

Composite materials based on high-performance polymer for high-tech applications

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Abstract: Composite materials have been used since ancient civilizations when chopped straw was added to brick to form building materials. In the present era, the development of polymer composites has attracted a lot of attention from researchers because of their significantly improved properties as compared to intrinsic polymers or conventional composites. A polymer composite is a lightweight multiphase material developed by combining two or more dissimilar materials. They are combined in such a way that the resulting composite material possesses excellent superior properties (thermal, mechanical, and morphological) which are not achieved with a single constituent's materials. These composite materials are supposed to replace the use of metals like iron, steel, copper, etc from various areas of society. Composite materials can be broadly classified into two categories natural and synthetic composite materials. Various advanced analytical techniques, including UTM, TGA, DSC, DMA, SEM, FTIR, and others, will be used to characterize the developed composites for their mechanical, thermal, structural, and morphological properties. In comparison to pure PEI, a significant enhancement was obtained at 2 wt% loading of HNTs in the PEI matrix, with about 8% enhancement in tensile stress, 4% modulus, 40% impact energy, and 43% izod impact strength. Thermo-gravimetric analysis (TGA) results of created composites demonstrate a 20°C increase in thermal stability with the addition of 2 wt% HNTs in the PEI matrix. Many outstanding properties of composites are achieved with the incorporation of nanofiller, so polymer composites and nanocomposites are used in many advanced applications such as aerospace, defense, drug delivery, computer field, solar cell, antistatic paint, railways, manufacturing industries, automotive, and wind energy, among others.

Keywords: Composites, Processing techniques, Testing, Applications.

1. Introduction

Polymer composites are high-tech materials composed of two or more distinct components: one is polymer matrix and the other is reinforcing elements such as fibers, particles, or fillers. These materials are mixed to form a synergistic blend of qualities that outperform the constituents individually [1]. A composite polymer matrix acts as the primary binder, binding the reinforcing components together and providing shape and structure. Polymers are chosen for their flexibility because they can be adapted to specific applications and are lightweight and corrosion-resistant in general. Thermosetting resins (e.g., epoxy, polyester) and thermoplastic polymers (e.g., polypropylene, polyethylene) are examples of common polymer matrices. Reinforcing materials play an important role in improving the mechanical, thermal, and electrical properties of a composite. Strength and stiffness are usually provided by fibers such as carbon, glass, or aramid, while particles or fillers can increase properties such as impact resistance, thermal conductivity, and flame resistance [2], [3].

Polymer composites can be found in a variety of industries, including aerospace, automotive, microelectronics, construction, and sporting goods because they combine desirable properties such as high strength-to-weight ratios, corrosion resistance, and design flexibility [4]. Researchers can produce

polymer composites to fulfill specific performance needs by carefully selecting the polymer matrix and reinforcing elements, making them an invaluable and flexible class of materials.

1.1 Historical development

Polymer composites' evolution over time illustrates a continual need to develop materials that provide superior performance and versatility in a wide range of industries, from ancient ceramics to innovative aerospace technology. This evolution is characterized by a constant search for lighter, stronger, and more sustainable materials, ensuring that polymer composites will continue to play an important role in modern engineering and production [5]–[7].

- **Ancient Composites:** The concept of incorporating materials to improve their properties has ancient roots. Natural fibers, such as straw, were employed by early civilizations to strengthen clay in pottery and bricks, resulting in composites with increased strength and endurance.
- **Early Plastics and Polymers:** The development of synthetic polymers such as Bakelite and celluloid in the nineteenth century laid the groundwork for current polymer composites. These early plastics have been used in a variety of applications, providing the way for the addition of reinforcing elements.
- **World War II:** During World War II, the requirement for lightweight and robust materials forced the development of polymer composites. Fiberglass, with its glass-fiber-reinforced plastic matrix, was used in aircraft, resulting in the creation of the composite industry.
- **Aerospace Advancements:** The aerospace sector has continued to drive innovation, resulting in the usage of sophisticated composites in aircraft, such as carbon-fiber-reinforced plastics, which provide great strength-to-weight ratios and fuel economy.
- **Automotive Revolution:** The automotive sector adopted polymer composites to reduce weight and improve fuel efficiency. Fiberglass and carbon composites found applications in car bodies and components.
- **Consumer Goods:** Polymer composites have become popular in consumer items ranging from recreational goods to electronics. Reinforced polymers give durability, lightweight construction, and a variety of aesthetic options.
- **Infrastructure and Construction:** Polymer composites have been employed in roadways, structures, and other building projects because of their corrosion resistance and structural strength, which reduces maintenance and extends the life of the construction.
- **Modern Applications:** Polymer composites are now essential to many industries, including healthcare, marine, and solar power. Developments in manufacturing processes and materials science have made it possible to develop composites that are specifically suited to particular applications.
- **Sustainability and Green Composites:** Sustainability is becoming increasingly important in the evolution of polymer composites. Researchers are investigating bio-based polymers and natural fibers to develop "green" composites with a lower environmental effect.
- **Future Prospects:** With continued research into nanocomposites, smart materials, and additive manufacturing techniques, the field of polymer composites continues to evolve. These advancements have the potential to transform the capabilities and applications of composite materials in future decades.

Because of its specialized characteristics, such as high strength-to-weight ratios, corrosion resistance, and design flexibility, polymer composites offer considerable advantages in a variety of industries. In the aerospace industry, aircraft weight is reduced to improve fuel economy. They are used in the car industry to improve fuel economy and crash resistance. Construction benefits from durability and corrosion resistance, whereas sporting goods and electronics rely on lightweight strength from composites. They are important in renewable energy, such as wind turbine blades, as well as medical equipment and marine applications. Polymer composites are advancing, driving innovation across industries and meeting crucial performance requirements.

1.2 Types of Polymer Matrix Materials

The matrix material in composites is often a polymer that helps to bind and maintain the reinforcing components (such as fibers or particles). Polymer matrix materials are available in a variety of forms, each with its own set of features and applications. These are a few examples of the most prevalent types:

- a. **Thermosetting polymer:** Thermosetting polymers, commonly known as thermoset, are a type of synthetic polymer that, when subjected to heat or other curing agents, undergo irreversible chemical reactions. This process results in the formation of a three-dimensional network structure, which makes them hard, rigid, and dimensionally stable. Thermosetting polymers, once cured, cannot be molded or melted. Epoxy resins, phenolic resins, and polyester resins are common examples. They are employed in industries like as aerospace, automotive, electronics, and construction as a result of their strength, heat resistance, and long lifespan [8].
- b. **Thermoplastics polymer:** Thermoplastic polymers are synthetic materials that can be melted and hardened repeatedly without chemical degradation. These polymers are extremely adaptable and retain their original properties even after multiple heating and cooling cycles. PE PP, and PVC are a few examples. Because of their ability to be molded and reshaped, they are perfect for a wide range of applications, including packaging, automotive components, and medical equipment. They soften and become malleable when heated, enabling easy processing and recycling [9], [10].
- c. **Elastomers:** Elastomers, also referred to as rubbers, are a type of polymer recognized for their high elasticity and durability. After being stretched or deformed, they can return to their former shape. Elastomers are used in tyres, seals, gaskets, and a variety of other items where flexibility and durability are required [11], [12].
- d. **Biopolymers:** Biopolymers are polymers that are obtained from environmentally friendly, natural sources such as plants, microorganisms, and algae. These biodegradable materials have a lesser environmental impact than typical petrochemical-based polymers. Polylactic acid (PLA) and polyhydroxyalkanoates (PHA) are two common examples [13]. As part of efforts to reduce plastic waste and promote sustainability, biopolymers have gained interest in a variety of industries, including packaging, textiles, and biomedical applications.

1.3 Reinforcements in Polymer Composites

Reinforcing components are important parts of composite materials because they improve their mechanical and functional characteristics. Tensile strength and stiffness are provided by fibers such as carbon, glass, and aramid. Impact resistance, thermal conductivity, and flame resistance are all improved

by particles or fillers such as silica or ceramic. At the nanoscale, nanomaterials have unique characteristics; carbon nanotubes and graphene, for example, improve electrical and thermal conductivity. These materials are carefully incorporated into a polymer matrix to generate composites that are appropriate for specific applications ranging from aerospace and automotive to construction and electronics and offer a range of characteristics and performance benefits. Reinforcing materials in composite materials are classified into several categories, each with its own set of features and applications [14], [15]. Table 1 shows some significant examples.

Table 1. Various types of reinforcing materials.

Sr. No.	Types	Description
1.	Glass Fibers	Glass fibers are widely utilized due to their high strength, low cost, and corrosion resistance. They are frequently used to reinforce composite structures and components in industries like as automotive and construction.
2.	Carbon Fibers	Carbon fibers have a high strength-to-weight ratio, stiffness, and minimal thermal expansion. They are widely used to reduce weight while retaining structural integrity in aerospace, automobile, and sports equipment.
3.	Aramid Fibers	Aramid fibers, like Kevlar, provide excellent impact and heat resistance. They are employed in difficult applications such as bulletproof clothing and protective gear.
4.	Natural Fibers	Sustainable reinforcing elements in eco-friendly composites such as flax, hemp, and jute are gaining favor. They provide adequate strength while having a low environmental impact.
5.	Nanomaterials	Carbon nanotubes and graphene are employed at the nanoscale to improve electrical and thermal conductivity in composites. They could be used in advanced electronics and materials science.
6.	Particles and Fillers	The materials, such as silica, alumina, or talc, are used to increase characteristics like as impact resistance, flame resistance, and thermal conductivity in composites. They are employed in a variety of industries, including automotive and construction.

1.4 Role of reinforcement in enhancing composite properties

Reinforcements are crucial in increasing composite properties by strengthening and raising their performance. They help to improve the following properties, which are listed below.

- **Strength:** Reinforcing materials, such as fibers or particles, improve the tensile, compressive, and flexural/bending strength of the composite, making it a stronger one and capable of withstanding mechanical stresses.
- **Stiffness:** Reinforcements strengthen the rigidity of the composite, minimizing deflection and improving dimensional stability.
- **Weight Reduction:** Carbon fibers and other high-strength, lightweight components reduce the overall weight of the composite, making it perfect for situations where weight reduction is crucial.
- **Thermal and Electrical Properties:** Certain reinforcements, like carbon nanotubes, can improve thermal and electrical conductivity, allowing them to be used in more specialized applications.

- **Toughness:** Reinforcements increase the composite's impact resistance, lowering the risk of fractures or damage.

2. Fabrication Techniques

Composite manufacturing procedures include a variety of techniques for developing composite materials, each adapted to a certain application. Table 2 depicts these in many ways.

Table 2. Various types of composite manufacturing techniques [16], [17].

Sr. No.	Process	Description
1.	Molding	Injection or compression molding processes form composites using a pre-made mixture, often in a mold or die, where heat and pressure solidify the material.
2.	Lay-up	Layering reinforcing materials and resin in a mold by hand or robotically, is subsequently cured under pressure and temperature.
3.	Pultrusion	A continuous process that involves pulling reinforcing fibers through a resin bath and shaping them into the desired shape before curing.
4.	Filament Winding	Continuous fibers or tapes are wound onto a revolving mandrel to create constructions with high strength-to-weight ratios, such as pressure vessels and pipes.
5.	Resin Transfer Molding (RTM)	A closed mold containing the fiber reinforcement is injected with liquid resin.

These processes enable the development of customized composites for use in aerospace, automotive, construction, and other fields. Composite curing procedures are critical in the manufacturing of composite materials because they ensure solidification and the necessary characteristics [18]. There are two common methods:

- **Autoclave Curing:** The composite is subjected to high pressure and heat within an autoclave, resulting in a controlled environment that promotes consistent curing. It is extensively utilized in outstanding performance. composites in aerospace.
- **Resin Infusion:** The composite is placed in a vacuum bag during resin infusion, and resin is infused into the fiber reinforcement under vacuum pressure. It is a more cost-effective and adaptable way of curing composites, and it is widely utilized in the marine, automotive, and sporting goods industries. These curing procedures aid in the optimization of composite mechanical and thermal properties for specific applications.

3. Properties and Characterization

Polymer composites have a unique set of characteristics that include strength, stiffness, thermal and electrical conductivity, durability, and corrosion resistance. Mechanical testing, microscopy, thermal analysis, and spectroscopy are among the techniques used to examine these aspects and guarantee that the composites meet particular performance requirements in a variety of applications [19]. Table 3 describes these properties.

Table 3. Various types of polymer properties [20].

Properties	Types	Description
Mechanical properties	Strength	It determines a material's ability to withstand a force without reversible distortion or failure. The enhancement in the mechanical properties at 2 wt% of HNT's in PEI matrix was obtained. The increment of 8% in tensile stress at maximum load, 4% in Young's modulus, 40% impact energy and 43% izod impact strength are found compared to pure PEI matrix [21].
	Stiffness	The stiffness of a material, also known as Young's modulus, is a measure of its resistance to deformation when subjected to external stress. High-stiffness materials deform extremely little under load.
	Toughness	The ability of a substance to absorb energy and deform plastically before fracture is measured by toughness. It combines strength with resilience, indicating the ability of the material to tolerate impacts or unexpected pressures.
Thermal properties	Glass Transition Temperature (T_g)	The temperature at which a polymer with an amorphous structure transition from a hard, glassy state to a more rubbery, viscous state is defined as T_g . The inclusion of inorganic components HNTs into PEI matrix can improve their thermal stability of nanocomposites materials.
	Melting Temperature (T_m)	The transition point of a crystalline polymer from solid to molten is denoted by T_m . It affects a material's suitability for applications that require high temperatures and processing ability.
	Thermal Conductivity	The ability of a material to conduct heat is indicated by this attribute. In insulating applications, low thermal conductivity is preferred, but high thermal conductivity is required for heat dissipation in electronics and thermal management.
Electrical properties	Electrical Conductivity	The ability of a material to carry electrical current is measured by this attribute. Conductivity is high in metals and some conductive polymers, but low in insulators. Semiconductors are in the middle and are essential in electronic devices such as transistors.
	Dielectric Constant (Relative Permittivity)	When exposed to an electric field, the dielectric constant characterizes a material's ability to store electrical energy. A greater dielectric constant suggests better energy storage capabilities in capacitors and insulating materials.

Polymer composite characterization procedures are critical for examining their properties and ensuring they meet certain performance requirements. Table 4 lists some key methods.

Table 4. Various characterization techniques are used for polymer composites [22].

Sr. No.	Types	Description
1.	Microscopy	SEM and Optical Microscopy enable a visual investigation of the composite's microstructure, exposing characteristics such as fiber orientation, voids, and resin distribution.
2.	Spectroscopy	Fourier Transform Infrared Spectroscopy (FTIR) and Nuclear Magnetic Resonance (NMR) techniques provide information about the chemical composition and molecular structure of composite materials.
3.	Mechanical Testing	ASTM and ISO standards define testing methodologies for tensile, compressive, flexural, and impact testing. Mechanical characteristics such as strength, stiffness, and toughness are evaluated in these tests.
4.	Thermal Analysis	Thermal characteristics such as T_g and thermal stability are assessed using Differential Scanning Calorimetry (DSC) and Thermogravimetric Analysis (TGA).
5.	Electrical Testing	Dielectric testing determines a composite's ability to retain electrical energy, which is important in electrical and electronic applications.

4. Significance and Applications of Polymer Composites

Because of their lightweight nature, high strength-to-weight ratio, corrosion resistance, and adaptability, polymer composites, in particular, have gained importance [21], [23]. This chapter explores the importance of polymer composites and their uses in a variety of industries, including sports, aerospace, automotive, construction, and healthcare.

4.1 Significance of Polymer Composites

- a. Weight Reduction:** One of the fundamental reasons for polymer composites' extensive use is their ability to lower the weight of components or structures while maintaining or even improving their mechanical properties. This weight reduction is particularly important in industries such as aerospace and automotive, where fuel efficiency, performance, and safety are critical.
- b. Corrosion Resistance:** Polymer composites are naturally corrosion resistant, making them perfect for applications such as marine and offshore structures that are exposed to moisture, chemicals, or salt. Because of its corrosion resistance, they can save money on maintenance and replacement.
- c. Design Flexibility:** Polymer composites' design versatility enables engineers and designers to construct sophisticated shapes and structures that would be difficult or impossible to achieve with traditional materials. This adaptability has resulted in novel designs in a variety of areas, including architecture and healthcare.

4.2 Applications of Polymer Composites

- a. Aerospace and Automotive Industries:** Composite materials are utilized to reduce weight and improve fuel efficiency in airplane components. They improve fuel economy and crash resistance in the automotive industry, making them excellent for body parts and structural components.

- b. Construction and Infrastructure:** Composites are useful for bridges, building materials, and reinforcement bars due to their great strength and corrosion resistance. They extend the life of structures and lower maintenance costs.
- c. Sports and Leisure Equipment:** Composite materials are commonly used in sporting items such as tennis rackets, golf clubs, and bicycles, where they provide a combination of strength and flexibility while improving performance.
- d. Healthcare and Biomedical Applications:** Because of their biocompatibility and adjustable characteristics, they are employed in prosthetics, dental materials, and medical equipment.
- e. Renewable Energy:** Composites are used in wind turbine blades and solar panels, allowing for lightweight and robust components that improve the efficiency and lifespan of these renewable energy systems.

5. Advancements in Polymer Composites

Polymer composite advancements promote innovation in a variety of industries such as:

- a. Nanocomposites and Nanotechnology:** The incorporation of nanomaterials such as carbon nanotubes and graphene improves composites' mechanical, thermal, and electrical properties. Nanotechnology enables exact control at the nanoscale, resulting in stronger, lighter materials [24], [25].
- b. Smart and Self-Healing Composites:** These composites are intended to respond to external stimuli and have applications in aerospace and structures where real-time monitoring and damage repair are critical, hence prolonging the material's lifecycle [26].
- c. Recycling and Sustainability:** Sustainable practices such as the use of bio-based polymers and improved recycling procedures are minimizing the environmental impact of composites, making them more environmentally friendly and harmonizing with worldwide initiatives to minimize waste and carbon footprint [27].

6. Challenges, Limitations and future scope

Polymer composites have many advantages, but they also have drawbacks and limitations. Cost can be a considerable disadvantage, especially for high-performance composites. Manufacturing processes can be complex, requiring specialised equipment and skilled labour. Concerns about the environment include the use of nonrenewable materials in some composites and energy-intensive manufacturing methods. To get higher strength and properties, filler dispersion in a polymer matrix is a difficult issue. Because recycling is limited, disposal and end-of-life management are challenging, resulting in potential waste issues. Addressing these constraints will need breakthroughs in sustainable materials, efficient production methods, recycling technologies, and the creation of legislation for responsible disposal, all of which will promote a more environmentally and economically viable future for polymer composites [28]–[30].

7. Conclusions

This chapter discusses polymer composites as a continually growing topic that has had a significant impact on a variety of sectors. These new materials offer a remarkable array of properties, including strength, lightweight design, and corrosion resistance, all of which contribute to improved performance and innovation. Nanotechnology, smart materials, and environmentally friendly practices promise an even

better future for polymer composites. However, costs, manufacturing complexity, environmental concerns, and disposal issues remain. Addressing these problems, as well as embracing future trends such as bio-based materials, additive manufacturing, and multifunctional composites, will be critical to maximizing the benefits of these flexible materials while minimizing their limitations and impact on the environment.

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