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A Comprehensive Review of Formulations, Polymers, Fibers, and Fillers for Enhanced Mechanical and Thermal Performance

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Abstract

In the current review study, a wide range of subjects are discussed, such as the kinds of polymers that are used (thermoplastic, elastomer, and thermosetting), the reinforcing with organic and/or inorganic fibers, and the insertion of a variety of fillers, including organic, mineral, and metallic elements. The review also examines the fabrication and composition of various macromolecular matrices, citing examples such as polycarbonate, poly hexamethylene sebacic, polyether sulfone, polyether ether ketone, polyether ketone, polyether imide, polyethylene terephthalate, phenoplasts, epoxy resin, and polyurethane. The study highlights many benefits of forming composite materials, including superior mechanical performance, high heat resistance, favorable fire behavior, remarkable impact resistance, optimal abrasion resistance, outstanding electrical insulation, and strong stiffness.

Keywords: Hybrid polymer composites, Fillers, fibers, mechanical, thermal, and electrical properties.

1. Introduction

The idea of formulation is extensive, including several businesses that create intermediary or final products by blending different basic components [1]. Formulation refers to the process of using knowledge and techniques to combine or shape elements of either natural or synthetic origin, which may not naturally work well together, to produce a commercial product that has specified functions and meets preset requirements [2]. In a recipe, active chemicals provide the main purpose, whereas formulation aids have secondary responsibilities. Formulated goods are composed of finely distributed phases that are not able to mix, giving the appearance of homogeneity on a large scale but heterogeneity on a small scale [3]. Examples of such products include paints, cosmetic creams, mayonnaise, and composite materials [4]. Ensuring that the combination meets the criteria for preparation and stability introduces intricacy. Composite materials are characterized as combinations of two or more materials that demonstrate qualities that are better than those of the separate components [5]. These materials typically consist of reinforcing structures or fillers that are embedded in a matrix. The matrix facilitates the integration and alignment of components, enabling the efficient transfer of stress [6]. Composite materials are characterized by their heterogeneity and frequent anisotropy, which are impacted by several aspects including the nature of the matrix and charge, form and proportion, interface quality, and manufacturing procedures [7]. Composite materials may include matrices and reinforcements made of metallic, ceramic, or plastic components, allowing for a wide range of possible combinations [8]. Composites may exhibit hybrid characteristics when they are made up of many discontinuous phases with differing properties [9].

The matrix is the continuous phase, whereas the reinforcement is the discontinuous phase. Composites are formed by combining components that possess physical and mechanical qualities that complement each other [10]. The incorporation of high-tensile strength reinforcements and modules into a polymer matrix improves the mechanical and thermal properties. Polymer matrix composites provide manufacturing benefits when compared to metals [11]. They allow for the production of intricate parts with lower density, which leads to decreased fuel consumption in the aviation and automotive industries, increased speed in competitive sports, extended missile range, and enhanced payload capacity in transportation [12]. Composite materials are classified into three groups: organic, mineral, and metallic, depending on the kind of matrix they use. Some examples of composites include cardboard, laminated tires, and reinforced plastics in organic composites [13]–[15]. In mineral composites, there are concrete, carbon–carbon composites, and ceramic composites. Metallic composites include aluminum/boron fibers and aluminum/carbon fibers [16]–[18]. These materials are used in many industries such as packaging, automotive, civil engineering, aviation, sports, biomedicine, thermomechanical components, and aerospace.

2. Composites and Fabrication Methods

2.1 Composite materials and their types

Composite materials are synthetic materials created by combining two or more component materials that possess distinct physical or chemical characteristics [19]. The use of these resources enables the production of a resultant product with improved and customized characteristics. The following are a few prevalent categories of composite materials:

2.1.1 Fiber-reinforced composites:

- Carbon Fiber Reinforced Polymer (CFRP) is a composite material where carbon fibers are incorporated into a polymer matrix, often epoxy, resulting in a material that is both lightweight and very strong. Carbon fiber reinforced polymer (CFRP) finds extensive use in the aerospace, automotive, and sports equipment industries [20].
- Glass Fiber Reinforced Polymer (GFRP): Glass fibers are often used as a means of reinforcement in polymer matrices. GFRP is renowned for its affordability, exceptional durability, and remarkable corrosion resistance. It is used in the construction, maritime, and automotive sectors [21].
- Aramid Fiber Reinforced Polymer (AFRP) refers to the use of aramid fibers, such as Kevlar, as a means of strengthening polymer matrices. AFRP has exceptional strength and resilience, making it a popular choice for applications requiring ballistic protection and aeronautical engineering [11].

2.1.2 Composite materials consisting of solid particles dispersed in a matrix.

- Metal Matrix Composites (MMC) refer to the combination of metal matrices, such as aluminum, with reinforced ceramic particles or fibers. Metal matrix composites (MMCs) provide enhanced tensile strength, rigidity, and durability against abrasion. Frequently used in aerospace and automotive industries [22].
- Polymer Matrix Composites (PMC) are polymers that are strengthened by the addition of particle fillers such as glass beads or carbon black. PMCs are used throughout many sectors, including automotive and construction [23].

2.1.3 Laminar composites:

- Fiber-reinforced laminates are composite materials consisting of alternating layers of polymer matrix and fibers, such as glass or carbon. This structure offers multidirectional strength. Frequently used in aeronautical and structural contexts [24].
- Metal Matrix Laminates are laminates that consist of metal matrices, similar to fiber-reinforced laminates. These composites possess exceptional strength and thermal conductivity [25].

2.1.4 Ceramic Matrix Composites (CMC)

Ceramic fibers are incorporated into a ceramic matrix. Ceramic matrix composites (CMCs) have exceptional heat resistance, making them very suitable for applications in aerospace, nuclear, and thermal management fields [23].

2.1.5 Composite materials made from natural fibers

Bio-composites are materials made by combining natural fibers, such as flax, hemp, or bamboo, with a polymer matrix for added strength and durability. Bio-composites are environmentally friendly substitutes that are used in the automobile industry for interior components and in the construction sector [26].

2.1.6 Hybrid composites:

Hybrid composites include the amalgamation of diverse reinforcements, such as a blend of carbon and glass fibers. This enables the achievement of a harmonious combination of characteristics that are customized to meet individual requirements [27].

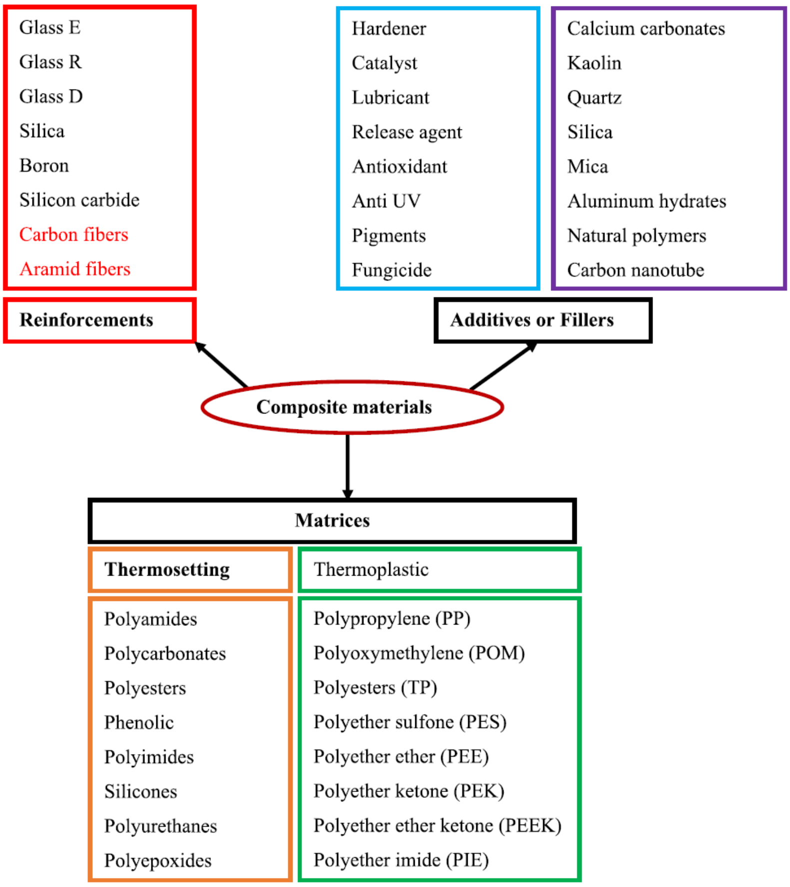

Figure 1: Composites and their fabrication

2.2 Composites Fabrication

The matrix material, fillers, and fibers are the different components in the fabrication of composites as mentioned in Figure 1.

2.2.1 Matrix

The matrix plays a vital role in the formation of composite materials by connecting reinforcing fibers, spreading stresses, offering chemical resistance, and molding the result.

2.2.1.1 Thermoplastic Polymers

Thermoplastic matrices are composed of linear chains that can change while in a molten state. During conventional production procedures, these matrices undergo heating and then undergo shaping by molding, injection, extrusion, or thermoforming. The following cooling step guarantees the preservation of the finished product's form, and this operation may be reversed. Currently, there exists a wide variety of thermoplastics, each possessing distinct and beneficial characteristics. They possess a remarkable level of flexibility equivalent to rubber, a high degree of rigidity comparable to metal and concrete, and the ability to be translucent like glass, making them appropriate for a wide range of applications. Thermoplastics are particularly noteworthy for their ability to resist oxidation, their great resistance to corrosion, and their exceptional qualities as thermal and electrical insulators [21].

2.2.1.2 Thermosetting Polymers

Thermosetting matrix structures, usually liquid at room temperature, solidify when heat and a hardening ingredient are applied during implementation. The solidification process entails a chemical alteration that leads to a strong and durable three-dimensional linkage between molecules. This transition is permanent, causing the material to become incapable of being melted and unable to dissolve in most solvents, such as alcohols, ketones, and hydrocarbons [28]. Frequently used thermosetting matrices comprise: Polyesters, Phenoplasts, Epoxy resins, Polyurethanes, Polyimides, etc. Thermosetting matrices possess key features such as:

- **Stiffness:** Thermosetting matrices often exhibit more rigidity compared to thermoplastic matrices.
- **Creep Resistance:** These materials have enhanced resistance to creep, making them well-suited for applications that need precise dimensional stability.
- **Molding Capabilities:** Thermosetting matrices are very suitable for the molding of big pieces, regardless of whether they comprise short, long, or woven fibers.

2.2.1.3 Thermosetting Polymers

Elastomers are materials that can stretch and return to their original shape after being deformed. Elastomers are polymers that have rubber-like elastic properties. Elastomers, in their unstrained condition, are composed of elongated molecular chains that are folded onto themselves. Under the influence of external pressures, these molecules can move about one another, resulting in deformation [29]. Vulcanization is used to improve the flexibility of the underlying material.

- Vulcanization Process: Vulcanization involves the transformation of the elastomer into a hardened state, resulting in the formation of a rather stiff three-dimensional network. However, the flexibility of the molecular chains is retained throughout this process. This procedure involves the introduction of sulfur, carbon, and other chemical agents into the elastomer. The outcome is a substance exhibiting enhanced elasticity and resilience.

- Synthetic rubbers may be created using various compositions to meet particular requirements for different uses. Elastomers are used in many applications, such as the production of cushions, specific insulators, shoe bottoms, and tires. An instance of an elastomeric substance is styrene-butadiene, a thermoplastic material acquired by polymerizing styrene in the presence of butadiene. This procedure yields a substance with characteristics similar to rubber and is often used in many applications.

2.2.2 Reinforcement

The reinforcing component in composite materials functions as the structural framework, imparting mechanical robustness, including tensile strength and stiffness. Reinforcement is naturally composed of filamentary materials, which may be either biological or inorganic fibers. These fibers can vary in form, from elongated particles to continuous fibers [17].

2.2.2.1 Glass Fibers

Glass fibers, specifically glass fibers made from E glass, are the predominant choice for reinforcing, accounting for more than 95% of all uses. Due to their adaptability, they are indispensable in several industrial sectors, imparting mechanical robustness to innovative composite materials.

2.2.2.2 Phenolic Fibers

The KYNOL brand produces phenolic fiber that has exceptional heat performance and dimensional stability. It is used as an industrial fiber reinforcement in composite products.

2.2.2.3 Polybenzimidazole Fibers

Polybenzimidazole (PBI) fiber, sometimes referred to as PBI fiber, has remarkable characteristics in the aerospace, automotive, and wind power industries. It is produced by spinning a solution of poly 2,20-(m-phenylene)-5,50-bibenzimidazole.

2.2.2.4 Aramid Fibers

Aramid fibers, such as the renowned KEVLAR, are used in sophisticated thermosetting composite materials. These fibers provide economic advantages due to their exceptional strength, resilience to impact, low weight, and long lifetime.

2.2.2.5 High-Strength Carbon Fiber

Carbon fibers are widely used in thermosetting composite materials in several sectors including space building, aeronautics, and automobiles. Carbon fibers, which are derived from polyacrylonitrile (PAN), provide outstanding mechanical and thermal resistance, as well as high tensile and compressive strength, and excellent stiffness.

2.2.3 Filler

Fillers, which are categorized as inactive compounds, are incorporated into the primary polymer to effectively modify mechanical, electrical, or thermal characteristics, improve surface aesthetics, or decrease material expenses [30]–[32]. Thermosetting materials often include fillers of many types and forms, typically at high mass percentages, reaching up to 60%.

2.2.3.1 Criteria for Plastics Fillers:

- Resin compatibility: The desired characteristics are non-toxicity, lack of coloring, chemical inertness, neutrality, stability under heat and light, minimal water absorption, and no negative impact on polymer stability or color.
- Wettability is responsible for facilitating the even dispersion of powders within the polymer matrix and promoting the attachment of fibers to the underlying polymer.
- Consistency in material qualities is ensured by the uniformity of quality and grain size.
- Reduced Abrasive Effect: Reduces the effect of abrasion on processing equipment.

2.2.4 Natural additives

Cellulose fillers are economical and lightweight substances that are used in conjunction with thermosetting resins, such as phenoplasts and aminoplasts. Their benefits include affordability and minimal mass [33], [34].

- Wood flour is used in combination with phenolic and aminoplast resins to increase impact resistance, decrease shrinkage during molding, and promote dimensional stability in molded products.
- Fruit bark flour is used as a reinforcing agent in thermoplastic matrices such as polypropylene (PP) and acrylonitrile–butadiene–styrene (ABS), as well as in phenolic resins. The range of incorporation rates varies from 9% to 23%.
- Vegetable fibers, such as cotton and wood, are composed of cellulose. They possess a low density, are sensitive to humidity, have moderate mechanical properties, exhibit decent wear resistance, and provide thermal and electrical insulation.
- Starches, which are obtained from plants, serve as fillers to get regulated biodegradability in plastics.

2.2.5 Inclusion of mineral fillers

2.2.5.1 Carbonates Chalk

Comprises of calcite up to 99%, used in conjunction with polyvinyl chloride (PVC) and thermosetting compounds.

2.2.5.2 Limestone and marble

Limestone and marble consist of 80-90% calcite and are used in conjunction with PVC and polyurethanes because of their hydrophobic nature.

2.2.5.3 Silica

Various kinds of silica enhance fuel economy, dielectric characteristics, wet traction, mechanical qualities, abrasion resistance, and resistance to heat and humidity.

2.2.5.4 Talc’s

Talcs are hydrous silicates used to improve thermal insulation, boost water resistance, and assist the process of molding. Frequently used in thermoplastics to enhance resistance to deformation under constant stress and to achieve higher stiffness.

2.2.5.5 Titanium Dioxide (TiO2)

Titanium Dioxide is a chemical compound with the formula TiO_2, which is utilized as a white pigment and ultraviolet (UV) barrier in thermoplastics and unsaturated polyesters.

2.2.5.6 Zinc and magnesium oxide

Zinc oxide functions as a white pigment and UV blocker, while also exhibiting electrical conductivity and strong heat resistance. Magnesium oxide enhances the stiffness, toughness, and ability to withstand deformation over time.

2.2.5.7 Alumina

Alumina is a compound composed of aluminum and oxygen. Alumina improves the electrical resistivity, thermal conductivity, stiffness, abrasion resistance, and fire resistance of composite resins.

2.2.5.8 Beryllium Oxide

Beryllium Oxide is a compound with the chemical formula BeO. Beryllium oxide, when in the form of microspheres, enhances both electrical and thermal conductivities. Utilized in epoxy resins and high-density structural foam.

2.2.5.8 Antimony oxide

Antimony oxide is a compound with the chemical formula Sb_2O_3. When coupled with halogenated compounds, it is used for its flame-retardant properties.

2.2.6 Charges of Metallic Elements

Aluminum, copper, zinc, and other metallic particles are included in polymers used in aircraft and electronics to enhance their electrical or thermal conductivity. Different metals provide enhancements in their physical characteristics.

2.2.7 Substances used to enhance or modify the properties of a product.

Additives are included in polymers to alter their rheological characteristics or enhance the qualities of the final products.

2.2.7.1 Lubricants

Lubricants, both external and internal, are used to facilitate the shaping of thermoplastics in processing equipment.

2.2.7.2 Substances used to increase the flexibility and durability

Plastics are used as an additive in polymers to decrease the temperature at which they become soft, enhance their flexibility, and enhance their ability to stretch. Frequently used in PVC and diverse polymers.

2.2.7.3 Stabilizers

Stabilizers prevent or slow down processes that lead to the deterioration of polymers. Stabilizers that are often used include antioxidants and anti-UV compounds.

2.2.7.4 Shock absorbers

Shock-absorbing compounds are used to disperse stresses and assimilate impact energy in plastic items.

2.2.7.5 Pigments and Dyes

Pigments and dyes are used to impart color to polymers, fulfilling various purposes such as enhancing visual appeal, fulfilling technical specifications, ensuring safety, facilitating identification, and enabling concealment.

3. Fabrication of Polymer Composites

- Initial Stage: Initiators possess unstable chemical bonds that may produce free radicals via the process of hemolytic cleavage. There are two primary categories: peroxides and azo derivatives. Radicals are generated in peroxides by the cleavage of OAO bonds. Benzoyl peroxide undergoes decomposition into radicals when exposed to heat. Radicals: There are two categories of radicals: benzoyloxy radicals and phenyl radicals. Benzoyloxy radicals can undergo β elimination, resulting in the formation of phenyl radicals and carbon dioxide (CO_2). Both categories of radicals can induce polymerization.
- The propagation phase is the primary step of radical polymerization, occurring at a frequency 10^3–10^4 times higher than initiation or termination. It entails the construction of the macromolecule by transferring the active center to additional monomers. Possible isomerism may occur during the propagation process, either by head-tail or head-head addition. The regioselectivity is influenced by factors such as the resonance stabilization of radicals, steric effects, and polarity.
- Termination Phase: Radical polymerization concludes when propagating radicals encounter and deactivate each other. Termination arises by either duplication or disproportionation. Duplication refers to the process of creating a σ bond by the collision of two propagating radicals, leading to the formation of a single chain. Disproportionation refers to the process in which a polymer radical captures a hydrogen atom, resulting in the formation of two macromolecules, one of which contains an unsaturated terminal unit.

4. Conclusions

The research examined thermoplastic, elastomer, and thermosetting polymers that were reinforced with fibers and formed with fillers. The study's findings may be summarized as follows:

1. Composite materials, particularly those with polymer matrices, have diverse uses in several industries, such as packaging, automotive, aerospace, and biomedical sectors.
2. The ongoing progress and use of sophisticated composite materials highlight their importance in attaining exceptional mechanical capabilities, resistance to heat, and a wide range of other desired characteristics.
3. Thermosetting composites possess remarkable mechanical and thermal durability when exposed to high temperatures.
4. Composite materials, which are strengthened by the addition of glass fibers and carbon fibers, have exceptional tensile and compressive strength.
5. The continuous investigation and use of these materials in many sectors demonstrate an increasing fascination with leveraging their distinct characteristics to tackle a wide range of technical obstacles.
6. There is a growing fascination in advanced composite materials in several sectors.

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