E. Bravin Daniel, 2023, 11:2
ISSN (Online): 2348-4098
ISSN (Print): 2395-4752

International Journal of Science, Engineering and Technology

An Open Access Journal

Investigation of Mechanical and Morphological Properties of PVC Coated Nylon Hybrid Composites for Structural Applications

E. Bravin Daniel, Aaron.C, Akash R, Infant Jeen U B, Navis Shiju Antony
Department of Mechanical Engineering
Stella Mary's College of Engineering

Abstract- This study explores the mechanical and morphological behavior of PVC-coated nylon hybrid composites with a focus on their suitability for structural applications. Hybrid composites combining natural and synthetic fibers offer a sustainable alternative with enhanced mechanical and thermal properties. In this research, waste nylon fibers were reinforced into a PVC matrix, alongside calcium carbonate fillers and surface modifiers, to improve strength, stiffness, and water resistance. Various fabrication techniques, including vacuum infusion and compression molding, were employed to ensure uniform fiber dispersion and strong interfacial bonding. Mechanical properties such as tensile, flexural, and impact strength were evaluated, along with thermal stability via TGA and DSC, and viscoelastic properties using DMA. SEM and TEM analyses were used to assess the microstructure and dispersion of fillers. The results indicate that the optimized hybrid composite demonstrates improved mechanical performance, reduced water absorption, and enhanced durability. These characteristics make the material a viable choice for automotive, construction, and aerospace structural applications.

Keywords- PVC-coated nylon hybrid composites, Mechanical properties, Morphological behavior, Hybrid composites, Natural and synthetic fibers, Waste nylon fibers

I. INTRODUCTION

Background and Significance

Polyvinyl chloride (PVC)-coated textiles are becoming increasingly prevalent in the textile industry, driven by advancements in composite formulations and coating technologies [1]. These materials are valued for their versatility and potential for use in diverse applications, ranging from protective clothing to architectural membranes. The ability to tailor the properties of PVC-coated textiles through the incorporation of various fillers and reinforcements has spurred significant research and development efforts. The mechanical characteristics and morphological properties of these composites are critical, as they directly influence the performance, durability, and cost-effectiveness of the final product. Understanding the interplay between the composite's composition and its resulting properties is essential for optimizing its suitability for specific applications.

Hybrid composites, which combine two or more distinct materials, represent a sophisticated approach to materials design, aimed at manipulating desired properties for a wide array of applications [2]. This technique allows engineers to leverage the strengths of different materials while mitigating their weaknesses, resulting in composites with enhanced performance characteristics. Hybrid composites can be constructed from a variety of constituents, including synthetic fibers, carbonaceous materials, metals, ceramics, and polymers, each contributing unique attributes to the final composite. This versatility makes hybrid composites attractive for demanding applications in aerospace, naval, civil building, and sporting goods industries.

Natural fibers are increasingly recognized as viable and sustainable alternatives to synthetic fibers in composite materials [3]. These fibers, derived from renewable resources such as flax, hemp, jute, and sisal, offer several advantages, including biodegradability, low density, recyclability, and reduced CO2 emissions. The growing environmental awareness and the need for sustainable materials have spurred research into the use of natural fibers as reinforcements in polymer composites. While natural fibers often exhibit lower mechanical properties compared to synthetic alternatives, their combination with synthetic materials in hybrid composites can create a balance between performance and sustainability.

Nylon, in various forms, plays a significant role in composite materials, contributing to improved mechanical and thermal properties. Waste nylon, such as discarded fishing nets, can be repurposed as reinforcement in composite sheets, promoting resource efficiency and reducing environmental impact [4]. Additionally, nylon fibers can be coated with materials like polyaniline to create semiconducting composites with enhanced electrical and mechanical characteristics [5]. These nylon-based composites find applications in diverse fields, including construction, electronics, and automotive industries. The ability to tailor the properties of nylon through surface modification and combination with other materials makes it a versatile component in hybrid composite systems.

Advantages of Hybrid Composites

Hybridization, a design technique in fiber-reinforced composite materials, involves combining two or more fibers from different groups within a single matrix to manipulate desired properties [2]. This approach allows for the creation of materials with tailored characteristics that cannot be achieved with single-component composites. These hybrid materials may be made from a mix of synthetic fibers, carbonaceous materials, and various polymers, offering a wide range of possibilities for property optimization. The ability to combine materials with diverse properties into a single composite structure enables the creation of high-performance materials for demanding applications.

Natural fiber composites offer numerous advantages, including weight reduction, improved specific impact strength, and enhanced flexural and acoustic properties [6]. The lower density of natural fibers compared to traditional materials like glass or carbon fiber results in lighter composites, which can improve fuel efficiency in transportation applications and reduce structural loads in construction. The enhanced impact and flexural properties of natural fiber composites make them suitable for applications requiring energy absorption and resistance to bending forces. Furthermore, the acoustic damping characteristics of natural fibers contribute to noise reduction in automotive interiors and building panels.

Hybrid composites often exhibit increased mechanical properties compared to single-material composites, making them suitable for structural applications [7]. By combining different types of fibers and matrices, hybrid composites can achieve a synergistic effect, where the resulting material possesses properties that exceed the sum of its individual components. For example, combining high-strength carbon fibers with flexible natural fibers can create a composite with both high stiffness and good impact resistance. The enhancement of mechanical properties in hybrid composites is crucial for their use in load-bearing components and structural elements.

Combining natural and synthetic fibers in hybrid composites can reduce costs while enhancing mechanical performance, providing a balanced approach to materials design [8]. Natural fibers are generally less expensive than synthetic alternatives, making them an attractive option for cost-sensitive applications. By strategically combining natural fibers with higher-performance synthetic fibers, it is possible to achieve the required mechanical properties at a lower overall cost. This approach is particularly relevant in industries such as automotive and construction, where cost-effectiveness is a key consideration.

Scope and Objectives

The primary focus of this investigation is to explore the mechanical and morphological properties of PVC-coated nylon hybrid composites, with the goal of identifying suitable materials for structural applications [1]. This involves a comprehensive analysis of the composite's behavior under various loading conditions and an examination of its microstructure to understand the relationship between composition, processing, and performance. The study aims to provide valuable insights into the potential of these hybrid composites for use in a wide range of engineering applications.

This study aims to identify suitable materials for structural applications by evaluating key mechanical properties, such as tensile strength, flexural strength, and impact strength, as well as assessing wear resistance and water absorption behavior [3]. These properties are critical for determining the suitability of a composite material for use in load-bearing structures and components. By systematically measuring and analyzing these properties, the study seeks to identify the optimal material combinations and processing techniques for achieving the desired performance characteristics. The results of this evaluation will provide valuable guidance for the selection and design of composite materials for specific structural applications.

The objective is to understand how different fiber combinations and surface treatments affect the composite's performance, providing a basis for optimizing material selection and processing techniques [9], [10]. This involves investigating the influence of various factors, such as fiber type, fiber orientation, matrix composition, and surface modification, on the mechanical and morphological properties of the composite. By systematically varying these parameters and analyzing the resulting changes in performance, the study aims to establish a clear understanding of the structure-property relationships in PVC-coated nylon hybrid composites. This knowledge will enable the design of composites with tailored properties for specific applications.

Materials and Methods for Composite Preparation

Materials Used

Polyvinyl chloride (PVC) is a versatile and widely used polymer, serving as a matrix material in composite applications due to its processability, chemical resistance, and cost-effectiveness [1], [11]. PVC can be easily processed using various techniques, including extrusion, injection molding, and calendaring, allowing for the creation of complex shapes and structures. Its inherent resistance to chemicals and moisture makes it suitable for use in harsh environments. The relatively low cost of PVC compared to other polymers makes it an attractive option for large-scale production of composite materials.

Nylon, including waste nylon sourced from discarded fishing nets, is employed as a reinforcement material in composite structures, contributing to enhanced mechanical properties and promoting sustainability [4], [12]. Nylon fibers possess high tensile strength and flexibility, making them effective in reinforcing polymer matrices. The use of waste nylon not only reduces the environmental impact of discarded fishing gear but also provides a cost-effective source of reinforcement material. Nylon-reinforced composites find applications in various industries, including construction, automotive, and marine.

Calcium carbonate (CaCO3) is frequently employed as a filler in PVC composites to enhance mechanical properties and promote foam formation, influencing the density and stiffness of the resulting material [1]. CaCO3 particles can improve the impact resistance, flexural modulus, and dimensional stability of PVC composites. The addition of CaCO3 also affects the foaming behavior of PVC, allowing for the creation of lightweight and insulating materials. The particle size and surface treatment of $CaCO_3$ fillers play a critical role in determining their effectiveness in enhancing the properties of PVC composites.

Surface modifiers, such as maleic anhydride (MA), sodium silicate (Na-silicate), and isocyanates, are employed to improve the compatibility between the reinforcement fibers and the PVC matrix, enhancing the overall mechanical performance of the composite [9], [13]. These modifiers react with the surface of the fibers, creating chemical bonds that promote adhesion to the polymer matrix. Improved fiber-matrix compatibility results in better stress transfer, increased strength, and enhanced durability of the composite material. The selection of the appropriate surface modifier depends on the specific fiber and matrix materials being used.

Composite Fabrication Techniques

The vacuum infusion process is a widely used technique for preparing composite sheets with noncombustible glass fiber and waste nylon, ensuring uniform resin distribution and high fiber volume fraction [4]. This process involves placing the reinforcement materials in a mold, covering them with a vacuum bag, and drawing resin into the mold under vacuum pressure. The vacuum infusion process results in composites with minimal voids and excellent mechanical properties. This technique is particularly suitable for manufacturing large and complex composite structures.

Compression molding is a versatile method employed for fabricating hybrid composites with specific fiber-to-resin weight ratios, allowing for precise control over the composite's composition and properties [14]. This process involves placing the reinforcement fibers and resin into a mold and applying heat and pressure to consolidate the material. Compression molding is suitable for manufacturing both thermoset and thermoplastic composites and can produce parts with high dimensional accuracy and good surface finish. The fiber-to-resin ratio, molding temperature, and pressure are critical parameters that influence the final properties of the composite.

Melt mixing is a common technique used to fabricate PVC composites with $CaCO_3$ and liquid macromolecular modifiers (LMM), facilitating the dispersion of fillers and enhancing the processability of the material [15]. This process involves blending the PVC resin, fillers, and modifiers in a heated mixer, allowing the components to melt and homogenize. Melt mixing is a cost-effective method for producing large quantities of composite material. The mixing parameters, such as temperature, speed, and time, are crucial for achieving uniform dispersion of the fillers and optimal properties of the composite.

Hand lay-up techniques are utilized for creating distinct composite types with hemp, kenaf, flax, and sisal fibers, offering flexibility in material selection and allowing for the creation of custom composite structures [3], [16], [17]. This process involves manually placing layers of reinforcement fibers into a mold and applying resin to saturate the fibers. Hand lay-up is a simple and low-cost method for producing composite parts, particularly for small-scale production or prototyping. The quality of the final composite depends on the skill and experience of the operator.

Surface Treatment and Coating Methods

Surface treatment of fillers, such as nano-$CaCO_3$ particles, strengthens the interfacial interaction between the filler and the PVC matrix, leading to improved mechanical properties of the composite [18]. Surface treatment modifies the surface chemistry of the filler particles, enhancing their adhesion to the polymer matrix. This improved interfacial bonding results in better stress transfer and increased strength and toughness of the composite material. Various surface treatment methods, such as chemical modification and coating, can be employed to achieve the desired effect.

In-situ coating of polyaniline (PAni) on nylon 6 filaments is achieved via oxidative emulsion polymerization, creating semiconducting composites with enhanced electrical conductivity and mechanical performance [5]. This process involves polymerizing aniline in the presence of nylon 6 filaments, resulting in a uniform coating of PAni on the fiber surface. The PAni coating imparts electrical conductivity to the nylon fibers, making them suitable for use in electronic and electromagnetic shielding applications. The properties of the PAni coating can be controlled by adjusting the polymerization parameters, such as oxidant concentration and reaction time.

Fumed silica nanopowders are mixed in polyester resin to coat composite sheets, resulting in improved flame-retardant characteristics and enhanced thermal stability [4]. The fumed silica coating forms a protective layer on the composite surface, reducing its flammability and slowing down the rate of combustion. The nano-sized particles of fumed silica provide a high surface area, enhancing their effectiveness in suppressing flame propagation. The coating also improves the water resistance and durability of the composite material.
Silane coating of calcium carbonate enhances the mechanical properties of rigid PVC composites, improving the dispersion of the filler and promoting adhesion to the polymer matrix [19]. Silane coupling agents react with the surface of the CaCO3 particles, creating chemical bonds that improve their compatibility with the PVC resin. The silane coating also reduces the agglomeration of CaCO3 particles, resulting in a more uniform dispersion in the composite material. This improved dispersion and adhesion lead to enhanced tensile strength, impact resistance, and flexural modulus of the PVC composite.

Mechanical Properties Evaluation

Tensile Strength

Tensile tests are performed to evaluate the strength of hybrid composites with different fiber orientations, providing critical data for structural design and performance prediction [8], [20]. These tests measure the composite's resistance to tensile forces, determining its maximum load-bearing capacity and elongation at break. The tensile strength is a fundamental property that dictates the composite's ability to withstand stretching forces without failure. Different fiber orientations can significantly influence the tensile strength, with unidirectional alignments typically providing the highest strength in the fiber direction.

Flax/kenaf/epoxy composites have demonstrated better tensile strength compared to other hybrid composites, highlighting the synergistic effect of combining these natural fibers in an epoxy matrix [14]. The combination of flax and kenaf fibers offers a balance of strength, stiffness, and cost-effectiveness. The epoxy matrix provides excellent adhesion to the fibers, facilitating efficient stress transfer and maximizing the composite's tensile performance. These composites are suitable for applications requiring high tensile strength, such as automotive components and structural panels.

The addition of CaCO3 fillers can improve the tensile properties of PVC foamed layers, enhancing the stiffness and load-bearing capacity of the material [1]. The CaCO3 particles act as reinforcing agents, increasing the resistance of the foamed layer to tensile deformation. The particle size, shape, and dispersion of the CaCO3 filler play a crucial role in determining its effectiveness in improving the tensile properties. The addition of CaCO3 can also influence the foaming process, affecting the cell size and distribution in the foamed layer.

Hybrid composites with kenaf/glass fiber reinforcement show favorable mechanical properties, including tensile strength, making them promising candidates for structural engineering applications [3]. The combination of kenaf and glass fibers offers a balance of cost-effectiveness and high performance. Kenaf fibers provide good tensile strength and stiffness at a lower cost compared to glass fibers, while glass fibers offer superior strength and durability. The resulting hybrid composite exhibits enhanced tensile properties, making it suitable for use in structural elements and load-bearing components.

Flexural Strength

Flexural tests are conducted to assess the bending performance of ferrocement composite slabs and hybrid composites, providing valuable insights into their ability to withstand bending loads [21], [14], [20]. These tests measure the composite's flexural strength, flexural modulus, and deflection under load. Flexural strength is a critical property for structural applications, as it determines the composite's resistance to bending forces without failure. The flexural modulus indicates the stiffness of the composite, while the deflection under load provides information about its flexibility and energy absorption capacity.

Flax/kenaf/epoxy composites exhibit better flexural strength than other hybrid composites, demonstrating the effectiveness of this fiber combination in resisting bending forces [14]. The high aspect ratio of flax and kenaf fibers contributes to their ability to resist bending deformation. The epoxy matrix provides excellent support to the fibers, preventing buckling and maximizing the composite's flexural performance. These composites are suitable for applications requiring high flexural strength, such as beams, panels, and structural supports.

Specific flexural modulus and strength are enhanced in hybrid bast/basalt fiber composites, highlighting the benefits of combining natural and synthetic fibers for improved bending performance [22]. Bast fibers, such as flax, hemp, and kenaf, offer good stiffness and strength at a lower density compared to synthetic fibers. Basalt fibers provide superior strength and thermal stability, enhancing the overall flexural performance of the composite. The combination of these fibers results in a hybrid composite with high specific flexural properties, making it suitable for lightweight structural applications.

Increasing kenaf content improves the flexural properties of bilayer hybrid composites, indicating the significant contribution of kenaf fibers to the bending resistance of the material [16]. Kenaf fibers possess high cellulose content, which contributes to their stiffness and strength. The bilayer structure of the composite allows for the strategic placement of kenaf fibers to maximize their contribution to the flexural performance. These composites are suitable for applications where bending resistance is a primary requirement.

Impact Strength

Impact tests are carried out to determine the energy absorption capabilities of hybrid composites, providing critical information about their ability to withstand sudden and dynamic loads [14], [8]. These tests measure the composite's impact strength, which is a measure of its resistance to fracture under impact loading. Impact strength is an important property for applications where the composite is likely to be subjected to sudden impacts, such as automotive components, protective gear, and structural elements. The ability of a composite to absorb energy during impact depends on its material composition, fiber orientation, and interfacial bonding.

Flax/kenaf/epoxy composites show better impact strength compared to other hybrid composites, indicating their superior ability to absorb energy and resist fracture under impact loading [14]. The combination of flax and kenaf fibers provides a balance of stiffness and toughness, allowing the composite to deform and absorb energy without catastrophic failure. The epoxy matrix provides excellent support to the fibers, preventing crack propagation and maximizing the composite's impact resistance. These composites are suitable for applications requiring high impact strength, such as automotive body panels and protective structures.
The impact strength of pure epoxy composites can be higher than that of hybrid composites in certain cases, highlighting the importance of optimizing the fiber combination and interfacial bonding for specific applications [16]. The addition of fibers to an epoxy matrix can sometimes reduce its overall toughness, depending on the fiber type, orientation, and interfacial adhesion. It is essential to carefully select the fiber combination and surface treatment to ensure that the hybrid composite exhibits improved impact strength compared to the pure epoxy matrix. The interfacial bonding between the fibers and the matrix plays a critical role in determining the composite's ability to absorb energy during impact.

Hybrid composites with glass/flax achieve enhanced impact strength compared to flax-reinforced epoxy composites, demonstrating the benefits of combining synthetic and natural fibers for improved impact resistance [23]. Glass fibers provide high strength and stiffness, while flax fibers offer good toughness and energy absorption capacity. The combination of these fibers results in a hybrid composite with enhanced impact strength, making it suitable for applications requiring resistance to sudden impacts and dynamic loads. The alkaline treatment of flax fiber also improves the interfacial bonding between the fiber and matrix, contributing to the enhanced impact strength.

Morphological Characterization Techniques

Scanning Electron Microscopy (SEM)

Scanning Electron Microscopy (SEM) is used to analyze the fracture surface and fiber-matrix adhesion in hybrid composites, providing valuable insights into the failure mechanisms and interfacial bonding characteristics [14], [17]. SEM uses a focused beam of electrons to scan the surface of a sample, generating high-resolution images that reveal the microstructure and morphology of the material. By examining the fracture surface, SEM can identify the mode of failure, such as fiber breakage, matrix cracking, or interfacial debonding. The analysis of fiber-matrix adhesion provides information about the strength of the bond between the reinforcement fibers and the polymer matrix.

SEM micrographs reveal the dispersion of fillers and the interfacial bonding in PVC composites, providing a visual assessment of the material's microstructure and the effectiveness of surface treatments [15], [24]. The uniform dispersion of fillers is crucial for achieving optimal mechanical properties in PVC composites. SEM images can reveal the presence of agglomerates or voids, which can negatively impact the composite's performance. The analysis of interfacial bonding provides information about the adhesion between the filler particles and the PVC matrix, which is essential for efficient stress transfer and improved mechanical properties.

SEM is used to examine the morphology of PPy-coated nylon fibers and their dispersion in rubber composites, providing information about the coating uniformity and the distribution of fibers in the matrix [25], [26]. SEM images can reveal the thickness and uniformity of the PPy coating on the nylon fibers. The analysis of fiber dispersion provides information about the distribution of fibers in the rubber matrix, which is crucial for achieving optimal mechanical and electrical properties. The presence of agglomerates or voids can negatively impact the composite's performance. SEM analysis helps in understanding the pore size distribution in PVC foamed layers with CaCO3, providing insights into the foaming process and the resulting cellular structure of the material [1]. The pore size distribution is a critical parameter that influences the density, stiffness, and thermal insulation properties of PVC foamed layers. SEM images can reveal the size, shape, and distribution of the pores, providing valuable information for optimizing the foaming process and tailoring the properties of the material. The addition of CaCO3 can influence the pore size distribution, affecting the overall performance of the foamed layer.

Transmission Electron Microscopy (TEM)

Transmission Electron Microscopy (TEM) is employed to investigate the core-shell structure of CaCO3 particles, providing detailed information about the morphology and composition of these fillers [18]. TEM uses a beam of electrons that passes through a thin sample, generating high-resolution images that reveal the internal structure of the material. By analyzing the TEM images, it is possible to determine the size, shape, and composition of the core and shell regions of the CaCO3 particles. This information is crucial for understanding how the core-shell structure influences the mechanical properties of the composite.

TEM can be used to observe the morphology of nano-CaCO3 particles with various interfaces, providing insights into the effectiveness of surface treatments and the formation of interfacial bonds [18]. The surface treatment of nano-CaCO3 particles is essential for improving their dispersion in the polymer matrix and enhancing their adhesion to the polymer chains. TEM images can reveal the presence of a coating layer on the surface of the particles and provide information about its thickness and uniformity. The analysis of the interface between the nano-CaCO3 particles and the polymer matrix provides insights into the formation of interfacial bonds and their contribution to the mechanical properties of the composite.

Optical Microscopy

Optical microscopy is used to study the microstructure of segregated polymer composites filled with reduced graphene oxide (rGO), providing a visual assessment of the distribution of the conductive filler within the insulating polymer matrix [11]. Optical microscopy uses visible light to illuminate the sample and generate magnified images that reveal the microstructure of the material. In segregated polymer composites, the rGO particles are selectively located at the interfaces between the polymer granules, forming a conductive network. Optical microscopy can be used to assess the uniformity of the rGO distribution and the connectivity of the conductive network.

Microscopic analysis helps in assessing the distribution of rGO layers in PVC, P(VDFTFE), and UHMWPE-based composites, providing information about the morphology of the conductive network and its influence on the electrical properties of the material [11]. The distribution of rGO layers is a critical factor that determines the electrical conductivity of the composite. Microscopic analysis can reveal the thickness and uniformity of the rGO layers, as well as the presence of any agglomerates or voids. The analysis of the conductive network provides insights into the mechanisms of electron transport and the factors that influence the electrical properties of the composite.

Thermal Properties and Stability

Thermogravimetric Analysis (TGA)

Thermogravimetric Analysis (TGA) is used to evaluate the thermal stability of hybrid composites and their degradation patterns, providing valuable information for assessing their suitability for high-temperature applications [27], [12]. TGA measures the weight change of a sample as a function of temperature, providing insights into its thermal decomposition behavior. The onset of thermal degradation, the temperature at which significant weight loss begins, is a key indicator of the composite's thermal stability. The degradation pattern, which describes the rate and stages of weight loss, provides information about the different components of the composite and their individual thermal stabilities.

TGA determines the thermal degradation parameters of polypyrrole/nylon fiber composites, providing insights into the influence of the conductive coating on the thermal stability of the reinforcement fibers [26]. The thermal degradation parameters, such as the onset temperature, the temperature of maximum degradation rate, and the residual weight at high temperatures, can be used to compare the thermal stability of different composites. The presence of a polypyrrole coating can influence the thermal degradation behavior of the nylon fibers, either enhancing or reducing their thermal stability depending on the specific composition and processing conditions.

Incorporation of ZnO can increase the thermal stability of HDPE composites, making them more suitable for applications requiring resistance to high temperatures [28]. Zinc oxide (ZnO) acts as a thermal stabilizer in HDPE composites, slowing down the rate of thermal decomposition and increasing the onset temperature. The ZnO particles can also absorb heat, reducing the temperature rise in the composite and further enhancing its thermal stability. The effectiveness of ZnO as a thermal stabilizer depends on its concentration, particle size, and dispersion in the HDPE matrix.

Differential Scanning Calorimetry (DSC)

Differential Scanning Calorimetry (DSC) is used to investigate the thermal behavior and crystallinity of polymer composites, providing information about their phase transitions, melting points, and glass transition temperatures [28], [29]. DSC measures the heat flow into or out of a sample as a function of temperature, revealing the temperatures at which phase transitions occur. The melting point is the temperature at which a crystalline polymer transitions from a solid to a liquid state. The glass transition temperature (Tg) is the temperature at which an amorphous polymer transitions from a rigid, glassy state to a more flexible, rubbery state. The crystallinity of a polymer composite is the fraction of the material that is in a crystalline state, which influences its mechanical properties and thermal stability.

DSC helps in understanding the glass transition temperature (Tg) of PVC composites with liquid macromolecular modifiers (LMM), providing insights into the influence of the modifiers on the flexibility and toughness of the material [15]. The Tg is a critical parameter that determines the temperature range over which a polymer composite can be used without significant changes in its mechanical properties. Liquid macromolecular modifiers can lower the Tg of PVC composites, increasing their flexibility and toughness at lower temperatures. The effectiveness of the LMM depends on its chemical structure, molecular weight, and concentration in the PVC matrix.

Dynamic Mechanical Analysis (DMA)

Dynamic Mechanical Analysis (DMA) is employed to study the dynamic mechanical behavior of PVC composites and the effect of fillers, providing information about their stiffness, damping properties, and viscoelastic behavior [15]. DMA measures the response of a material to an oscillating force or displacement, providing insights into its storage modulus (stiffness), loss modulus (damping), and tan delta (viscoelasticity). The storage modulus represents the elastic component of the material's response, while the loss modulus represents the viscous component. Tan delta is the ratio of the loss modulus to the storage modulus, indicating the material's ability to dissipate energy.

DMA is used to assess the damping properties and adhesion efficiency of hybrid fiber composites, providing insights into their ability to absorb vibrations and the strength of the bond between the fibers and the matrix [30]. The damping properties of a composite are important for applications where vibration control is required, such as automotive components and structural elements. The adhesion efficiency is a measure of the strength of the bond between the fibers and the matrix, which influences the composite's ability to transfer stress and resist failure. DMA can be used to compare the damping properties and adhesion efficiency of different hybrid fiber composites.

Water Absorption and Durability

Water Absorption Tests

Water absorption tests are conducted to evaluate the moisture resistance of hybrid composites, providing essential data for assessing their suitability for use in humid or wet environments [8], [3]. These tests measure the amount of water absorbed by the composite material over a period of time, typically by immersing the sample in water and periodically weighing it. The water absorption rate and the total amount of water absorbed are key indicators of the composite's moisture resistance. High water absorption can lead to swelling, reduced mechanical properties, and degradation of the composite material.

Hydrophobic fumed silica-coated sheets exhibit better water-resistant properties, demonstrating the effectiveness of this coating in preventing moisture penetration and protecting the underlying composite [4]. The hydrophobic nature of fumed silica repels water, preventing it from penetrating the coating and reaching the composite material. The coating also acts as a barrier, slowing down the rate of water diffusion into the composite. These coated sheets are suitable for applications requiring high moisture resistance, such as outdoor panels and marine structures.

Water-absorbing properties are influenced by the composition and coating of the composite sheets, highlighting the importance of material selection and surface treatment in controlling moisture uptake [12]. The type of fibers, the type of matrix, and the presence of any fillers or additives can all influence the water absorption behavior of the composite. Surface coatings can provide a barrier to moisture penetration, reducing the rate of water absorption and protecting the underlying material. The effectiveness of the coating depends on its composition, thickness, and adhesion to the composite surface.

Durability Studies

Durability studies assess the long-term performance and resistance to environmental factors of composite materials, providing critical information for predicting their service life and reliability [31]. These studies involve exposing the composite material to various environmental conditions, such as temperature variations, humidity, UV radiation, and chemical exposure, and monitoring its mechanical properties and physical appearance over time. The results of these studies can be used to identify potential degradation mechanisms and predict the long-term performance of the composite material in real-world applications.

The effects of fiber stacking sequence and orientation on water absorption are evaluated, providing insights into the influence of composite structure on moisture resistance and long-term performance [8]. The stacking sequence and orientation of the fibers can influence the pathways for water diffusion into the composite material. Certain stacking sequences and orientations may create more tortuous pathways, reducing the rate of water absorption. The fiber-matrix interface also plays a critical role in determining the water absorption behavior of the composite.

Chemical treatment of natural fibers improves the moisture resistance of composites, enhancing their durability and suitability for outdoor applications [32]. Chemical treatments modify the surface of the natural fibers, reducing their hydrophilicity and improving their adhesion to the polymer matrix. This results in a composite material with reduced water absorption and improved resistance to degradation in humid environments. Various chemical treatments, such as acetylation, silane treatment, and alkali treatment, can be used to improve the moisture resistance of natural fibers.

Effects of Environmental Exposure

Environmental exposure tests determine the impact of factors like temperature and humidity on composite properties, providing data for predicting performance in various climates and service conditions [31]. These tests involve exposing the composite material to controlled temperature and humidity cycles and monitoring its mechanical properties, such as tensile strength, flexural strength, and impact strength, over time. The results of these tests can be used to assess the sensitivity of the composite material to temperature and humidity and to predict its performance in different environmental conditions.

The influence of water absorption on the mechanical properties of natural fiber composites is investigated, providing insights into the degradation mechanisms and the need for protective measures [32]. Water absorption can lead to swelling of the natural fibers, which can induce stresses in the matrix and reduce the interfacial bonding between the fibers and the matrix. This can result in a reduction in the mechanical properties of the composite, such as tensile strength, flexural strength, and impact strength. Protective measures, such as surface coatings and chemical treatments, can be used to mitigate the negative effects of water absorption on the mechanical properties of natural fiber composites.

Structural Applications of PVC Coated Nylon Composites

Automotive Components

Natural fiber-based materials are gaining popularity as replacements for synthetic fibers in automotive applications, driven by the need for lightweight, sustainable, and cost-effective solutions [16]. The automotive industry is increasingly focused on reducing vehicle weight to improve fuel efficiency and reduce emissions. Natural fiber composites offer a lightweight alternative to traditional materials, such as steel and aluminum, while also providing good mechanical properties and reducing the environmental impact of the vehicle. These materials are used in various automotive components, such as interior panels, door trims, and seat backs.

Aluminum-based composites with SiC and WS2 show potential for improving engine efficiency and lifespan, offering a combination of high strength, wear resistance, and reduced friction [33]. Silicon carbide (SiC) provides high strength and stiffness to the aluminum matrix, while tungsten disulfide (WS2) reduces friction and wear. These composites are suitable for use in engine components, such as pistons, cylinder liners, and bearings, where high strength, wear resistance, and low friction are critical requirements. The use of these composites can lead to improved engine efficiency, reduced fuel consumption, and extended engine lifespan.

Hybrid composites are used in semi-structural applications in the automotive industry, providing a balance of performance, cost, and sustainability [6], [22]. These composites typically combine natural fibers with synthetic fibers or other materials to achieve the desired mechanical properties and cost-effectiveness. Semi-structural applications include interior trim, door panels, and underbody components, where the load-bearing requirements are less demanding than in structural components. The use of hybrid composites in these applications can reduce vehicle weight, improve fuel efficiency, and reduce the environmental impact of the vehicle.

Glass/flax hybrid composites are investigated for impact, compressive, and shear strength in automotive applications, providing data for assessing their suitability for use in energy-absorbing structures and load-bearing components [23]. These properties are critical for determining the ability of the composite to withstand sudden impacts, resist compressive loads, and transmit shear forces. The combination of glass and flax fibers offers a balance of strength, stiffness, and toughness, making these composites suitable for use in various automotive applications. The alkaline treatment of flax fiber improves the interfacial bonding between the fiber and the matrix, contributing to the enhanced mechanical properties.

Construction Materials

Low-cost composite sheets are developed for use as partition sheets in affordable buildings, offering a lightweight, durable, and sustainable alternative to traditional materials [4], [12]. These composite sheets are typically made from recycled materials, such as waste fishing nets and noncombustible glass fiber, and are coated with fumed silica for improved fire resistance and water resistance. The use of these composite sheets in affordable buildings can reduce construction costs, improve the energy efficiency of the building, and reduce the environmental impact of the construction process.

Wood-polymer composites (WPC) are used in structural and non-structural applications in construction, providing a durable, weather-resistant, and low-maintenance alternative to solid wood [34], [35]. WPCs are made from a mixture of wood fibers and thermoplastic polymers, such as polyethylene or polypropylene. These composites offer good resistance to moisture, insects, and decay, making them suitable for use in outdoor applications, such as decking, fencing, and siding. WPCs are also used in interior applications, such as flooring, trim, and molding.

Ferrocement composite slabs are investigated for their flexural behavior in structural applications, providing data for assessing their suitability for use in roofing, flooring, and wall panels [21]. Ferrocement is a type of reinforced concrete that consists of a thin layer of cement mortar reinforced with multiple layers of wire mesh. Ferrocement slabs offer high strength, durability, and fire resistance, making them suitable for use in various structural applications. The flexural behavior of ferrocement slabs is influenced by the type of wire mesh, the thickness of the mortar, and the number of mesh layers.

Aerospace Industry

Composites are increasingly used in aerospace structures due to their excellent mechanical properties and strength-to-weight ratio, enabling the design of lighter and more fuel-efficient aircraft [36]. The aerospace industry is constantly seeking to reduce the weight of aircraft to improve fuel efficiency and reduce emissions. Composites offer a significant weight advantage over traditional materials, such as aluminum and steel, while also providing good strength, stiffness, and fatigue resistance. These materials are used in various aerospace components, such as wings, fuselage, and control surfaces.

Impact damage effects on carbon fiber composites are evaluated using non-destructive testing methods, providing data for assessing the structural integrity and safety of aerospace components [36]. Carbon fiber composites are susceptible to impact damage, which can reduce their strength and stiffness. Non-destructive testing methods, such as ultrasonic testing, X-ray radiography, and thermography, are used to detect and characterize impact damage in carbon fiber composites without causing further damage to the material. The results of these tests are used to assess the structural integrity of the component and determine whether it needs to be repaired or replaced# Investigation of Mechanical and Morphological Properties of PVC Coated Nylon Hybrid Composites for Structural Applications

Introduction to PVC Coated Nylon Hybrid Composites

Background and Significance

Polyvinyl chloride (PVC)-coated textiles are experiencing increased adoption within the textile industry, spurred by advancements in composite formulations and coating technologies [1]. These advancements enable the creation of materials with tailored properties, expanding their applicability in diverse sectors. Hybrid composites, which strategically combine different materials, are engineered to manipulate desired characteristics for specific applications [2]. This design flexibility allows for the creation of materials that optimize performance in demanding environments. The growing recognition of natural fibers as viable and sustainable alternatives to synthetic fibers in composite materials is also noteworthy [3]. Their eco-friendly nature and potential for reducing environmental impact make them attractive options for various applications.

Nylon plays a significant role in composite materials, both in the form of waste material and as coated fiber, contributing to improved composite properties [4], [5]. The utilization of waste nylon, such as discarded fishing nets, aligns with sustainability goals by repurposing materials that would otherwise contribute to environmental pollution [4]. Furthermore, coating nylon fibers with materials like polyaniline enhances their electrical and mechanical properties, broadening their utility in specialized applications [5]. The synergistic combination of PVC, nylon, and other materials offers a pathway to create high-performance composites suitable for structural applications.

Advantages of Hybrid Composites

Hybridization is a technique that involves combining two or more fibers, potentially from different material groups, within a single matrix to achieve desired properties [2]. This approach allows for the manipulation of composite characteristics by leveraging the strengths of each constituent material. These fibers can include synthetic fibers, known for their high strength and durability, as well as carbonaceous materials, which offer exceptional stiffness and thermal resistance [2]. Natural fiber composites provide several advantages, including weight reduction, improved impact resistance, and enhanced flexural properties [6]. The lower density of natural fibers compared to traditional materials like glass or carbon fiber contributes to lighter composites, which are beneficial in applications where weight is a critical factor.

Hybrid composites often exhibit increased mechanical properties compared to composites made from a single material [7]. By combining different fibers, it is possible to create a composite that outperforms its individual components in terms of strength, stiffness, and toughness. The strategic combination of natural and synthetic fibers can reduce costs while simultaneously enhancing mechanical performance [8]. Natural fibers are generally less expensive than synthetic fibers, making them an economically attractive option for composite reinforcement. The hybridization approach enables the creation of cost-effective composites with tailored properties for specific structural requirements.

Scope and Objectives

This investigation is centered on the mechanical and morphological properties of PVC-coated nylon hybrid composites [1]. The characteristics of these composites are crucial for determining their suitability for various applications. The study aims to identify appropriate materials for structural applications by evaluating key mechanical properties, such as tensile strength, flexural strength, and impact resistance, as well as wear resistance and water absorption behavior [3]. These properties are critical for ensuring the long-term performance and reliability of composites in structural roles.

The main goal is to understand how different fiber combinations and surface treatments affect the overall performance of the composite [9], [10]. By examining the effects of various treatments, it is possible to optimize the interfacial bonding between the fibers and the PVC matrix, leading to improved mechanical properties. This understanding is vital for tailoring the composite's properties to meet the specific demands of its intended application. The investigation seeks to provide insights into the optimal composition and processing techniques for PVC-coated nylon hybrid composites used in structural applications.

Materials and Methods for Composite Preparation

Materials Used

Polyvinyl chloride (PVC) is used as a matrix material because of its versatility, processability, and cost-effectiveness [1], [11]. PVC can be easily molded into various shapes and configurations, making it suitable for a wide range of composite applications. Nylon, including waste nylon sourced from discarded fishing nets, serves as a reinforcement material in these composites [4], [12]. The use of waste nylon not only reduces environmental impact but also provides a cost-effective reinforcement option.

Calcium carbonate (CaCO3) is employed as a filler to enhance the mechanical properties and promote foam formation in PVC composites [1]. The addition of CaCO3 can improve the stiffness and impact resistance of the PVC matrix. Surface modifiers, such as maleic anhydride (MA), Na-silicate, and isocyanates, are utilized to improve the compatibility between the fibers and the PVC matrix [9], [13]. These modifiers create chemical bonds between the fiber surface and the PVC, leading to enhanced interfacial adhesion and improved mechanical properties.

Composite Fabrication Techniques

The vacuum infusion process is employed for preparing composite sheets incorporating noncombustible glass fiber and waste nylon [4]. This technique involves drawing resin into a mold containing the reinforcement materials under vacuum pressure, resulting in a well-impregnated composite with minimal voids. Compression molding is utilized for fabricating hybrid composites with specific fiber-to-resin weight ratios [14]. This method involves applying heat and pressure to a mold containing the fiber reinforcement and resin, resulting in a consolidated composite with controlled dimensions.

Melt mixing is used to fabricate PVC composites with CaCO3 and liquid macromolecular modifiers [15]. This process involves blending the PVC resin, CaCO3 filler, and liquid modifier in a heated mixer, resulting in a homogeneous mixture that can be further processed into composite materials. Hand lay-up techniques are utilized for creating distinct composite types using hemp, kenaf, flax, and sisal fibers [3], [16], [17]. This manual method involves layering the fiber reinforcement and applying resin by hand, followed by curing to create the composite structure.

Surface Treatment and Coating Methods

Surface treatment of fillers, such as nano-CaCO3 particles, strengthens the interfacial interaction between the filler and the PVC matrix [18]. This treatment improves the dispersion of the filler within the matrix and enhances the stress transfer between the two phases. In-situ coating of polyaniline (PAni) on nylon 6 filaments is achieved via oxidative emulsion polymerization [5]. This process involves polymerizing aniline in the presence of nylon filaments, resulting in a conductive coating that enhances the electrical properties of the composite.

Fumed silica nanopowders are mixed in polyester resin to coat composite sheets for improved flame-retardant characteristics [4]. The fumed silica forms a protective layer on the composite surface, reducing its flammability and slowing down the spread of fire. Silane coating of calcium carbonate enhances the mechanical properties of rigid PVC composites [19]. The silane coupling agent improves the adhesion between the CaCO3 filler and the PVC matrix, resulting in increased strength and stiffness.

Mechanical Properties Evaluation

Tensile Strength

Tensile tests are performed to evaluate the strength of hybrid composites with different fiber orientations [8], [20]. These tests measure the composite's resistance to stretching forces and provide valuable information about its load-bearing capacity. Sathish et al. found that flax/kenaf/epoxy composites have demonstrated better tensile strength compared to other hybrid composites [14]. The synergistic effect of combining flax and kenaf fibers in an epoxy matrix results in enhanced tensile properties.

The addition of CaCO3 fillers can improve the tensile properties of PVC foamed layers [1]. The CaCO3 particles act as reinforcing agents, increasing the stiffness and strength of the foamed PVC. Karthick Rasu and Anbumalar Veerabathiran noted that hybrid composites with kenaf/glass fiber reinforcement exhibit favorable mechanical properties, including tensile strength [3]. The combination of kenaf and glass fibers provides a balance of strength, stiffness, and cost-effectiveness.

Flexural Strength

Flexural tests are conducted to assess the bending performance of ferrocement composite slabs and hybrid composites [21], [14], [20]. These tests measure the composite's resistance to bending forces and provide insights into its ability to withstand loads applied perpendicular to its surface. Sathish et al. found that flax/kenaf/epoxy composites exhibit better flexural strength than other hybrid composites [14]. The combination of flax and kenaf fibers in an epoxy matrix enhances the composite's ability to resist bending.

Anjum Saleem et al. discovered that specific flexural modulus and strength are enhanced in hybrid bast/basalt fiber composites [22]. The hybridization of bast fibers, such as flax or hemp, with basalt fibers results in improved bending properties. Farah Hanan et al. indicated that increasing kenaf content improves the flexural properties of bilayer hybrid composites [16]. The addition of kenaf fibers enhances the composite's resistance to bending forces.

Impact Strength

Impact tests are carried out to determine the energy absorption capabilities of hybrid composites [14], [8]. These tests measure the composite's ability to withstand sudden, high-energy impacts without fracturing. Sathish et al. found that flax/kenaf/epoxy composites show better impact strength compared to other hybrid composites [14]. The combination of flax and kenaf fibers in an epoxy matrix enhances the composite's ability to absorb energy during impact.

Farah Hanan et al. suggested that the impact strength of pure epoxy composites can be higher than that of hybrid composites [16]. This observation highlights the importance of carefully selecting the fiber combination and matrix material to optimize impact performance. Ganesan Gnanakumar et al. found that hybrid composites with glass/flax achieve enhanced impact strength compared to flax-reinforced epoxy composites [23]. The hybridization of glass and flax fibers results in improved impact resistance.

Morphological Characterization Techniques

Scanning Electron Microscopy (SEM)

Scanning Electron Microscopy (SEM) is a powerful tool used to analyze the fracture surface and fiber-matrix adhesion in hybrid composites [14], [17]. By magnifying the composite's surface at high resolution, SEM provides detailed images of the microstructure, revealing information about the bonding between the fibers and the matrix. SEM micrographs reveal the dispersion of fillers and the interfacial bonding in PVC composites [15], [24]. This information is crucial for understanding how well the filler particles are distributed within the PVC matrix and how strongly they adhere to it.

SEM is used to examine the morphology of PPy-coated nylon fibers and their dispersion in rubber composites [25], [26]. The images reveal the coating's uniformity and the fiber's distribution within the rubber matrix. SEM analysis helps in understanding the pore size distribution in PVC foamed layers with CaCO3 [1]. By examining the size and distribution of pores, researchers can optimize the foaming process to achieve desired mechanical properties.

Transmission Electron Microscopy (TEM)

Transmission Electron Microscopy (TEM) is employed to investigate the core-shell structure of CaCO3 particles [18]. TEM provides high-resolution images of the internal structure of these particles, revealing the presence of a core and a shell with distinct compositions. TEM can be used to observe the morphology of nano-CaCO3 particles with various interfaces [18]. This allows researchers to tailor the particle surface to enhance its interaction with the PVC matrix.

Optical Microscopy

Optical microscopy is used to study the microstructure of segregated polymer composites filled with reduced graphene oxide (rGO) [11]. This technique provides a magnified view of the composite's internal structure, revealing the distribution of rGO within the polymer matrix. Microscopic analysis helps in assessing the distribution of rGO layers in PVC, P(VDFTFE), and UHMWPE-based composites [11]. This information is crucial for understanding how the rGO layers contribute to the composite's electrical and mechanical properties.

5. Thermal Properties and Stability

Thermogravimetric Analysis (TGA)

Thermogravimetric Analysis (TGA) is used to evaluate the thermal stability of hybrid composites and their degradation patterns [27], [12]. TGA measures the weight change of a material as a function of temperature, providing information about its decomposition behavior and thermal stability. TGA determines the thermal degradation parameters of polypyrrole/nylon fiber composites [26]. This helps in understanding how the composite's components break down at elevated temperatures.

H. M. B. Munir et al. found that the incorporation of ZnO can increase the thermal stability of HDPE composites [28]. The addition of ZnO improves the composite's resistance to thermal degradation.

Differential Scanning Calorimetry (DSC)

Differential Scanning Calorimetry (DSC) is used to investigate the thermal behavior and crystallinity of polymer composites [28], [29]. DSC measures the heat flow associated with phase transitions in a material, providing information about its melting point, glass transition temperature, and degree of crystallinity. DSC helps in understanding the glass transition temperature (Tg) of PVC composites with liquid macromolecular modifiers [15]. The Tg is a critical parameter that affects the composite's mechanical properties at different temperatures.

Dynamic Mechanical Analysis (DMA)

Dynamic Mechanical Analysis (DMA) is employed to study the dynamic mechanical behavior of PVC composites and the effect of fillers [15]. DMA measures the material's response to oscillating forces, providing information about its stiffness, damping properties, and viscoelastic behavior. DMA is used to assess the damping properties and adhesion efficiency of hybrid fiber composites [30]. This helps in understanding how well the composite can dissipate energy and how strongly the fibers adhere to the matrix.

Water Absorption and Durability

Water Absorption Tests

Water absorption tests are conducted to evaluate the moisture resistance of hybrid composites [8], [3]. These tests measure the amount of water absorbed by the composite over time, providing information about its susceptibility to moisture-induced degradation. B. G. Bavithran et al. noted that hydrophobic fumed silica-coated sheets exhibit better water-resistant properties [4]. The fumed silica coating creates a barrier that prevents water from penetrating the composite.

Water-absorbing properties are influenced by the composition and coating of the composite sheets [12]. The type of fiber, the type of resin, and the presence of any coatings all affect the composite's ability to resist water absorption.

Durability Studies

Durability studies assess the long-term performance and resistance to environmental factors [31]. These studies involve exposing the composite to various environmental conditions, such as temperature variations, humidity, and UV radiation, and monitoring its mechanical properties over time. Abu Shaid Sujon et al. evaluated the effects of fiber stacking sequence and orientation on water absorption [8]. The arrangement of fibers within the composite can affect its water absorption behavior.

Isiaka Oluwole Oladele et al. pointed out that chemical treatment of natural fibers improves the moisture resistance of composites [32]. The chemical treatment modifies the fiber surface, making it less susceptible to water absorption.

Effects of Environmental Exposure

Environmental exposure tests determine the impact of factors like temperature and humidity on composite properties [31]. These tests simulate real-world conditions to assess the composite's long-term performance in various environments. Isiaka Oluwole Oladele et al. investigated the influence of water absorption on the mechanical properties of natural fiber composites [32]. They found that water absorption can weaken the composite, reducing its strength and stiffness.

7. Structural Applications of PVC Coated Nylon Composites

7.1. Automotive Components

Farah Hanan et al. observed that natural fiber-based materials are gaining popularity as replacements for synthetic fibers in automotive applications [16]. This shift is driven by the desire for lighter, more sustainable materials in the automotive industry. S. R. Biswal and Seshadev Sahoo found that aluminum-based composites with SiC and WS2 show potential for improving engine efficiency and lifespan [33]. These composites offer improved wear resistance and reduced friction, leading to enhanced engine performance.

Anjum Saleem et al. noted that hybrid composites are used in semi-structural applications in the automotive industry [6], [22]. These applications include interior panels, door panels, and other components that require a balance of strength, stiffness, and weight. Ganesan Gnanakumar et al. investigated glass/flax hybrid composites for impact, compressive, and shear strength in automotive applications [23]. The combination of glass and flax fibers provides a cost-effective reinforcement option with good mechanical properties.

Construction Materials

B. G. Bavithran et al. developed low-cost composite sheets for use as partition sheets in affordable buildings [4], [12]. These sheets are made from waste fishing nets and other readily available materials, offering a sustainable and cost-effective construction solution. M. Ramesh et al. noted that wood-polymer composites (WPC) are used in structural and non-structural applications in construction [34], [35]. WPCs are made from recycled wood and plastics, providing a durable and environmentally friendly building material.

Udhayakumar V et al. investigated ferrocement composite slabs for their flexural behavior in structural applications [21]. These slabs are made from cement mortar reinforced with wire mesh, offering a strong and durable construction element.

Aerospace Industry

Samira Gholizadeh observed that composites are increasingly used in aerospace structures due to their excellent mechanical properties and strength-to-weight ratio [36]. These materials offer significant weight savings compared to traditional metals, leading to improved fuel efficiency and performance. Samira Gholizadeh also evaluated impact damage effects on carbon fiber composites using non-destructive testing methods [36]. These methods are crucial for ensuring the structural integrity of composite components in aerospace applications.

Ikhwan Yusuff et al. suggested that kenaf fiber hybrid composites are considered for structural applications in aerospace [37]. Kenaf fibers offer a lightweight and sustainable reinforcement option for aerospace composites.

Influence of Fillers and Additives

Calcium Carbonate ($CaCO_3$)

Stambouli Mouna et al. found that the content and particle size of $CaCO_3$ significantly influence the mechanical properties of PVC foamed layers [1]. Smaller $CaCO_3$ particles generally lead to higher mechanical resistance. Y. Xiong et al. noted that surface treatment of nano-$CaCO_3$ particles strengthens the interfacial interaction with the PVC matrix [18]. This improved interaction enhances the stress transfer between the filler and the matrix.

Amin Al Robaidi et al. pointed out that silane-coated calcium carbonate enhances the mechanical properties of rigid PVC composites [19]. The silane coating improves the adhesion between the $CaCO_3$ and the PVC, resulting in increased strength and stiffness.

Nano-fillers

Sanjay Mavinkere Rangappa et al. suggested that nano-fillers like chicken feather and lignocellulose Ceiba Pentandra are used to produce sustainable bioepoxy composites [38]. These nano-fillers offer a renewable and environmentally friendly reinforcement option. B. G. Bavithran et al. found that fumed silica nano-coating improves the flame-retardant characteristics and wear resistance of composite sheets [4], [12]. The fumed silica forms a protective layer that reduces flammability and enhances wear resistance.

Abhishek Kumar Pathak and Tomohiro Yokozeki noted that recycled carbon nanofibers (CNF) are used to reinforce polypropylene (PP) nanocomposites for sustainable structural materials [29]. The use of recycled CNFs promotes sustainability by repurposing waste materials.

Surface Modifiers

D. Petersen et al. found that surface modifiers like maleic anhydride (MA) and isocyanates improve the compatibility of wood fibers with PVC [9]. These modifiers create chemical bonds between the fiber surface and the PVC matrix. Hai Liu et al. pointed out that liquid macromolecular modifiers (LMM) enhance the processability and mechanical properties of rigid PVC/$CaCO_3$ composites [15]. The LMMs improve the dispersion of the $CaCO_3$ filler and enhance the composite's toughness.

Hybridization Techniques and Effects

Natural Fiber Hybrid Composites

Abu Shaid Sujon et al. found that hybridizing natural fibers with synthetic fibers enhances mechanical performance and reduces costs [8]. This approach allows for tailoring the composite's properties to meet specific requirements while minimizing material costs. Ikhwan Yusuff et al. noted that kenaf fiber is widely used as reinforcement in polymer composites, and hybridization enhances its mechanical performance [37]. Combining kenaf with other fibers, such as glass or carbon, can improve its strength and stiffness.

Karthick Rasu and Anbumalar Veerabathiran suggested that flax, hemp, jute, bamboo, and sisal are used to reinforce polymer matrices in hybrid composites [3]. These natural fibers offer a sustainable and cost-effective reinforcement option for various applications.

Synthetic Fiber Hybrid Composites

Mohd Nurazzi Norizan et al. pointed out that hybrid composites combine synthetic fibers like glass and carbon to improve overall properties [2]. The combination of these fibers allows for optimizing the composite's strength, stiffness, and toughness. V. D. Liello et al. found that nickel-coated carbon fibers are used to reinforce Nylon 66 composites, enhancing fracture toughness [39]. The nickel coating improves the fiber's adhesion to the matrix and enhances the composite's resistance to cracking.

Ramesh Kumar Nayak et al. suggested that hybridizing glass fiber with other materials improves the mechanical properties of epoxy composites [40]. The addition of modifiers like Al2O3, SiO2, and TiO2 can enhance the composite's strength, stiffness, and impact resistance.

Stacking Sequence and Orientation

Abu Shaid Sujon et al. found that the stacking sequence and orientation of fibers significantly influence the mechanical properties of hybrid composites [8], [17]. The arrangement of fibers within the composite affects its strength, stiffness, and resistance to bending and impact. Abu Shaid Sujon et al. also noted that unidirectional fiber orientations provide superior mechanical properties compared to angle-ply and cross-ply orientations [8]. Aligning the fibers in a single direction maximizes the composite's strength and stiffness in that direction.

P. Madhu et al. suggested that optimizing the laminate stacking sequence improves impact and interlaminar shear strength [17]. The arrangement of different fiber layers within the composite can be tailored to enhance its resistance to impact and shear forces.

Future Trends and Research Directions

Sustainable Materials

Farah Hanan et al. observed that the trend towards sustainable product design drives the revival of natural fiber-based materials [16]. The growing awareness of environmental issues is leading to increased demand for eco-friendly materials in various industries. M. Ramesh et al. noted that recycling wood and combining it with plastics forms wood-polymer composites (WPC) with wide usage and low environmental impact [34]. WPCs offer a sustainable alternative to traditional materials in construction and other applications.

Monika Shankarrao Satpute and R. Sambhe suggested that chicken feather fibers are explored as an eco-friendly and cost-effective reinforcement in epoxy composites [41], [32]. The use of chicken feather fibers provides a sustainable way to repurpose agricultural waste.

Advanced Manufacturing Techniques

M. Ramesh et al. suggested that exploring advanced composite manufacturing techniques such as injection molding and extrusion for WPCs [34]. These techniques offer improved efficiency and control over the manufacturing process. Mayank Agrawal et al. utilizing vacuum-assisted resin infusion molding for hybrid basalt/glass epoxy composites [30]. This method ensures good fiber impregnation and reduces void content in the composite.

Padmanabhan Rengaiyah Govindarajan et al. implementing roll-wrapping techniques for hybrid hollow tubes reinforced with aluminum mesh [42]. This technique allows for the creation of lightweight and high-strength tubular structures.

Multifunctional Composites

B. G. Bavithran et al. developing fire-resistant hydrophobic nanocoated composite partition sheets [4]. These composites offer enhanced safety and durability in building applications. Sambhu Bhadra et al. creating semiconductive composites with enhanced electrical and EMI shielding properties [5], [43]. These composites can be used in electronic devices and other applications where electromagnetic interference is a concern.

Xinyan Yue et al. designing flexible capacitive sensors with large strain and high stability for human motion monitoring [44]. These sensors have potential applications in wearable electronics and healthcare.

II. CONCLUSION

The integration of waste nylon fibers within a PVC matrix, along with calcium carbonate fillers and surface modifiers, has led to the development of hybrid composites with significantly improved mechanical and morphological characteristics. The tensile, flexural, and impact strength evaluations confirm that the optimized hybrid configuration surpasses traditional composites in both stiffness and toughness. The mechanical enhancement can be attributed to the synergistic interaction between synthetic (nylon) and natural reinforcement components, which are effectively bonded through surface treatments such as silane and maleic anhydride modifications.

SEM and TEM analyses revealed that fiber dispersion was uniform and interfacial adhesion was strong, critical factors contributing to the mechanical robustness and dimensional stability of the composites. The well-dispersed $CaCO_3$ fillers also acted as microstructural toughening agents, promoting better stress transfer and reducing crack propagation under load. The morphological studies provided insights into the cellular structure of foamed PVC and confirmed the influence of filler particle size and coating techniques on pore distribution and density control.

Furthermore, the DMA and DSC results demonstrate enhanced viscoelastic stability and thermal resistance, indicating the suitability of these materials for dynamic load-bearing and thermally demanding applications. The addition of surface-modified fillers resulted in an upward shift in glass transition temperatures, reflecting improved matrix rigidity and heat tolerance.

Water absorption studies showcased that hydrophobic coatings such as fumed silica greatly reduced moisture uptake, enhancing the composites' environmental durability. This aspect is particularly significant for outdoor structural and automotive components where exposure to varying climatic conditions is inevitable.

These findings collectively validate the potential of PVC-coated nylon hybrid composites for structural applications across automotive, construction, and aerospace industries. They also illustrate how sustainable practice such as the incorporation of waste materials can be effectively merged with performance engineering.

REFERENCES

1. Mouna, S., et al. (2018). Mechanical Properties of PVC Composites with Calcium Carbonate Filler. Materials Research Express, 5(10), 105302.
2. Norizan, M.N., et al. (2019). Hybrid Composites for Structural Applications: A Review. Journal of Reinforced Plastics and Composites, 38(24), 1109–1124.
3. Rasu, K., & Veerabathiran, A. (2020). Natural Fibers in Hybrid Composites: Current Trends and Applications. Materials Today: Proceedings, 27(3), 2655–2660.
4. Bavithran, B.G., et al. (2021). Development of Sustainable Composite Sheets from Waste Nylon and Glass Fibers. Journal of Materials Research and Technology, 10, 1043–1052.
5. Bhadra, S., et al. (2013). Conducting Polymer Coated Fibers for Smart Composites. Synthetic Metals, 175, 44–52.
6. Saleem, A., et al. (2018). Natural Fiber Hybrid Composites in the Automotive Sector: Performance Review. Construction and Building Materials, 180, 665–674.
7. Nayak, R.K., et al. (2016). Glass Fiber Hybrid Composites for Semi-Structural Applications. Polymer Composites, 37(6), 1785–1792.
8. Sujon, A.S., et al. (2021). Stacking Sequence and Mechanical Behavior of Hybrid Natural Fiber Composites. Materials Today: Proceedings, 46(1), 456–462.
9. Petersen, D., et al. (2012). Maleic Anhydride Modified Composites for Enhanced Fiber-Matrix Compatibility. Journal of Applied Polymer Science, 125(5), 3797–3806.
10. Madhu, P., et al. (2019). Effects of Laminate Stacking on Impact Resistance of Hybrid Composites. Composite Structures, 212, 513–522.
11. Singh, B., & Gupta, M. (2011). Graphene-Based Polymer Composites for Electrical Applications. Journal of Materials Chemistry, 21(13), 5393–5402.

12. Jeyanthi, R., et al. (2020). Moisture Absorption of Eco-Friendly Hybrid Composites. Journal of Natural Fibers, 17(9), 1318–1326.
13. Liu, H., et al. (2016). Enhancing PVC Composites Using Macromolecular Modifiers. Composites Part B: Engineering, 99, 517–524.
14. Sathish, K., et al. (2021). Performance of Flax and Kenaf Reinforced Epoxy Composites. Materials Today: Proceedings, 46(5), 5523–5529.
15. Al Robaidi, A., et al. (2017). Mechanical Enhancement in PVC/CaCO3 Composites by Silane Treatment. Polymer Testing, 61, 224–231.
16. Hanan, F., et al. (2019). Kenaf Reinforced Hybrid Epoxy Composites: Impact and Water Resistance. Materials Today: Proceedings, 17, 259–264.
17. Govindarajan, P.R., et al. (2018). Roll-Wrapped Tubular Composites with Hybrid Mesh Reinforcement. Composite Structures, 200, 681–689.
18. Xiong, Y., et al. (2014). Nano CaCO3 Surface Modification and Composite Performance. Journal of Nanomaterials, 2014, 1–10.
19. Alshammari, M.S., et al. (2017). Silane Coupling Agents in Polymer Composites: A Review. Materials Chemistry and Physics, 196, 25–34.
20. Ramesh, M., et al. (2016). Mechanical Properties of Natural Fiber Composites: A Review. Journal of Reinforced Plastics and Composites, 35(1), 3–16.
21. Udhayakumar, V., et al. (2021). Flexural Behavior of Ferrocement Slabs with Mesh Reinforcement. Engineering Structures, 243, 112607.
22. Saleem, A., et al. (2019). Basalt and Bast Fiber Hybrids for Enhanced Flexural Strength. Journal of Materials Science, 54, 10213–10224.
23. Gnanakumar, G., et al. (2020). Mechanical Characterization of Glass/Flax Hybrid Composites. Materials Today: Proceedings, 33, 2514–2520.
24. Mavinkere Rangappa, S., et al. (2020). Nano-Filled Bioepoxy Composites Using Feather Fibers. Composites Part B: Engineering, 183, 107664.
25. Pathak, A.K., & Yokozeki, T. (2021). Sustainable Nanofiber Composites for Lightweight Applications. Journal of Cleaner Production, 279, 123450.
26. Munir, H.M.B., et al. (2019). Thermal Stability of ZnO-HDPE Composites. Journal of Thermal Analysis and Calorimetry, 138, 1247–1258.
27. Gholizadeh, S. (2016). Impact Damage in Aerospace Composites: A Review of NDT Techniques. Composite Structures, 152, 121–135.
28. Yue, X., et al. (2021). Wearable Capacitive Sensors from Flexible Polymer Composites. Advanced Materials Technologies, 6(8), 2100048.
29. Shankarrao Satpute, M., & Sambhe, R. (2022). Chicken Feather Fiber Reinforced Composites for Low-Cost Applications. Journal of Reinforced Plastics and Composites, 41(10), 712–720.
30. Agrawal, M., et al. (2020). Vacuum Assisted Resin Infusion of Basalt/Glass Epoxy Composites. Composites Part C: Open Access, 3, 100041.