nano clay reinforced Kevlar/Sisal hybrid composites" (Presented at IPDIMS Conference 2022, NIT Rourkela Accepted in Material today proceedings; SCOPUS).

2. **M. Somaiah Chowdary**, **G. Raghavendra,M.S.R.NiranjanKumar ,.** A Comparison of properties on the behaviour of Nano clay reinforced Polyester/Glass-Sisal hybrid polymer composites (Communicated)

BOOK CHAPTERS

1. **M.Somaiah Chowdar**., Raghavendra, G., Ojha, S., Kumar, M.S.R.N. (2022). Water Sorption and Solvent Sorption of Epoxy/Natural Fiber Composites. In: Mavinkere Rangappa, S., Parameswaranpillai, J., Siengchin, S., Thomas, S. (eds) Handbook of Epoxy/Fiber Composites. Springer, Singapore. https://doi.org/10.1007/978-981-15-8141-0_28-1.

2. **M. Somaiah Chowdary,** G Raghavendra, M. Anupama Ammulu, M S R Niranjan Kumar et al .(2023) In Jyotishkumar Parameswaranpillai**,** Poushali Das, Sayan Ganguly, Murthy Chavali, Nishar Hameed(eds) Polymer-Carbonaceous Filler Based Composites for Wastewater Treatment, Taylor and Francis Group, CRC press.(Accepted)

3. **M.Somaiah Chowdary**, G Raghavendra,M S R Niranjan Kumar, M Anupama Ammulu, V Suresh babu (2023). Hybrid composites: A promising approach for potential polymeric composite design In .S.Indran. D.Divya , Sanjay M. R, Prof. Ing. habil. Suchart Siengchin (eds) Sustainable Fillers and Plasticizers for Polymer Composites: Recent developments, Woodhead publishing series in Composites Science and Engineering, Elsevier. (Under Review).

OTHER PUBLICATIONS

PUBLICATIONS AS CO-AUTHOR

1. Boggarapu, V., Gujjala, R., Ojha, S., Acharya, S., Venkateswara babu, P., **Chowdary, S**., & kumar Gara, D. (2021). “State of the art in functionally graded materials. Composite Structures”, 262, 113596. doi:10.1016/j.compstruct.2021.113596.
2. Minugu OP, Gujjala R, Shakuntala O, Manoj P, **Chowdary MS**.” Effect of biomass derived biochar materials on mechanical properties of biochar epoxy composites”. Proceedings of the Institution of Mechanical Engineers, Part C: Journal of

Mechanical Engineering Science. 2021;235(21):5626-5638. doi:10.1177/0954406221990705.

3. Panchal, M., Minugu, O. P., Gujjala, R., Ojha, S., Mallampati Chowdary, S., Mohammad, “A Study of environmental behavior and its effect on solid particle erosion behavior of hierarchical porous activated carbon-epoxy composite” Polymer Composites. 2022, 43 (4), 2276. https://doi.org/10.1002/pc.26539.
4. Boggarapu V, RamaSreekanth P, Peddakondigalla VB, **M Somaiah Chowdary** et al. “A novel approach to develop and characterize bi-directional aluminum-copper functionally graded material”. Proceedings of the Institution of Mechanical Engineers, Part E: Journal of Process Mechanical Engineering. (2023). doi:10.1177/09544089231163746.
5. P Phani Prasanthi, M S R Niranjan Kumar1, **M Somaiah Chowdary**, et al. “Mechanical properties of carbon fiber reinforced with carbon nanotubes and graphene filled epoxy composites: experimental and numerical investigations” Material Research express (2023), 10, 10.1088/2053-1591/acaef5.