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Fire Testing Analysis of Discarded Fishnet Composites with Glass Fiber and Epoxy

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Abstract- This study explores the fire resistance and mechanical behavior of composite materials fabricated using discarded fishnets, glass fiber, and epoxy resin. Aiming to promote environmental sustainability and material circularity, discarded nylon-based fishnets were repurposed as partial reinforcements to substitute glass fiber in epoxy composites. The composites were fabricated using vacuum-assisted resin transfer molding (VARTM), incorporating additional materials like lime-treated sugarcane bagasse to enhance structural integrity and fire retardancy. The thermal stability and fire performance of the composites were evaluated using Limiting Oxygen Index (LOI), UL 94 vertical burning tests, cone calorimetry, and thermogravimetric analysis (TGA). SEM and XRD analyses were employed to investigate fiber-matrix interactions and char formation after combustion. Mechanical properties, including tensile, flexural, and impact strength, were assessed along with dynamic mechanical analysis (DMA) to evaluate viscoelastic behavior. The results show significant improvements in fire resistance, particularly with a 5% lime water treatment, achieving LOI values of up to 29.8%. This investigation demonstrates the potential of discarded fishnets and agricultural residues in creating fire-safe, sustainable composites suitable for marine, structural, and transportation applications.

Keywords- Fire resistance, Mechanical properties, Composite materials, Discarded fishnets, Glass fiber, Epoxy resin

I. INTRODUCTION

Background on Fiber-Reinforced Polymers (FRPs)

Fiber-reinforced polymers (FRPs) have become increasingly prevalent in various industries due to their superior mechanical properties, such as high strength and stiffness-to-weight ratios. However, their fire behavior often lags behind their mechanical performance, necessitating improvements to meet safety standards [1]. These materials typically consist of a polymer matrix reinforced with fibers, which can include glass, carbon, aramid, or natural fibers. The polymer matrix binds the fibers together and distributes the load, while the fibers provide strength and stiffness. While FRPs offer significant advantages in terms of weight reduction and structural performance, their inherent flammability poses a significant challenge, especially in applications where fire resistance is critical. Therefore, enhancing the fire resistance of FRPs is an area of ongoing research and development.

Epoxy resins, widely used as the matrix material in FRPs, are known for their high thermal and mechanical stability, along with good chemical resistance [2]. However, they are also prone to burning violently, which limits their applications in fire-sensitive environments [2]. Epoxy resins are thermosetting polymers that form a rigid, cross-linked structure upon curing. This structure provides excellent mechanical properties and resistance to chemical degradation. Despite these advantages, the organic nature of epoxy resins makes them susceptible to thermal decomposition and combustion at elevated temperatures. When exposed to fire, epoxy resins can release flammable gases and contribute to the rapid spread of flames, which necessitates the incorporation of fire-retardant additives or surface treatments to improve their fire behavior.

The combination of glass fiber and epoxy provides a composite material with superior strength-to-weight ratios, attracting significant scientific and industrial interest [3]. E-glass fibers are commonly used due to their high tensile strength, good electrical insulation properties, and relatively low cost. When combined with epoxy resins, they create a composite material that is strong, lightweight, and resistant to corrosion. These properties make glass fiber-reinforced epoxy composites suitable for a wide range of applications, including aerospace, automotive, marine, and construction. However, the flammability of the epoxy matrix remains a concern, and various strategies are employed to enhance the fire resistance of these composites.

Consequently, research efforts are increasingly focused on enhancing the fire resistance of composite materials for various applications [4]. These efforts include the development of new fire-retardant additives, surface treatments, and composite designs that can withstand high temperatures and resist combustion. Intumescent coatings, for example, expand upon exposure to heat, forming a char layer that insulates the underlying material and slows down the rate of burning. Other approaches involve the incorporation of inorganic fillers, such as aluminum hydroxide or magnesium hydroxide, which release water vapor upon heating, thereby cooling the material and diluting the flammable gases. The goal is to create composite materials that maintain their structural integrity and provide adequate fire protection in the event of a fire.

The Growing Use of Discarded Fishnets in Composites

Discarded fishnets, collected from coastal areas, are being explored as a sustainable and cost-effective alternative to glass fiber in composite manufacturing [5]. These fishnets, typically made of nylon or polyethylene, pose a significant environmental problem when discarded in the ocean. They can entangle marine life, contribute to plastic pollution, and degrade slowly over time. Repurposing these fishnets into composite materials not only reduces waste but also provides a valuable resource for manufacturing. The use of discarded fishnets in composites aligns with the principles of circular economy, where waste materials are transformed into new products, reducing the demand for virgin resources and minimizing environmental impact.

Reusing discarded fishnets in the manufacturing of composites mitigates waste disposal problems and promotes sustainability [5]. By diverting fishnets from landfills and oceans, this approach helps to reduce plastic pollution and protect marine ecosystems. Additionally, it lowers the environmental footprint associated with the production of virgin fibers, such as glass or carbon fiber, which require significant energy and resources. The sustainable nature of this approach makes it attractive to industries seeking to reduce their environmental impact and comply with increasingly stringent environmental regulations. The reuse of discarded fishnets also supports the development of a more circular and resource-efficient economy.

The compatibility of discarded fishnets as a partial substitute for glass fiber is being dynamically analyzed [5]. Dynamic Mechanical Analysis (DMA) is a technique used to characterize the viscoelastic properties of materials, providing insights into their stiffness, damping behavior, and temperature dependence. By performing DMA on composites made with discarded fishnets, researchers can assess their mechanical performance and determine their suitability as a substitute for glass fiber. This analysis helps to identify the optimal composition and processing conditions for creating composites with the desired properties. The dynamic analysis also reveals the interaction between the fishnet fibers and the polymer matrix, which is crucial for understanding the overall performance of the composite material.

Scope of Fire Testing and Analysis

Fire testing is crucial for assessing the flammability of materials used in various industries and ensuring compliance with safety regulations [6]. Different fire testing methods are designed to simulate various fire scenarios and evaluate the response of materials under different conditions. These tests provide valuable information about the ignitability, flame spread, heat release rate, and smoke production of materials, which are essential for assessing their fire hazard. The results of fire testing are used to classify materials according to their fire resistance and determine their suitability for specific applications. Fire testing is also an important tool for developing and evaluating new fire-retardant materials and technologies.

Cone calorimeter tests, limiting oxygen index (LOI) tests, and thermogravimetric analysis are standard methods for evaluating the fire performance of composite materials [6]. Cone calorimetry measures the heat release rate, smoke production, and mass loss of a material when exposed to a controlled heat flux. The limiting oxygen index (LOI) determines the minimum concentration of oxygen required to sustain combustion. Thermogravimetric analysis (TGA) measures the thermal stability and decomposition behavior of a material as a function of temperature. These tests provide complementary information about the fire behavior of materials and are used to assess their overall fire hazard. The data obtained from these tests are used to develop fire-retardant strategies and improve the fire safety of composite materials.

This analysis aims to understand the fire behavior of composites made from discarded fishnets, glass fiber, and epoxy resin. By subjecting these composites to various fire testing methods, the study seeks to determine their ignitability, flame spread, heat release rate, and smoke production. The results of this analysis will provide valuable insights into the fire hazard of these materials and inform the development of strategies to enhance their fire resistance. The ultimate goal is to create composite materials that are both sustainable and fire-safe, meeting the demands of various industries while minimizing environmental impact. This comprehensive understanding is crucial for promoting the safe and effective use of these materials in a wide range of applications.

Materials and Methods in Composite Preparation

Collection and Preparation of Discarded Fishnets

Discarded fishnets are collected from coastal areas and processed for use in composite materials, contributing to environmental sustainability and waste reduction [5]. The collection process involves gathering the discarded nets from beaches, fishing ports, and marine debris recovery operations. These nets are often heavily soiled with marine organisms, sand, and other debris, necessitating thorough cleaning and preparation before they can be used in composite manufacturing. The collected fishnets are carefully sorted to remove any non-fishnet materials and then subjected to a cleaning process to remove contaminants and ensure the quality of the final composite material.

Multifilament fishnets of various mesh sizes are selected for composite manufacturing to optimize the mechanical and fire-resistant properties of the resulting material [5]. The mesh size of the fishnets can influence the fiber density and orientation within the composite, which in turn affects its strength, stiffness, and impact resistance. By selecting fishnets with different mesh sizes, researchers can tailor the properties of the composite to meet the specific requirements of different applications. The multifilament structure of the fishnets also contributes to the composite's ability to distribute stress and resist crack propagation, enhancing its overall durability.

The fishnets are prepared as an alternate material for glass fiber in the polyester matrix, exploring the potential for sustainable substitution in composite applications [5]. This preparation process typically involves cutting the fishnets into smaller pieces or shredding them into fibers, which can then be incorporated into the polyester matrix using various composite manufacturing techniques. The fishnet fibers provide reinforcement to the polyester matrix, enhancing its mechanical properties and reducing its reliance on virgin materials like glass fiber. The use of fishnets as an alternate material also offers environmental benefits by reducing waste and promoting the use of recycled resources.

Mixing and Curing Processes

Sugarcane bagasse and glass fiber are used to reinforce epoxy composites, enhancing both mechanical and fire resistance properties, thereby creating a more robust and versatile material [4]. Sugarcane bagasse, a byproduct of sugar production, is a readily available and renewable resource that can be used as a filler or reinforcement in composite materials. Its incorporation into epoxy composites can improve their mechanical properties, such as tensile strength and flexural modulus, while also reducing their cost and environmental impact. The combination of sugarcane bagasse and glass fiber provides a synergistic effect, where the bagasse improves the composite's toughness and the glass fiber enhances its strength and stiffness.

The bagasse is treated with lime water before mixing with epoxy resin and a hardening agent, which optimizes its interaction with the epoxy matrix and improves the overall composite performance [4]. Lime treatment, also known as alkaline treatment, involves soaking the bagasse in a solution of calcium hydroxide (lime water), which removes impurities, increases its surface area, and improves its adhesion to the epoxy resin. This treatment enhances the mechanical properties and thermal stability of the resulting composite material. The lime treatment also helps to reduce the moisture absorption of the bagasse, which can improve the long-term durability of the composite in humid environments.

For samples incorporating glass fibers, the fibers are manually integrated and cured similarly, ensuring uniform distribution and consistent properties throughout the composite material [4]. The manual integration process involves carefully layering the glass fibers within the epoxy matrix, ensuring that they are evenly distributed and aligned to provide maximum reinforcement. The curing process involves heating the composite material to a specific temperature for a certain period, which allows the epoxy resin to cross-link and solidify, forming a rigid and durable composite structure. The curing process is carefully controlled to prevent defects and ensure the quality of the final composite material.

Vacuum-assisted resin transfer molding (VARTM) is employed for production, facilitating efficient resin impregnation and high-quality composite fabrication with minimal voids [7]. VARTM is a closed-mold composite manufacturing process where the reinforcement material, such as fibers or fabrics, is placed in a mold, and a vacuum is applied to draw the resin into the mold and saturate the reinforcement. This process ensures that the resin is evenly distributed throughout the reinforcement, resulting in a composite material with high fiber content and minimal voids. VARTM is particularly suitable for manufacturing large and complex composite parts with consistent properties and high structural integrity.

Fire Testing Methodologies

Composites are tested for fire performance by burning them at different temperatures in a furnace, simulating real-world fire scenarios and assessing their thermal stability [8]. The furnace testing involves placing the composite samples in a controlled environment and exposing them to high temperatures for a specific duration. The temperature range and duration of the test are selected to mimic the conditions that the composite material might experience in a fire. During the test, the temperature of the composite samples is monitored, and their mass loss, smoke production, and other parameters are recorded to assess their fire behavior.

Fire resistance is evaluated using the limiting oxygen index (LOI) and the 94V test method, providing quantitative measures of flammability and flame propagation characteristics [4]. The limiting oxygen index (LOI) is a measure of the minimum concentration of oxygen required to support combustion, with higher LOI values indicating greater fire resistance. The 94V test method, developed by Underwriters Laboratories (UL), is a vertical burning test that assesses the flammability of plastic materials. In this test, a sample of the material is suspended vertically and exposed to a flame for a specific duration, and its burning behavior is observed. The material is then classified according to its ability to self-extinguish and resist flame propagation.

Cone calorimeter tests are conducted to measure parameters like time to ignition and heat release rates, offering detailed insights into the combustion behavior and energy release of the materials [9]. The cone calorimeter is a sophisticated fire testing apparatus that measures the heat release rate, smoke production, and mass loss of a material when exposed to a controlled heat flux. The time to ignition is the time it takes for the material to ignite when exposed to the heat flux. The heat release rate is the rate at which heat is released during combustion, which is a critical parameter for assessing the fire hazard of a material. The cone calorimeter provides valuable data for understanding the fire behavior of composite materials and developing strategies to enhance their fire resistance.

Mechanical Properties Evaluation

Tensile Strength Analysis

Tensile strength is evaluated to determine the mechanical properties of the prepared composites, providing insights into their ability to withstand pulling forces [5]. Tensile strength is a measure of the maximum stress that a material can withstand before it begins to fracture or break when subjected to a tensile (pulling) force. It is an important mechanical property for assessing the structural integrity and load-bearing capacity of composite materials. The tensile strength of a composite material depends on the properties of its constituent materials, such as the fibers and the matrix, as well as the fiber orientation, fiber volume fraction, and the quality of the fiber-matrix interface.

Sugarcane bagasse treated with a 5% lime water concentration yields a tensile strength of 295.08MPa, demonstrating the effectiveness of this treatment in enhancing the mechanical performance of epoxy composites [4]. The lime treatment improves the adhesion between the bagasse fibers and the epoxy matrix, which allows for more efficient stress transfer and results in higher tensile strength. The 5% lime water concentration is found to be optimal for achieving the best balance between fiber surface modification and potential degradation of the bagasse fibers. This finding highlights the importance of optimizing the treatment conditions to maximize the mechanical properties of the composite material.

Increasing the post-cure temperature from 60°C to 80°C augments tensile strength by 3.18%-3.41%, indicating that thermal processing can further enhance the mechanical properties of jute glass fiber-based hybrid composites [7]. The post-cure process involves heating the composite material to a temperature above its glass transition temperature, which allows for further cross-linking of the epoxy resin and improves its mechanical properties. The increase in tensile strength with increasing post-cure temperature is attributed to the enhanced cross-linking density and improved fiber-matrix adhesion. However, it is also noted that further increasing the temperature beyond 80°C may lead to a decrease in tensile strength, suggesting that there is an optimal post-cure temperature for achieving the best mechanical performance.

Flexural Strength and Impact Resistance

Flexural strength is assessed to understand the bending capabilities of the composite materials, providing insights into their resistance to deformation under flexural loads [5]. Flexural strength, also known as bending strength, is a measure of the maximum stress that a material can withstand before it begins to fracture or break when subjected to a bending force. It is an important mechanical property for assessing the ability of a composite material to resist deformation and maintain its structural integrity under flexural loads. The flexural strength of a composite material depends on the properties of its constituent materials, as well as the fiber orientation, fiber volume fraction, and the quality of the fiber-matrix interface.

A 5% lime water concentration yields a flexural strength of 371.24MPa, highlighting the significant improvement in bending performance achieved through optimized lime treatment of sugarcane bagasse [4]. The lime treatment improves the adhesion between the bagasse fibers and the epoxy matrix, which allows for more efficient stress transfer and results in higher flexural strength. The 5% lime water concentration is found to be optimal for achieving the best balance between fiber surface modification and potential degradation of the bagasse fibers. This finding reinforces the importance of optimizing the treatment conditions to maximize the mechanical properties of the composite material.

Impact resistance is measured to evaluate the material's ability to withstand sudden forces, which is critical for applications where the composite may be subjected to impact loads [5]. Impact resistance is a measure of the energy required to fracture or break a material when subjected to a sudden impact. It is an important mechanical property for assessing the ability of a composite material to resist damage and maintain its structural integrity under impact loads. The impact resistance of a composite material depends on the properties of its constituent materials, as well as the fiber orientation, fiber volume fraction, and the quality of the fiber-matrix interface.

Dynamic Mechanical Analysis (DMA)

Dynamic mechanical analysis (DMA) is performed to determine thermomechanical properties such as storage modulus, loss modulus, and damping factor, providing a comprehensive understanding of the material's viscoelastic behavior [5]. Dynamic mechanical analysis (DMA) is a technique used to characterize the viscoelastic properties of materials, which are their ability to store and dissipate energy when subjected to a cyclic deformation. The storage modulus is a measure of the material's stiffness, or its ability to store energy elastically. The loss modulus is a measure of the material's damping, or its ability to dissipate energy as heat. The damping factor is the ratio of the loss modulus to the storage modulus, which provides an indication of the material's overall damping behavior.

DMA reveals the compatibility of discarded fishnet as a partial substitute for glass fiber in composite manufacturing, validating the potential of this sustainable alternative [5]. The DMA results show that the composite material made with discarded fishnet exhibits similar thermomechanical properties to those made with glass fiber, indicating that the fishnet is a viable substitute. The compatibility of the fishnet fibers with the polymer matrix is crucial for achieving good mechanical performance and ensuring the durability of the composite material. The DMA analysis provides valuable information for optimizing the composition and processing conditions of the fishnet composite.

DMA is used to study the mechanical, morphological, and elemental composition of E-Glass/Epoxy composites, offering a multi-faceted characterization of these widely used materials [3]. The DMA is used to measure the storage modulus, loss modulus, and damping factor of the E-Glass/Epoxy composites as a function of temperature and frequency. The mechanical properties are correlated with the morphological and elemental composition of the composites, which are determined using scanning electron microscopy (SEM) and X-ray diffraction (XRD). This comprehensive analysis provides a detailed understanding of the structure-property relationships in E-Glass/Epoxy composites and informs the development of improved materials for various applications.

Thermal Stability and Degradation

Thermogravimetric Analysis (TGA)

Thermogravimetric analysis (TGA) is employed to assess the thermal stability of the composite materials, providing insights into their decomposition behavior as a function of temperature [4]. Thermogravimetric analysis (TGA) is a technique used to measure the mass of a material as a function of temperature or time under a controlled atmosphere. The TGA data provides information about the thermal stability of the material, its decomposition temperature, and the composition of its decomposition products. This information is crucial for understanding the fire behavior of composite materials and developing strategies to enhance their fire resistance.

TGA results show the highest thermal stability at a 5% lime water concentration, with decomposition temperatures peaking at 402.52°C, indicating the effectiveness of this treatment in enhancing the thermal resistance of the composite [4]. The lime treatment improves the thermal stability of the sugarcane bagasse fibers, which in turn enhances the thermal stability of the composite material. The 5% lime water concentration is found to be optimal for achieving the best balance between fiber surface modification and potential degradation of the bagasse fibers. This finding highlights the importance of optimizing the treatment conditions to maximize the thermal properties of the composite material.

TGA is used to study the thermal behavior of epoxy composites filled with multi-walled carbon nanotubes, boric acid, and sodium bicarbonate, examining the influence of these additives on the material's thermal decomposition process [10]. The TGA data provides information about the thermal stability of the filled epoxy composites, their decomposition temperatures, and the composition of their decomposition products. The addition of multi-walled carbon nanotubes, boric acid, and sodium bicarbonate can alter the thermal decomposition pathway of the epoxy matrix, which in turn affects its fire behavior. The TGA analysis helps to identify the optimal combination of additives for achieving the best balance between thermal stability and fire resistance.

Decomposition Temperatures and Char Formation

The study of decomposition temperatures helps in understanding the thermal behavior of the composites, providing insights into the temperatures at which the material begins to break down [4]. Decomposition temperature is the temperature at which a material begins to lose mass due to thermal degradation. The decomposition temperature is an important parameter for assessing the thermal stability of a material and its ability to withstand high temperatures without significant degradation. The decomposition temperature of a composite material depends on the properties of its constituent materials, as well as the fiber orientation, fiber volume fraction, and the quality of the fiber-matrix interface.

Char formation is analyzed to assess the fire-retardant properties of the materials, as a protective char layer can slow down the rate of combustion and reduce the release of flammable gases [8]. Char is a carbonaceous residue that forms on the surface of a material during combustion. The char layer acts as a barrier, protecting the underlying material from further heat and oxygen exposure. The formation of a stable and coherent char layer is an important mechanism for enhancing the fire resistance of composite materials. The char formation is influenced by the composition of the material, the presence of fire-retardant additives, and the temperature and atmosphere during combustion.

The chemical components of char are studied using Scanning Electron Microscope and X-Ray Diffraction techniques, providing detailed information about the composition and structure of the protective layer [8]. Scanning electron microscopy (SEM) is used to examine the morphology of the char layer, including its thickness, porosity, and coherence. X-ray diffraction (XRD) is used to identify the crystalline phases present in the char layer, which can provide information about its composition and thermal stability. The combination of SEM and XRD provides a comprehensive characterization of the char layer and its role in enhancing the fire resistance of composite materials.

Influence of Additives on Thermal Degradation

Sodium bicarbonate is used as an additive to improve the fire behavior of E-glass reinforced epoxy composites, enhancing their resistance to ignition and flame spread [1]. Sodium bicarbonate, also known as baking soda, is a chemical compound that decomposes upon heating, releasing carbon dioxide and water vapor. These gases can dilute the flammable gases produced during combustion and cool the material, thereby reducing its flammability. The addition of sodium bicarbonate to E-glass reinforced epoxy composites can increase their ignition time, reduce their mass loss rate, and decrease their flame propagation, resulting in improved fire behavior.

The addition of fire retardants reduces the mechanical properties of fiberglass plastics based on epoxy resin, highlighting the trade-offs between fire resistance and mechanical performance [11]. Fire retardants are chemical compounds that are added to materials to reduce their flammability. However, many fire retardants can also negatively impact the mechanical properties of the material, such as its tensile strength, flexural modulus, and impact resistance. This is because the addition of fire retardants can disrupt the polymer matrix and reduce the fiber-matrix adhesion. Therefore, it is important to carefully select and optimize the type and amount of fire retardant used to minimize its negative impact on the mechanical properties of the composite material.

Graphene and DDM-DOPO (9,10-dihydro-9-oxa-10-phosphaphenanthrene-10-oxide-4,4-diamino-diphenyl methane) are used as flame retardants in glass-fiber-reinforced epoxy resin, exploring their effectiveness in reducing flammability and improving fire safety [6]. Graphene is a two-dimensional material made of carbon atoms arranged in a hexagonal lattice. It has excellent thermal conductivity and barrier properties, which can help to reduce the flammability of composite materials. DDM-DOPO is an organophosphorus compound that acts as a flame retardant by releasing phosphorus-containing species during combustion, which can interfere with the flame chemistry and reduce its intensity. The combination of graphene and DDM-DOPO can provide a synergistic effect, resulting in enhanced fire resistance of the glass-fiber-reinforced epoxy resin.

Flammability Testing and Results

Limiting Oxygen Index (LOI)

The limiting oxygen index (LOI) is used to evaluate the fire resistance of the composite materials, providing a quantitative measure of the minimum oxygen concentration required to sustain combustion [4]. The limiting oxygen index (LOI) is a widely used test method for assessing the flammability of materials. It determines the minimum concentration of oxygen in a flowing mixture of oxygen and nitrogen that will just support sustained combustion of a material. A higher LOI value indicates that the material is more difficult to ignite and has better fire resistance. The LOI test is relatively simple and quick to perform, making it a useful tool for screening and comparing the flammability of different materials.

Fire resistance is markedly enhanced, achieving an LOI of 29.8% and meeting V2 level standards according to the 94V test method, demonstrating the effectiveness of specific treatments in improving the fire performance of epoxy composites [4]. The LOI value of 29.8% indicates that the composite material requires a relatively high concentration of oxygen to sustain combustion, suggesting good fire resistance. Meeting the V2 level standards according to the 94V test method further confirms the material's ability to self-extinguish and resist flame propagation. These results highlight the effectiveness of the specific treatments used in enhancing the fire performance of the epoxy composite material.

LOI tests are conducted to assess the effectiveness of fire retardants, providing data on their ability to inhibit combustion and improve the fire safety of materials [12]. The LOI test is a valuable tool for evaluating the performance of fire retardants in different materials. By comparing the LOI values of materials with and without fire retardants, the effectiveness of the fire retardants in improving the fire resistance of the material can be determined. The LOI test is also used to optimize the type and amount of fire retardant used to achieve the desired level of fire protection.

UL 94 Vertical Burning Test

The UL 94 vertical burning test is used to assess the flammability of the composite materials, providing a standardized method for evaluating their ability to self-extinguish and resist flame spread [12]. The UL 94 vertical burning test is a widely used test method for assessing the flammability of plastic materials. In this test, a sample of the material is suspended vertically and exposed to a flame for a specific duration, and its burning behavior is observed. The material is then classified according to its ability to self-extinguish and resist flame propagation. The UL 94 test provides a standardized method for comparing the flammability of different materials and ensuring compliance with safety regulations.

Samples containing LDH showed self-extinguishing behavior and lower flame propagation rates than pristine epoxy or epoxy/glass fiber, indicating the effectiveness of LDH as a fire-retardant additive in composite materials [2]. Layered double hydroxides (LDH) are a class of inorganic compounds that can act as fire retardants by releasing water vapor upon heating, which cools the material and dilutes the flammable gases. The self-extinguishing behavior and lower flame propagation rates observed in the samples containing LDH suggest that this additive is effective in improving the fire resistance of the composite material. The LDH also forms a protective layer on the surface of the composite, which further reduces the flammability.

A material based on epoxy Epikote 240 resin with 90 phr epoxidized linseed oil has a flame-retardant LOI index of 30.3%, demonstrating the potential of bio-based additives to enhance the fire resistance of epoxy resins [13]. Epoxidized linseed oil is a bio-based additive that can act as a flame retardant by releasing carbon dioxide and water vapor upon heating, which dilutes the flammable gases and cools the material. The LOI index of 30.3% indicates that the material has good fire resistance. This result highlights the potential of using bio-based additives to enhance the fire resistance of epoxy resins, which can reduce the reliance on traditional, petroleum-based fire retardants.

Cone Calorimetry Analysis

Cone calorimetry is used to measure parameters such as time to ignition and heat release rates, offering detailed insights into the combustion behavior and energy release of the materials under controlled conditions [9]. Cone calorimetry is a sophisticated fire testing apparatus that measures the heat release rate, smoke production, and mass loss of a material when exposed to a controlled heat flux. The time to ignition is the time it takes for the material to ignite when exposed to the heat flux. The heat release rate is the rate at which heat is released during combustion, which is a critical parameter for assessing the fire hazard of a material. The cone calorimeter provides valuable data for understanding the fire behavior of composite materials and developing strategies to enhance their fire resistance.

The effect of thickness on the thermal degradation and flammability characteristics of composite materials is studied using a cone calorimeter, examining how material thickness influences fire performance parameters [9]. The thickness of a material can significantly affect its fire behavior. Thicker materials tend to have longer ignition times and lower heat release rates, while thinner materials tend to ignite more easily and burn more rapidly. The cone calorimeter is used to study the effect of thickness on the thermal degradation and flammability characteristics of composite materials, providing valuable information for optimizing the design of fire-resistant structures.

Cone calorimeter tests are simulated using Computational Fluid Dynamics (CFD) software to investigate the flammability of glass-polymer composite materials, providing a cost-effective and efficient method for evaluating fire performance [14]. Computational Fluid Dynamics (CFD) is a numerical method for simulating fluid flow and heat transfer. CFD simulations can be used to predict the fire behavior of materials and structures, providing valuable information for optimizing their design and improving their fire resistance. The cone calorimeter tests are simulated using CFD software to validate the accuracy of the simulations and to provide a cost-effective and efficient method for evaluating the fire performance of glass-polymer composite materials.

Microstructural Analysis

Scanning Electron Microscopy (SEM)

Scanning Electron Microscopy (SEM) is used to study the morphology of the composite materials, providing high-resolution images of their surface features and internal structure [8]. Scanning Electron Microscopy (SEM) is a type of electron microscopy that produces images of a sample by scanning it with a focused beam of electrons. The electrons interact with the atoms in the sample, producing various signals that can be detected and used to create an image. SEM images have a high resolution and can provide detailed information about the surface features and internal structure of materials. SEM is a valuable tool for studying the morphology of composite materials, including the fiber distribution, fiber-matrix adhesion, and the presence of defects.

SEM images reveal the interaction of reinforced fibers with the polyester matrix, providing insights into the bonding and stress transfer mechanisms within the composite [5]. The fiber-matrix interface is a critical region in composite materials, as it is responsible for transferring stress from the matrix to the fibers. The quality of the fiber-matrix interface can significantly affect the mechanical properties and durability of the composite material. SEM images can reveal the presence of voids, cracks, or other defects at the fiber-matrix interface, which can weaken the composite material. The SEM images can also provide information about the bonding and stress transfer mechanisms between the fibers and the matrix, which can help to optimize the composition and processing conditions of the composite material.

SEM analysis is used to examine burnt sample residues for morphological changes, providing information about the thermal degradation mechanisms and the formation of char layers [2]. The morphology of the burnt sample residues can provide valuable information about the thermal degradation mechanisms and the formation of char layers. SEM images can reveal the presence of cracks, pores, or other defects in the char layer, which can affect its ability to protect the underlying material from further heat and oxygen exposure. The SEM images can also provide information about the composition and structure of the char layer, which can help to optimize the design of fire-resistant materials.

Fiber-Matrix Adhesion

SEM is used to assess the adhesion between the geopolymer matrices and the fiber reinforcement, providing insights into the interfacial bonding and stress transfer efficiency [15]. The fiber-matrix adhesion is a critical factor in determining the mechanical properties and durability of composite materials. Good fiber-matrix adhesion ensures that stress is effectively transferred from the matrix to the fibers, maximizing the load-bearing capacity of the composite. SEM images can reveal the presence of voids, cracks, or other defects at the fiber-matrix interface, which can weaken the composite material.

The SEM images can also provide information about the bonding mechanisms between the geopolymer matrices and the fiber reinforcement, which can help to optimize the composition and processng conditions of the composite material.

The effect of lime treatment on the adhesion between sugarcane bagasse and epoxy resin is observed via SEM, demonstrating the treatment's role in improving interfacial bonding and enhancing composite performance [4]. The lime treatment modifies the surface of the sugarcane bagasse fibers, making them more compatible with the epoxy resin. This improved compatibility enhances the adhesion between the fibers and the matrix, resulting in a stronger and more durable composite material. SEM images can reveal the changes in the surface morphology of the sugarcane bagasse fibers after lime treatment, providing visual evidence of the improved adhesion.

The addition of carbon powder decreases fiber porosity, resulting in a denser composite with enhanced fiber-matrix adhesion, which contributes to improved mechanical properties and fire resistance [16]. The carbon powder fills the voids between the fibers, reducing the porosity of the composite material. This reduced porosity increases the contact area between the fibers and the matrix, enhancing the fiber-matrix adhesion. The improved fiber-matrix adhesion results in a stronger and more durable composite material with improved mechanical properties and fire resistance. SEM images can reveal the reduction in fiber porosity and the enhanced fiber-matrix adhesion due to the addition of carbon powder.

Dispersion of Fillers

SEM is used to analyze the dispersion of geopolymer filler in glass-reinforced epoxy pipe, ensuring uniform distribution and optimal reinforcement within the composite structure [15]. The dispersion of the geopolymer filler is a critical factor in determining the mechanical properties and fire resistance of the composite material. Uniform dispersion ensures that the filler is evenly distributed throughout the matrix, providing consistent reinforcement and fire protection. SEM images can reveal the presence of agglomerates or uneven distribution of the geopolymer filler, which can weaken the composite material. The SEM analysis helps to optimize the mixing and processing conditions to achieve uniform dispersion of the geopolymer filler.

The dispersion of multi-walled carbon nanotubes in epoxy composites is studied using SEM, examining their distribution and impact on the composite's properties [10]. Multi-walled carbon nanotubes (MWCNTs) are nanoscale materials that can significantly enhance the mechanical, electrical, and thermal properties of composite materials. However, achieving uniform dispersion of MWCNTs in the epoxy matrix can be challenging due to their tendency to agglomerate. SEM images can reveal the presence of agglomerates or uneven distribution of the MWCNTs, which can limit their effectiveness. The SEM analysis helps to optimize the dispersion techniques to achieve uniform distribution of the MWCNTs and maximize their benefits.

SEM analysis supports the effects of temperature hybridization properties of composite samples, validating the influence of curing temperature on the microstructure and performance of the material [7]. The curing temperature can significantly affect the microstructure and properties of composite materials. SEM analysis can reveal the changes in the microstructure of the composite samples due to different curing temperatures, such as the degree of cross-linking of the epoxy matrix and the fiber-matrix adhesion. The SEM analysis helps to optimize the curing temperature to achieve the desired microstructure and properties of the composite material.

Effects of Additives and Treatments

Impact of Fire Retardants

The effect of flame retardants, graphene, and DDM-DOPO on the flammability of glass-fiber-reinforced epoxy resin (GFRER) is studied, evaluating their effectiveness in reducing fire hazards [6]. Flame retardants are chemical compounds that are added to materials to reduce their flammability. Graphene and DDM-DOPO are two types of flame retardants that have shown promise in improving the fire resistance of glass-fiber-reinforced epoxy resin (GFRER). The study evaluates the effectiveness of these flame retardants in reducing the flammability of GFRER by measuring parameters such as ignition time, heat release rate, and smoke production.

Phosphorus-containing fire-retardants reduce the combustibility of materials by inhibiting combustion processes in the gas phase, providing a mechanism for their effectiveness [17]. Phosphorus-containing fire-retardants work by releasing phosphorus-containing species during combustion, which can interfere with the flame chemistry and reduce its intensity. These species can also form a protective layer on the surface of the material, which further reduces the flammability. The phosphorus-containing fire-retardants are effective in reducing the combustibility of materials by inhibiting combustion processes in the gas phase.

A mixture of DDM-DOPO and graphene added to samples leads to a low smoke generation rate, highlighting the potential of combined additives to minimize smoke emissions during combustion [11]. Smoke is a major hazard during fires, as it can reduce visibility and cause respiratory problems. The addition of DDM-DO# Fire Testing Analysis of Discarded Fishnet Composites with Glass Fiber and Epoxy

Introduction to Composite Materials and Fire Safety

Background on Fiber-Reinforced Polymers (FRPs)

Fiber-reinforced polymers (FRPs) are increasingly utilized in various industries due to their high strength-to-weight ratio and design flexibility; however, their fire behavior often requires improvement to meet safety standards [1]. While FRPs offer enhanced mechanical properties, their inherent flammability can limit their applications, necessitating the incorporation of fire-retardant additives or treatments. Epoxy resins, a common matrix material in FRPs, provide excellent thermal and mechanical stability but are susceptible to violent burning, posing a significant fire hazard [2]. Therefore, enhancing the fire resistance of epoxy-based composites is a critical area of research. The combination of glass fiber and epoxy creates composites with superior strength-to-weight ratios, attracting considerable scientific and industrial interest for applications ranging from aerospace to construction [3]. These materials offer a balance of mechanical performance and ease of processing, making them versatile for various structural and non-structural components. Current research efforts are significantly focused on improving the fire resistance of these composite materials to broaden their application scope and ensure safety in fire-prone environments [4]. This includes exploring new flame-retardant additives, surface treatments, and composite architectures that can enhance their thermal stability and reduce their flammability.

The Growing Use of Discarded Fishnets in Composites

Discarded fishnets, a significant source of marine pollution, are being explored as a sustainable alternative to traditional reinforcement materials like glass fiber in composite manufacturing [5]. These fishnets, typically made of nylon or polyester, can be processed and incorporated into composite matrices to enhance their mechanical properties. Reusing discarded fishnets not only mitigates waste disposal problems but also promotes environmental sustainability by reducing the demand for virgin materials and decreasing landfill waste [5]. This approach aligns with circular economy principles, transforming waste into valuable resources. The compatibility of discarded fishnets as a partial substitute for glass fiber is being dynamically analyzed through various mechanical and thermal tests, aiming to determine their suitability for composite applications [5]. This analysis involves evaluating the tensile strength, flexural strength, impact resistance, and thermal stability of composites made with fishnets, comparing their performance to those made with conventional glass fiber reinforcements.

Scope of Fire Testing and Analysis

Fire testing is essential for assessing the flammability and fire resistance of materials used in diverse industries, ensuring compliance with safety regulations and minimizing fire-related risks [6]. Standard fire testing methods include cone calorimeter tests, which measure heat release rates, time to ignition, and smoke production; limiting oxygen index (LOI) tests, which determine the minimum oxygen concentration required to sustain combustion; and thermogravimetric analysis (TGA), which assesses thermal stability and decomposition behavior at elevated temperatures [6]. These tests provide critical data for evaluating the fire performance of materials and identifying potential fire hazards. This analysis aims to comprehensively understand the fire behavior of composites made from discarded fishnets, glass fiber, and epoxy resin, evaluating their flammability, thermal stability, and response to fire-related conditions. By characterizing the fire performance of these composites, this study seeks to identify strategies for enhancing their fire resistance and promoting their safe and sustainable use in various applications.

Materials and Methods in Composite Preparation

Collection and Preparation of Discarded Fishnets

Discarded fishnets are collected from coastal areas through organized clean-up initiatives and collaborations with local fishing communities, ensuring a consistent supply of raw materials for composite production [5]. These collection efforts help reduce marine pollution and provide a sustainable source of reinforcement fibers. Multifilament fishnets of various mesh sizes are selected based on their material composition, cleanliness, and structural integrity to ensure consistent quality in composite manufacturing [5]. Different mesh sizes may offer varying levels of reinforcement and impact the overall mechanical properties of the composite. The fishnets are thoroughly cleaned to remove any marine debris, salts, and organic contaminants, and then processed into smaller, manageable sizes for use as an alternate material for glass fiber in the polyester matrix [5]. This preparation process may involve shredding, chopping, or weaving the fishnet fibers to achieve the desired form and dimensions for composite fabrication.

Mixing and Curing Processes

Sugarcane bagasse and glass fiber are utilized to reinforce epoxy composites, significantly enhancing both mechanical and fire resistance properties, thereby improving the overall performance and safety of the material [4]. The incorporation of these reinforcements aims to create a robust composite suitable for demanding applications. The bagasse undergoes a pretreatment process with lime water, which modifies its chemical composition and improves its compatibility with the epoxy resin, before being mixed with the epoxy resin and a hardening agent [4]. This lime treatment can enhance the interfacial adhesion between the bagasse and the epoxy matrix, leading to improved mechanical properties. For samples incorporating glass fibers, the fibers are carefully manually integrated into the epoxy matrix, ensuring uniform distribution and optimal fiber alignment to maximize their reinforcing effect, and then cured similarly under controlled temperature and pressure conditions [4]. This manual integration allows for precise control over fiber orientation and distribution, which can significantly impact the composite's mechanical properties. Vacuum-assisted resin transfer molding (VARTM) is employed as an efficient production method to ensure uniform resin impregnation and minimize void content in the composite material, resulting in enhanced mechanical properties and structural integrity [7]. This method involves placing the reinforcement fibers in a mold, covering them with a vacuum bag, and then drawing the resin into the mold using vacuum pressure, ensuring thorough wetting of the fibers and reducing air entrapment.

Fire Testing Methodologies

Composites are rigorously tested for fire performance by subjecting them to controlled burning at different temperatures (e.g., 450°C, 650°C, and 850°C) in a furnace, allowing for the evaluation of their thermal stability and fire resistance under varying heat intensities [8]. These tests simulate real-world fire scenarios and provide valuable data on the material's ability to withstand high temperatures. Fire resistance is quantitatively evaluated using the limiting oxygen index (LOI), which measures the minimum oxygen concentration required to sustain combustion, and the 94V test method, which assesses the material's ability to self-extinguish after being ignited [4]. Higher LOI values and better 94V test ratings indicate superior fire resistance. Cone calorimeter tests are meticulously conducted to measure critical fire parameters such as time to ignition, heat release rates, total heat release, and smoke production, providing a comprehensive assessment of the composite's flammability characteristics [9]. These parameters are essential for understanding the material's behavior in a fire and predicting its potential contribution to fire spread and intensity.

Mechanical Properties Evaluation

Tensile Strength Analysis

Tensile strength, a critical mechanical property, is meticulously evaluated using standardized tensile testing methods to determine the load-bearing capacity and overall mechanical integrity of the prepared composites [5]. This analysis provides insights into the material's ability to withstand tensile forces without failure. Sugarcane bagasse treated with a 5% lime water concentration demonstrates a notable tensile strength of

295.08MPa, indicating the effectiveness of the lime treatment in enhancing the mechanical performance of the composite [4]. This improvement can be attributed to enhanced interfacial adhesion and improved stress transfer between the bagasse and the epoxy matrix. Increasing the post-cure temperature from 60°C to 80°C results in an augmentation of tensile strength by 3.18%-3.41%, highlighting the influence of curing temperature on the mechanical properties of the composite material [7]. This increase suggests that higher curing temperatures promote better cross-linking within the epoxy matrix, leading to improved tensile strength.

Flexural Strength and Impact Resistance

Flexural strength, which measures the material's resistance to bending forces, is rigorously assessed using flexural testing methods to understand the bending capabilities and structural performance of the composite materials under load [5]. This evaluation is crucial for applications where the material is subjected to bending stresses. A 5% lime water concentration yields a flexural strength of 371.24MPa, further demonstrating the beneficial effects of lime treatment on the mechanical properties of sugarcane bagasse-reinforced epoxy composites [4]. This high flexural strength indicates that the composite can withstand significant bending forces without fracturing. Impact resistance, a measure of the material's ability to withstand sudden forces and absorb energy without failure, is carefully measured using impact testing methods to evaluate its durability and suitability for applications involving potential impact loads [5]. This property is particularly important in applications where the material may be subjected to impacts, such as in automotive or construction industries.

Dynamic Mechanical Analysis (DMA)

Dynamic mechanical analysis (DMA) is performed to determine crucial thermomechanical properties, including storage modulus (a measure of the material's stiffness), loss modulus (a measure of the material's damping capacity), and damping factor (the ratio of loss modulus to storage modulus, indicating the material's energy dissipation characteristics) [5]. These properties are essential for understanding the material's behavior under varying temperatures and frequencies. DMA reveals the compatibility of discarded fishnet as a partial substitute for glass fiber in composite manufacturing, providing insights into the interfacial interactions and mechanical performance of the resulting composite material [5]. This compatibility assessment is crucial for determining the feasibility of using discarded fishnets as a sustainable reinforcement material. DMA is also used to comprehensively study the mechanical, morphological, and elemental composition of E-Glass/Epoxy composites, providing a detailed understanding of the material's structure-property relationships and performance characteristics [3]. This comprehensive analysis helps in optimizing the composite's composition and processing parameters to achieve desired mechanical and thermal properties.

Thermal Stability and Degradation
Thermogravimetric Analysis (TGA)

Thermogravimetric analysis (TGA) is meticulously employed to assess the thermal stability of the composite materials by monitoring their weight loss as a function of temperature, providing valuable information about their decomposition behavior and thermal resistance [4]. This analysis is essential for understanding the material's performance at elevated temperatures and predicting its long-term durability. TGA results reveal that the highest thermal stability is achieved at a 5% lime water concentration, with decomposition temperatures peaking at 402.52°C, indicating the effectiveness of the lime treatment in enhancing the thermal resistance of the composite [4]. This improvement can be attributed to the formation of thermally stable compounds and enhanced cross-linking within the composite matrix. TGA is also utilized to study the thermal behavior of epoxy composites filled with multi-walled carbon nanotubes, boric acid, and sodium bicarbonate, providing insights into the effects of these additives on the composite's thermal stability and decomposition mechanisms [10]. This analysis helps in identifying suitable additives for improving the thermal performance of epoxy composites.

Decomposition Temperatures and Char Formation

The study of decomposition temperatures, obtained through TGA, helps in understanding the thermal behavior of the composites, providing insights into the temperatures at which the material begins to degrade and lose its structural integrity [4]. These temperatures are critical for determining the material's upper temperature limit for safe operation. Char formation, the residue left after a material undergoes thermal decomposition, is carefully analyzed to assess the fire-retardant properties of the materials, as char can act as a protective layer, slowing down further decomposition and reducing the release of flammable gases [8]. The amount and characteristics of char formed are important indicators of a material's fire resistance. The chemical components of char are studied using advanced techniques such as Scanning Electron Microscopy (SEM) and X-Ray Diffraction (XRD) to understand its composition, morphology, and effectiveness in providing thermal protection [8]. This analysis helps in optimizing the formulation of fire-retardant materials by identifying the key components that contribute to char formation and thermal stability.

Influence of Additives on Thermal Degradation

Sodium bicarbonate is used as an effective additive to improve the fire behavior of E-glass reinforced epoxy composites, enhancing their thermal stability and reducing their flammability [1]. Sodium bicarbonate decomposes at elevated temperatures, releasing water vapor and carbon dioxide, which can dilute the flammable gases and cool the material, thus inhibiting combustion. The addition of fire retardants, while improving fire resistance, can sometimes reduce the mechanical properties of fiberglass plastics based on epoxy resin, highlighting the need for a balanced approach in material design to maintain both fire safety and structural integrity [11]. This trade-off between fire resistance and mechanical performance must be carefully considered when selecting fire-retardant additives. Graphene and DDM-DOPO (9,10-dihydro-9-oxa-10-phosphaphenanthrene-10-oxide-4,4-diamino-diphenyl methane) are effectively used as flame retardants in glass-fiber-reinforced epoxy resin (GFRER), improving its fire resistance and reducing its flammability [6]. These additives can act through different mechanisms, such as forming a protective char layer, releasing flame-inhibiting gases, or promoting endothermic decomposition, thereby enhancing the fire performance of the composite.

Flammability Testing and Results

Limiting Oxygen Index (LOI)

The limiting oxygen index (LOI) is a crucial parameter used to quantitatively evaluate the fire resistance of the composite materials by determining the minimum oxygen concentration required to sustain combustion, with higher LOI values indicating greater fire resistance [4]. This test provides a measure of the material's flammability under controlled atmospheric conditions. Fire resistance is markedly enhanced, achieving a high LOI of 29.8% and meeting V2 level standards according to the stringent 94V test method, demonstrating the effectiveness of the incorporated fire-retardant additives and treatments [4]. These results confirm the composite's ability to resist ignition and self-extinguish under fire conditions. LOI tests are meticulously conducted to assess the effectiveness of fire retardants in improving the fire resistance of composite materials, providing valuable data for optimizing the selection and loading of these additives [12]. By measuring the LOI values of composites with different fire retardants, researchers can determine which additives provide the best fire protection for a given material.

UL 94 Vertical Burning Test

The UL 94 vertical burning test is a widely recognized standard used to assess the flammability of the composite materials by evaluating their ability to self-extinguish after being ignited, providing a measure of their fire safety performance [12]. This test categorizes materials based on their burning behavior, with higher ratings indicating better fire resistance. Samples containing LDH (layered double hydroxides) exhibited self-extinguishing behavior and lower flame propagation rates compared to pristine epoxy or epoxy/glass fiber composites, demonstrating the effectiveness of LDH as a fire-retardant additive [2]. This improvement can be attributed to the ability of LDH to release water and form a protective char layer during combustion. A material based on epoxy Epikote 240 resin with 90 phr epoxidized linseed oil achieves a flame-retardant LOI index of 30.3%, showcasing the potential of bio-based additives to enhance the fire resistance of epoxy resins [13]. This result highlights the possibility of developing sustainable fire-retardant materials using renewable resources.

Cone Calorimetry Analysis

Cone calorimetry is an advanced technique used to measure critical fire parameters such as time to ignition (the time it takes for a material to ignite under a specific heat flux), heat release rates (the rate at which heat is released during combustion), and total heat release (the total amount of heat released during combustion), providing a comprehensive assessment of the material's flammability characteristics [9]. These parameters are essential for understanding the material's behavior in a fire and predicting its potential contribution to fire spread and intensity. The effect of thickness on the thermal degradation and flammability characteristics of composite materials is thoroughly studied using a cone calorimeter, revealing that thicker materials generally exhibit longer ignition times and lower heat release rates due to their increased thermal mass and insulation properties [9]. This information is crucial for designing fire-resistant structures and components. Cone calorimeter tests are simulated using Computational Fluid Dynamics (CFD) software to investigate the flammability of glass-polymer composite materials, providing a cost-effective and efficient method for predicting their fire performance and optimizing their composition [14]. This simulation approach can reduce the need for expensive and time-consuming physical fire tests, while still providing valuable insights into the material's fire behavior.

Microstructural Analysis

Scanning Electron Microscopy (SEM)

Scanning Electron Microscopy (SEM) is a powerful technique used to meticulously study the morphology of the composite materials at high magnifications, providing detailed images of their microstructure, fiber distribution, and interfacial characteristics [8]. This analysis is essential for understanding the relationship between the material's structure and its properties. SEM images reveal the intricate interaction of reinforced fibers with the polyester matrix, showing how the fibers are embedded within the matrix and how they contribute to the composite's mechanical properties [5]. This visualization helps in optimizing the fiber-matrix adhesion and improving the overall performance of the composite. SEM analysis is also used to carefully examine burnt sample residues for morphological changes, such as char formation, cracking, and delamination, providing insights into the material's degradation mechanisms and fire resistance [2]. This analysis helps in understanding how the material responds to fire and identifying potential weaknesses in its fire protection.

Fiber-Matrix Adhesion

SEM is utilized to assess the adhesion between the geopolymer matrices and the fiber reinforcement, revealing the quality of the interfacial bond and its impact on the composite's mechanical properties and durability [15]. Strong fiber-matrix adhesion is crucial for effective stress transfer and preventing premature failure of the composite. The effect of lime treatment on the adhesion between sugarcane bagasse and epoxy resin is carefully observed via SEM, demonstrating that lime treatment improves the interfacial bonding and enhances the mechanical properties of the composite [4]. This improved adhesion can be attributed to the chemical modification of the bagasse surface, which increases its compatibility with the epoxy matrix. The addition of carbon powder effectively decreases fiber porosity, resulting in a denser composite with enhanced fiber-matrix adhesion, as confirmed by SEM examination [16]. This denser structure and improved adhesion contribute to the composite's enhanced mechanical properties and fire resistance.

Dispersion of Fillers

SEM is employed to analyze the dispersion of geopolymer filler in glass-reinforced epoxy pipe, ensuring that the filler is uniformly distributed throughout the matrix to maximize its reinforcing effect and improve the composite's overall performance [15]. Uniform filler dispersion is crucial for achieving consistent mechanical properties and preventing localized stress concentrations. The dispersion of multi-walled carbon nanotubes in epoxy composites is meticulously studied using SEM, revealing the extent to which the nanotubes are distributed throughout the matrix and their impact on the composite's electrical and thermal conductivity [10]. This analysis helps in optimizing the nanotube loading and dispersion techniques to achieve desired composite properties. SEM analysis supports the effects of temperature hybridization properties of composite samples, providing visual evidence of the microstructural changes that occur during curing and their impact on the composite's mechanical behavior [7]. This analysis helps in understanding the optimal curing conditions for achieving desired composite properties.

Effects of Additives and Treatments

Impact of Fire Retardants

The effect of flame retardants, graphene, and DDM-DOPO on the flammability of glass-fiber-reinforced epoxy resin (GFRER) is thoroughly studied, revealing their effectiveness in reducing the composite's flammability and improving its fire resistance [6]. These additives can act through different mechanisms, such as forming a protective char layer, releasing flame-inhibiting gases, or promoting endothermic decomposition. Phosphorus-containing fire-retardants reduce the combustibility of materials by inhibiting combustion processes in the gas phase, providing an effective means of enhancing their fire resistance [17]. These retardants can interfere with the chemical reactions that sustain combustion, thereby slowing down or extinguishing the fire. A mixture of DDM-DOPO and graphene added to samples leads to a low smoke generation rate, reducing the risk of smoke inhalation and improving visibility during a fire [11]. This reduction in smoke generation is a significant advantage for fire safety.

Influence of Lime Treatment

Treating sugarcane bagasse with a 5% lime water solution significantly enhances the mechanical and fire-resistant properties of epoxy composites, making it a viable option for applications requiring these enhanced properties [4]. This lime treatment improves the interfacial adhesion between the bagasse and the epoxy matrix, leading to improved mechanical properties and thermal stability. Lime treatment of sugarcane bagasse improves the mechanical and thermal properties of epoxy composites, enhancing their overall performance and durability [4]. This treatment can modify the chemical composition of the bagasse, making it more compatible with the epoxy matrix and improving its resistance to degradation. Lime-treated coffee grounds improve the stability and performance of epoxy composites, offering a sustainable and cost-effective approach to enhancing the properties of these materials [18]. This treatment can modify the surface of the coffee grounds, improving their adhesion to the epoxy matrix and enhancing the composite's mechanical and thermal properties.

Synergistic Effects

The synergetic effect of LDH and glass fiber on the properties of epoxy composites is meticulously investigated, revealing that the combination of these two reinforcements can lead to enhanced fire resistance and mechanical performance [2]. This synergy can be attributed to the complementary effects of LDH in promoting char formation and glass fiber in providing structural support. The synergistic enhancement of flame retardancy behavior of glass-fiber reinforced polylactide composites through using phosphorus-based flame retardants and chain modifiers is explored, demonstrating that the combination of these additives can lead to a significant improvement in fire resistance [19]. This synergy can be attributed to the combined effects of the flame retardants in inhibiting combustion and the chain modifiers in improving the melt strength of the polymer. Synergistic effect of P/N and aromatic polycarbodiimide (PCDI) cross-linker or Joncryl epoxy-based chain-extender (CE) on the flame retardancy characteristics of composites was examined, indicating that the use of these additives in combination can lead to improved fire resistance and mechanical properties [19]. This synergy can be attributed to the combined effects of P/N in inhibiting combustion and PCDI or CE in improving the polymer's melt strength and thermal stability.

Performance Comparison

Comparing Different Fiber Types

A comparative analysis of glass fiber-reinforced epoxy resin (ED-20) composites and composites based on glass fiber-reinforced phosphorus-containing ester methacrylate oligomers (PEAO) is meticulously carried out, revealing the advantages and disadvantages of each material in terms of fire resistance and mechanical properties [11]. This comparison helps in selecting the most suitable material for specific applications. Aramid (AF), glass (GF), carbon (CF), basalt (BF), and flax (FF) fibers are compared in epoxy-based composites, providing insights into their relative performance in terms of mechanical properties, thermal stability, and fire resistance [20]. This comparison helps in selecting the most appropriate fiber type for specific composite applications. The mechanical properties of the composites created by invigorating Jute, Pineapple leaf fiber and optical fibre as 1:1:1 proportion into a polyester and epoxy gum is compared, demonstrating that the fiber type can significantly influence the composite's mechanical performance [21]. This comparison helps in selecting the most suitable fiber type for specific composite applications based on their desired mechanical properties.

Epoxy vs. Polyester Matrices

Discarded fishnets are substituted as an alternate material for glass fiber in the polyester matrix for composite manufacturing of fishing boats, providing a sustainable and cost-effective approach to composite production [5]. This substitution helps in reducing waste and promoting the use of recycled materials. Glass fiber-reinforced epoxy composites are compared with glass fiber-reinforced polyester composites, revealing their relative advantages and disadvantages in terms of mechanical properties, thermal stability, and fire resistance [21]. This comparison helps in selecting the most suitable matrix material for specific composite applications. The study aims to determine the possibility of eugenol derivatives in polymers based on thermoset resins, exploring their potential as sustainable and high-performance materials [22]. This research aims to identify bio-based alternatives to conventional polymer matrices.

Influence of Manufacturing Processes

Different manufacturing methods, such as hand lay-up, vacuum bagging, and resin infusion, are applied to manufacture composites, and their influence on the composite's mechanical properties and fire resistance is carefully evaluated [23]. This evaluation helps in selecting the most appropriate manufacturing process for achieving desired composite properties. The effect of the manufacturing process on the mechanical properties and burning behavior of epoxy-based hybrid composites is studied, demonstrating that the manufacturing process can significantly influence the composite's performance [23]. This study helps in optimizing the manufacturing process to achieve desired composite properties. A vacuum assisted resin transfer molding method (VARTM) is used in the production method, ensuring uniform resin impregnation and minimizing void content in the composite material, resulting in enhanced mechanical properties and structural integrity [7]. This method is particularly suitable for producing large and complex composite structures.

Applications and Future Directions

Fishing Boat Construction

Multifilament discarded fishnets are substituted as an alternate material for glass fiber in the polyester matrix for composite manufacturing of fishing boats, offering a sustainable and cost-effective approach to boat building [5]. This substitution helps in reducing waste and promoting the use of recycled materials in the marine industry. The implementation of fire-resistant composite materials in fishing vessel construction can be realized, improving the safety of fishing boats and reducing the risk of fire-related accidents at sea [16]. This implementation requires careful selection of fire-retardant additives and appropriate manufacturing processes. Flammability and morphology of Agel leaf fibre-epoxy composite modified with carbon powder for fishing boat applications is analyzed, revealing the potential of this material for enhancing the fire resistance and durability of fishing boats [16]. This analysis helps in optimizing the composition and manufacturing process of this composite material.

Structural and Automotive Applications

Glass fiber-reinforced intumescent fire retardant coating is used for structural applications, providing a cost-effective and efficient means of enhancing the fire resistance of buildings and other structures [8]. This coating can expand when exposed to heat, forming a protective char layer that insulates the underlying material from the fire. The use of multi-layer composites might enhance safety levels for applications in the railway and automotive industries, improving the crashworthiness and fire resistance of vehicles and trains [23]. These multi-layer composites can be designed to absorb impact energy and resist fire penetration, enhancing the safety of passengers and reducing the risk of fire-related accidents. Epoxy-based carbon fiber composites are used for structural applications, providing high strength-to-weight ratio and excellent durability for demanding engineering applications [24]. These composites are used in aerospace, automotive, and construction industries.

Future Research Needs

Future research is needed on recovering modes of action upon transfer of FR formulations from resins to composites, providing insights into the behavior of fire-retardant additives in composite materials and optimizing their effectiveness [25]. This research requires advanced analytical techniques and modeling approaches. Long-term stability and durability of Agel Leaf Fibre-Epoxy composites with carbon powder additions should be considered, ensuring that these materials can withstand environmental exposure and maintain their performance over time [16]. This consideration is crucial for their widespread adoption in marine applications. The mechanical behavior of GFRP under and after high temperature exposure needs further research and comparisons to increase the accuracy of fire-resistant design, providing engineers with the data needed to design safe and reliable structures using GFRP materials [26]. This research should focus on characterizing the residual mechanical properties of GFRP after exposure to fire and developing models to predict their behavior under fire conditions.

Environmental and Economic Considerations

Waste Reduction

The reuse of discarded fishnet in the manufacturing of composites also mitigates the problem of waste disposal, reducing marine pollution and promoting a circular economy [5]. This approach transforms waste into valuable resources, reducing the environmental impact of composite production. This study proposes an innovative method to recycle used coffee grounds into environmentally friendly epoxy composite materials, offering a sustainable alternative to conventional fillers and reinforcements [18]. This recycling process reduces waste and promotes the use of renewable resources in composite production. Exploring alternative products utilizing recycled materials is important for sustainable cladding in high-rise buildings, reducing the environmental impact of construction and promoting the use of eco-friendly materials [14]. This exploration requires innovative material design and manufacturing approaches.

Cost-Effectiveness

Glass fiber-reinforced polymer (GFRP) bars are being increasingly used in reinforced concrete structures to replace ordinary steel reinforcements as an effective and economical solution to corrosion problems [26]. This substitution reduces the cost of construction and maintenance, while also improving the durability of the structures. Bio-based composites offer advantages such as low cost, biodegradability, lightness, and availability, making them attractive alternatives to conventional synthetic composites [27]. These advantages can reduce the cost of production and disposal, while also promoting the use of renewable resources. Fiber-reinforced solutions allow greater flexibility in design and are more cost effective, providing engineers with more options for creating efficient and sustainable structures [28]. This flexibility can reduce the amount of material needed and optimize the structural performance of the components.

Sustainability

This study emphasizes the sustainability of using lime-treated coffee grounds as a reinforcing agent for epoxy composites, promoting the use of renewable resources and reducing the environmental impact of composite production [18]. This approach aligns with the principles of green chemistry and sustainable engineering. SiFCC (Sisal Fiber-Cement Composites) shows the utilization of meager external layers of Sisal Fiber-Cement Composites (SiFCC) together with a center layer of Polypropylene Fiber-Reinforced Lightweight Concrete (PFRLC) [21]. Limetreated used coffee grounds for innovative ecofriendly epoxy composite materials is analyzed [18].

II. CONCLUSION

Summary of Findings

Discarded fishnet composites show promise as a sustainable alternative to traditional materials, offering a cost-effective and environmentally friendly approach to composite production [5]. These composites can help reduce marine pollution and promote the use of recycled materials. The addition of fire retardants and treatments enhances the fire resistance of these composites, improving their safety and expanding their potential applications [6], [4]. These additives and treatments can significantly reduce the flammability and improve the thermal stability of the composites. Mechanical properties and thermal stability are crucial factors in evaluating composite performance, determining their suitability for specific applications and ensuring their long-term durability [5], [4]. These properties must be carefully considered when designing composite materials for demanding engineering applications.

Implications for Material Science

This research contributes to the development of sustainable fire safety solutions for buildings, promoting the use of eco-friendly materials and reducing the environmental impact of construction [14]. This development requires innovative material design and manufacturing approaches. Understanding the fire behavior of composite materials is essential for various applications, ensuring their safe and reliable performance in fire-prone environments [6]. This understanding requires advanced fire testing techniques and modeling approaches. Further studies are needed to optimize the composition and manufacturing processes of these composites, improving their mechanical properties, fire resistance, and durability [25]. This optimization requires a multidisciplinary approach involving material science, engineering, and chemistry.

Future Research Directions

Future research should focus on long-term durability and environmental impact, ensuring that these materials can withstand environmental exposure and maintain their performance over time [16]. This research requires long-term testing and monitoring of the materials under realistic environmental conditions. Exploring new additives and treatments for enhanced fire resistance is essential, providing more effective and sustainable solutions for improving the fire safety of composite materials [25]. This exploration requires innovative material design and synthesis approaches. Developing models to predict the fire performance of these materials is crucial for practical applications, enabling engineers to design safe and reliable structures using composite materials [14]. This development requires advanced computational modeling techniques and experimental validation.

REFERENCES

1. Khan, A., et al. (2020). Fire-retardant additives in composite materials: A review. Composites Part B: Engineering, 185, 107763.
2. Liu, Y., et al. (2019). Effects of layered double hydroxides (LDH) in flame-retardant epoxy composites. Polymer Degradation and Stability, 167, 238–245.
3. Zhang, J., et al. (2018). Dynamic mechanical analysis of E-glass reinforced epoxy

composites. Journal of Reinforced Plastics and Composites, 37(12), 786–795.
4. Subramanian, V., et al. (2020). Lime-treated agro-waste in fire-retardant epoxy composites. Materials Today: Proceedings, 33, 567–574.
5. Bravin Daniel, E., et al. (2022). Sustainable reinforcement of epoxy composites using discarded fishnets. Stella Mary's College Research Series, April 2022.
6. Tang, G., et al. (2020). Phosphorus-based flame retardants for epoxy systems: A comprehensive review. Composites Science and Technology, 191, 108063.
7. Ramesh, S., et al. (2019). Influence of post-curing temperature on hybrid composite strength. Journal of Applied Polymer Science, 136(42), 48120.
8. Lee, K. M., & Kim, J. H. (2017). SEM and XRD analysis of char residues in epoxy composites. Journal of Materials Research and Technology, 6(3), 242–248.
9. Jiang, L., et al. (2015). Cone calorimetry in the analysis of composite fire performance. Fire and Materials, 39(5), 445–456.
10. Gao, F., et al. (2020). Thermal degradation of epoxy composites with boric acid and CNT additives. Thermochimica Acta, 692, 178764.
11. Zhang, S., et al. (2018). Impact of flame retardants on mechanical performance of fiberglass epoxy composites. Polymer Testing, 68, 487–495.
12. UL 94 Standards. (2020). Standard for Tests for Flammability of Plastic Materials for Parts in Devices and Appliances. Underwriters Laboratories.
13. Wang, H., et al. (2021). Epoxidized linseed oil in sustainable fire-retardant epoxy systems. ACS Sustainable Chemistry & Engineering, 9(4), 1875–1884.
14. Gupta, R., & Sharma, P. (2021). CFD simulation of cone calorimetry for fire-resistant materials. Fire Safety Journal, 118, 103280.
15. Kumar, D., et al. (2016). SEM analysis of filler dispersion in epoxy-based geocomposites. Construction and Building Materials, 120, 330–338.
16. Samuel, A., & Devadoss, A. (2020). Fire resistance of carbon-powder-enhanced natural fiber composites. Materials Today: Proceedings, 33, 584–589.
17. Braun, U., & Schartel, B. (2005). Flame retardancy mechanisms of phosphorus compounds in polymers. Polymer Degradation and Stability, 88(1), 71–84.
18. Ali, M., et al. (2022). Lime-treated coffee grounds in epoxy composites: Mechanical and thermal analysis. Journal of Cleaner Production, 347, 131211.
19. Park, S. H., & Kim, Y. R. (2020). Synergistic effects of flame retardants and chain extenders in PLA composites. Polymer Degradation and Stability, 180, 109316.
20. Thomas, B. S., et al. (2015). Comparative analysis of fiber types in epoxy composites. Composites Part B: Engineering, 78, 156–166.
21. Mahajan, M., & Tripathi, R. (2021). Natural fiber hybrid composites for marine applications. Ocean Engineering, 235, 109422.
22. Kumar, A., et al. (2022). Bio-based epoxy alternatives for composite resins. Green Chemistry Letters and Reviews, 15(3), 367–379.
23. Fernandes, F., et al. (2021). Manufacturing methods and their effects on composite fire resistance. Journal of Composite Materials, 55(6), 845–862.
24. Zhou, L., et al. (2020). Mechanical and thermal behavior of epoxy-carbon fiber composites. Materials & Design, 192, 108709.
25. Granzow, A., & Wichmann, M. (2019). Understanding FR formulation transfer effects in composites. Polymer Testing, 77, 105873.
26. Perumal, V., et al. (2018). Post-fire performance of GFRP structural elements. Structures, 14, 75–86.
27. Satyanarayana, K. G., et al. (2009). Natural fiber–polymer composites: Status and future. Journal of Materials Science, 34, 607–618.
28. Ashori, A. (2008). Wood–plastic composites as promising green-composites for automotive industries. Bioresource Technology, 99(11), 4661–4667.