# Characterizing Composite Materials for High-performance Applications: A Review of Testing Methods

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# Characterizing Composite Materials for High-performance Applications: A Review of Testing Methods

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**Abstract**: Composite materials are extensively used in various industries due to their superior mechanical, thermal, and chemical properties. However, assessing and characterizing these materials require a comprehensive understanding of their behavior under different loading and environmental conditions. This review paper provides an overview of the most commonly used testing methods for evaluating the mechanical, thermal, chemical, and surface properties of composite materials. The paper discusses the purpose, objective, setup, sample results, significance, and description of each testing method, covering a wide range of characterization techniques from macroscopic mechanical testing to nanoscale surface analysis. The testing methods discussed include tensile testing, compression testing, flexural testing, shear testing, peel testing, interlaminar shear testing, impact testing, fatigue testing, creep testing, hygrothermal testing, electrical testing, thermal testing, microscopic analysis, spectroscopic techniques, rheological testing, and various other specialized tests. Each testing method is described in detail, highlighting its importance in assessing material performance, structural integrity, durability, and suitability for specific applications. Additionally, relevant standards and guidelines are referenced to ensure accurate and reliable characterization of composite materials. This comprehensive review serves as a valuable resource for researchers, engineers, and practitioners involved in the design, manufacturing, and evaluation of composite materials for diverse applications.

Keywords: Composite Materials Characterization; Mechanical Testing Techniques; Thermal and Chemical Analysis; Structural Integrity Evaluation; Advanced Spectroscopic Techniques; Material Performance Standards

## 1. Introduction

### 1.1 Importance of Composite Materials in Modern Industries

Composite materials, characterized by their engineered combination of two or more constituents with distinct physical or chemical properties, have revolutionized numerous industries with their unparalleled advantages. Figure 1 gives composites significance in modern applications cannot be overstated, primarily due to their superior mechanical, thermal, and chemical properties which offer enhanced performance over traditional materials. Industries such as aerospace, automotive, construction and renewable energy systems heavily rely on composites for their lightweight, high strength-to-weight ratio, corrosion resistance, and flexibility in design and functionality.

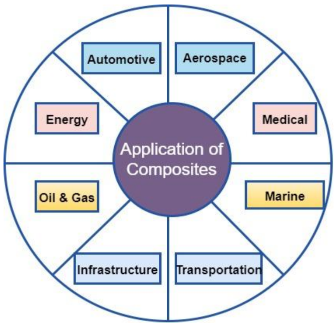


**Fig. 1:** Applications of composite materials.

For instance, the aerospace industry leverages carbon fiber-reinforced polymers for critical structural components to achieve significant weight savings and fuel efficiency. Similarly, in the automotive sector, composites contribute to vehicle lightweighting, impacting fuel consumption and emissions positively.

### 1.2 Challenges in Characterizing Composite Materials

The complexity and variety of composite materials present substantial characterisation issues notwithstanding their advantages. For the design, development, and use of composites in engineering projects, it is essential to comprehend how they behave under varied loads and environmental circumstances. Anisotropy and heterogeneity, which cause direction-dependent properties that complicate behavior prediction under multi-axial loads and environmental conditions, the complex microstructure resulting from the varied nature of composite constituents (fiber, matrix, and interfaces), and the requirement for characterization techniques that span different scales from macroscopic mechanical properties to nanoscale features, requiring advanced and diverse testing methods, are the main challenges. Furthermore, complex and time-consuming testing techniques are required to evaluate the long-term performance of composites under real-world situations such moisture, temperature changes, and UV exposure.

### 1.3 Objectives of the Review Paper

The objectives of the paper are to consolidate testing methods by presenting an organized compilation of various techniques, including tensile, compression, flexural, and impact testing, among others, highlighting their purpose, setup, and significance; to highlight industry standards by referencing relevant guidelines for each testing method to ensure accurate, reliable, and reproducible characterization outcomes; to bridge knowledge gaps by serving as an educational resource for researchers, engineers, and practitioners, facilitating a deeper understanding of the complexities involved in characterizing composite materials; and to guide future research by identifying areas where current testing methods fall short and suggesting directions for the development of innovative characterization techniques to address emerging challenges.

Figure 2 shows the methods for characterization of composite materials. Modern industries rely heavily on composite materials because they provide improved performance and facilitate design and functionality advancements. However, because of their anisotropic characteristics and intricate microstructures, these materials pose special difficulties in terms of characterization.

In order to meet the industry's demand for standardized characterization approaches, this document plays a crucial role in compiling the body of information already known about testing methodologies. It provides present practitioners with a useful resource and establishes the foundation for further developments in composite material characterization.

## 2. Mechanical Testing Methods

Tensile test evaluates a composite material's tensile strength using a Universal Testing Machine (UTM) to identify the maximum stress it can bear before failing. The test generates a stress-strain curve that reveals the material's ultimate tensile strength, yield strength, and elasticity modulus, crucial for determining its performance and appropriateness for structural use. It involves stretching a standardized sample until it breaks, guided by the ASTM D3039/D3039M standard for composite materials[1,2].

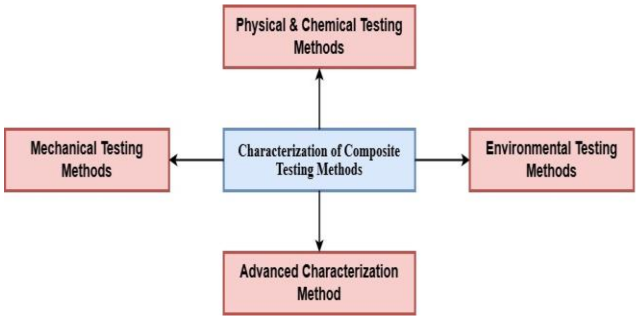


**Fig. 2:** Characterization of composite materials methods.

Compression Testing succinctly assesses a material's compressive strength, specifically its resistance to size-reducing loads, using a compression testing machine[3,4]. This method, guided by ASTM D6641/D6641M standards for composite materials, yields a stress-strain curve to evaluate compressive strength and modulus, crucial for understanding material behavior in structural design[5,6].

Flexural Testing Summary: Flexural testing evaluates the bending resistance and stiffness of composite materials using a three-point or four-point bending setup on a flexural testing machine[7,8]. It produces a load-displacement curve to determine flexural strength and modulus, guided by ASTM D790/D790M standards. This test is crucial for assessing material suitability for applications like beams and panels, which endure bending loads[9,10].

Shear Testing aims to assess the shear strength and modulus of composite materials by measuring their resistance to deformation along planes parallel to the force applied. This involves using a shear testing apparatus to apply force until the material fractures, producing a shear stress-strain curve that highlights the material's shear properties. This method, guided by ASTM D4255 standards, is crucial for evaluating material behavior under shear loads, aiding in structural design[11,12].

The updated text emphasises how mechanical test results are impacted by material anisotropy, which is prevalent in composites. The orientation of a material's fibres or grains frequently affects its tensile and shear characteristics. Tensile strength of fiber-reinforced composites, for example, is substantially greater along the fibre direction than in transverse orientations. Because of the poorer interlaminar bonding, shear tests also show reduced strength in off-axis orientations. Ignoring anisotropy might result in inaccurate material performance findings. The paper proposes testing in several orientations to capture the entire range of mechanical characteristics in order to remedy this. Unidirectional composite laminates are one example, where the degree of anisotropy may be demonstrated by longitudinal and transverse testing.

Peel testing assesses the bond strength between composite layers by measuring the force needed to separate them. This involves using a peel testing machine equipped with specific fixtures to apply a tensile load at a set angle until the bonded surfaces fail, producing a peel force-displacement curve that indicates peel strength. It's critical for evaluating bonding quality in structures like laminates and adhesive joints, guided by ASTM D903/D903M standard test methods[13].

Interlaminar Shear Testing aims to evaluate a composite material's resistance to shear force between its layers, using a specific testing fixture to produce a stress-strain curve that reflects shear strength and modulus. This test, guided by ASTM D2344/D2344M, is crucial for assessing laminate bonding quality and delamination resistance[14,15].

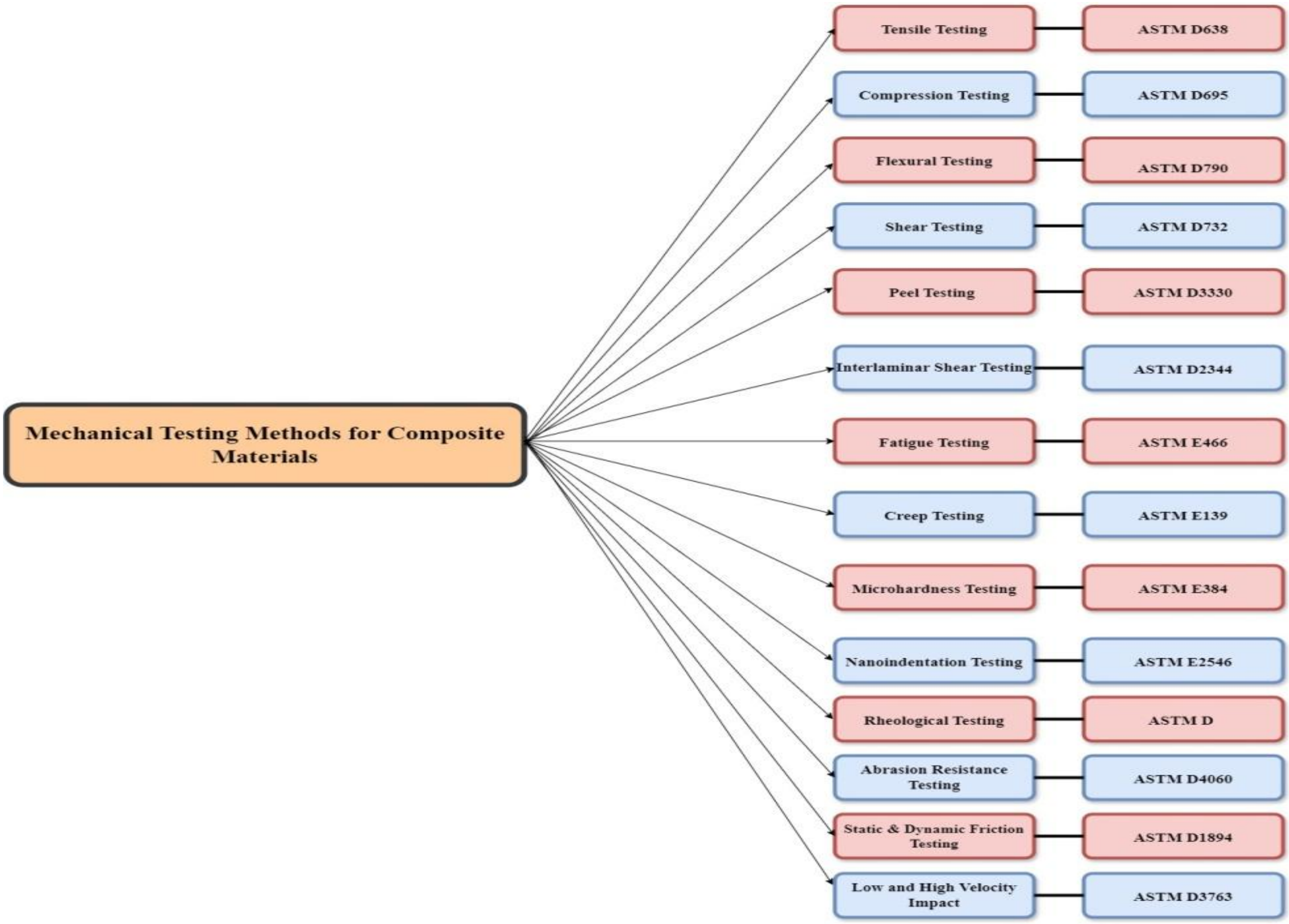


**Fig. 3:** Mechanical testing methods for composite materials.

Figure 3 provides mechanical testing methods for composite materials with astm standards. Meanwhile, Impact Testing evaluates a composite's ability to absorb energy during a sudden impact, using Charpy or Izod machines to generate an energy-absorption curve[16,17]. This test, defined by ASTM D256/D256M, is vital for understanding material behavior under impact, especially in safety-critical applications[18].

Fatigue testing aims to evaluate the endurance and fatigue strength of composite materials by assessing their resistance to cyclic loading to estimate their operational lifespan. This test uses a fatigue testing machine fitted with specific fixtures to apply repeated stress on a material, resulting in a fatigue life curve that shows stress against the cycle count to failure[19]. It's crucial for determining a material's reliability under variable loads, guided by ASTM D3479/D3479M for tensile fatigue properties in composites[20,21].

Creep testing is conducted to understand the creep behavior and time-dependent deformation of composites under constant stress, using a creep testing setup with a load cell and displacement sensor. The outcome is a creep curve, plotting creep strain over time, essential for assessing a material's stability and integrity under prolonged loads. This test, guided by ASTM D2990, aids in the design process by evaluating the creep properties of polymer matrix composites[22,23]. High temperatures hasten creep deformation in composites is covered in the updated section. Matrix materials soften at high temperatures, particularly in polymer composites, which lessens their resistance to long-term deformation under load. In carbon fiber-reinforced polymers, for example, the creep rate rises sharply above the glass transition temperature. Applications in power generation and aerospace, where materials are exposed to high temperatures for extended periods of time, depend on this behaviour. Turbine blades and spaceship parts are two examples where precise creep life prediction is crucial. The selection of composites for dependable, long-term usage in harsh settings is made possible by the use of temperature-dependent creep testing, which offers insights into material performance.

Microhardness testing is used to check the surface hardness and mechanical properties of composite materials at the micro-level by their resistance to plastic-type deformation under loaded, localized applications. The test is carried out using a microhardness tester in which Vickers or Knoop indenters are used to obtain sample results showing the hardness of the material[24]. The test is vital for giving information on material homogeneity, phase distribution, and the role of processing in mechanical properties. In this test, the applied load is controlled and restricted to a small indenter into a material surface; thus, the size or depth of the indentation left behind becomes a measure that gives information about the surface hardness and material behavior under localized loading[25,26].

Nanoindentation testing aims at probing the mechanical properties and deformation behavior of composite materials at the nanoscale. This micromechanical test is built upon critical points, such as high-resolution measurements in hardness, elastic modulus, and creep resistance. The experimental approach utilizes the nanoindenter machine, equipped with a sharp indenter and a displacement sensor. This is significant in characterizing nanomechanical behavior, such as hardness, stiffness, and deformation mechanisms, which are critical for material design and optimization. A measure of mechanical properties can be represented by the load-displacement curve obtained with the nanoindentation setup[27]. The test involves the application of a controlled load to the material surface with the help of a sharp indenter; the resulting displacement is measured, and the obtained results include information on nanoscale mechanical properties and deformation behavior[28,29]. The distinctions between macroscopic and nanoscale testing are explained in a new section. Macroscopic testing techniques, like impact and tensile tests, assess bulk material qualities like toughness and strength under typical load scenarios. On the other hand, localised characteristics like hardness, elastic modulus, and surface roughness at the micro- or nanometre scale are the main focus of nanoscale testing techniques like AFM and nanoindentation. The article now describes how both methods are compatible for thorough material characterisation since macroscopic testing offers a broad evaluation of material performance, while nanoscale testing offers in-depth understanding of microstructural behaviour.

For precise microhardness and nanoindentation findings, surface pretreatment is essential. Inconsistent measurements may result from artefacts like scratches or residual strains introduced by improper polishing or etching. The updated text explains how methods like thorough washing and progressive polishing with finer abrasives reduce surface imperfections. A flat, smooth surface is necessary for nanoindentation in order to determine the modulus and indentation depth precisely. Hardness levels can also be impacted by surface property changes brought about by preparation variations, such as excessive polishing. To increase measurement repeatability and reliability, best practices are highlighted, such as uniform polishing procedures and consistent cleaning agent usage.

Rheological testing describes the flow behavior and viscosity of composite materials being processed at a given time by the measurement of the response under conditions of shear stress or strain. Dispensing a rheometer or viscometer with controlled shear rate or stress allows the plotting of rheological curves of the viscosity versus shear rate or stress. It is essential testing applicable to assessing processability, mixing uniformity, and flow stability during manufacturing composites[30]. The test is to subject the material to controlled shear stress or strain and to measure the resulting deformation or flow behavior to provide information about viscosity, shear thinning, or viscoelastic properties[31,32].

GPC characterizes the molecular weight distribution and polymer composition of composite materials through a technique in which polymer chains are separated and described according to size and molecular weight. The configuration involves a GPC instrument equipped with a column, solvent delivery system, and detector providing a GPC chromatogram showing molecular weight distribution. This test is critical to get information on the purity of polymers, average molecular weights, and polymerization kinetics for material synthesis and quality control. GPC involves the passage of a polymer solution through a column packed with porous beads that give information about molecular weight distribution and polymer composition by measuring the elution times of the polymer chains. Gas permeability testing measures the gas transmission rate through a material to evaluate its barrier properties and permeability toward gases under controlled conditions. The test is carried out on a gas permeation tester with a flow controller and permeation cell, and the gas permeability coefficient reflects the material's resistance to gas diffusion. This is quite significant testing in assessing material suitability for packaging, membrane separation, and applications in gas storage. The test is carried out by exposing a material to a gas flow at a constant pressure and by measuring the permeating gas flow through the material to derive barrier properties and gas transport mechanisms[33,34)].

Water absorption testing involves the determination of the moisture pick-up and hygroscopic behavior of composite materials through the measurement of the absorbed water quantity under immersion or humid conditions. The setup involves equipment for a water absorption test with some set temperature and humidity. Therefore, the water absorption percentages obtained give the material hygroscopicity[35)]. Such testing is essential to engineering applications to check material stability, dimensional changes, and durability in an engineering atmosphere. This involves the material being soaked in water or exposed to high relative humidity for a specific time and subsequently weighing the specimen to quantify the increase in mass as an indicator of the moisture absorption kinetics and the compatibility of the material in wet environments[36,37)].

In other words, accelerated aging testing is carried out to predict the long-term performance and durability of composite materials under accelerated aging conditions that simulate the environmental degradation mechanism: UV radiation, temperature, and humidity. It is done in a chamber with a controlled temperature and humidity setup and UV exposure after which accelerated aging is done in a chamber to create changes in material properties or appearance[38)]. It is crucial in the determination of service life, the estimation of material stability, and the confirmation of earlier performance predictions. These include testing the material under heightened temperature, humidity, and UV radiation conditions for a specified duration while noting the changes in material property or degradation mechanisms[39,40)].

Flammability tests are conducted to investigate the resistance to fire and the flammability of composite materials by measuring their characteristics in ignition, flame spread, and smoke generation. The setup involves a flammability test apparatus with a controlled ignition source and relevant flame spread measurement, yielding ratings or performance indices based on ignition time, flame spread rate, or smoke density. This testing is essential in assessing material safety, fire hazard potential, and regulatory standards that provide building codes and transportation applications[41)]. The test is designed based on the controlled ignition source exposure and measurement of a series of parameters like, but not limited to, the ignition time, flame-spread rate, and smoke production, providing data about fire resistance and flammability characteristics[42,43)].

In essence, colorfastness testing is a method used to evaluate color stability and fading resistance of composite materials to high energy, such as light, heat, and environmental conditions. Through measuring changes in color intensities or hue after exposure to simulated sunlight or artificial light sources, the setup includes a colorfastness test apparatus that contains controlled light intensity and exposure duration to measure the color variation, usually through color difference measurements, or fading ratings determined by visual assessment or colorimetric analysis. This is a critical test for material colorfastness and durability; it also includes the testing of a material's fade resistance in outdoor applications and for an aesthetic component[44)]. This test consists of the exposure of a material to a light source simulating sunlight or artificial light and the measurement of changes in color appearance or intensity over time[45,46)].

Such testing evaluates abrasion resistance, the resistance to wear, and durability of the surface using measurement of surface roughness after an abrasive wear test or mass loss. It includes abrasion test setups that house an abrasion apparatus, a rotating or reciprocating abrasive wheel, and specimen holders. Such testing is highly critical for assessing material resistance to abrasive wear, scratching, and surface damage for applications in engineering and product durability[47)]. During the test, the abrasive contact of the test material surface is made by a standardized abrasive wheel or material, and the inflicted wear or surface damage is measured[48,49)].

Scratch resistance tests are tests that determine the ability of composite materials to resist scratching and indentation forces in association with changes in apparent surface condition and the assessment of damage after scratch testing. The test machine consists of a scratch test machine fitted with a fixed stylus or an indenter integrated with a sample holder for scratch properties rating and penetration depth determination. This test is essential for material resistance to surface scratching, abrasion, and wear to optimize product durability and performance. It determines the resistance of materials to surface scratching, abrasion, or wearing through the imposition of a controlled load or force on a material surface with a sharp stylus or indenter and measuring the depth of the surface damage or scratch depth produced[50,51].

Static friction testing measures the resistance to motion or sliding between two contacting surfaces, determining the frictional behavior and surface interaction of composite materials under static contact conditions. The equipment constitutes a test fixture for friction provided with controlled average load and sliding motion; this configuration leads to a coefficient of static friction that shows resistance to motion. It is so helpful that it can be applied in testing different material tribological properties for engineering applications and product performance, such as friction, wear, and lubrication requirements. The test evaluates how the material resists movement or sliding under a controlled average load in a situation of static contact[52].

Dynamic friction tests measure the frictional characteristics and energy losses of composite materials under dynamic contact conditions through the resistance to motion or sliding between two contacting surfaces. That is, the contacting surfaces oscillate or reciprocate. The system has a frame in which the dynamic friction test arrangement has been done. Autorotation or alternate pendulum-type arrangements have also been incorporated. Such tests are necessary for the evaluation of the tribological properties of the material about dynamic friction, wear, and lubrication performance towards varied engineering applications and product designs [53]. The test involves exposing the material surface to an oscillatory or reciprocating motion against a counterpart surface and measuring the frictional force or coefficient of friction generated from the subject material surface[54,55].

Fretting fatigue testing is a standard method of testing to measure damage accumulation and lifetime evaluation of the fatigue properties of composite material under cyclic loading and small-amplitude oscillatory motion or changes of material properties in a forming process using wear conditions. The measurement system in use to evaluate the fatigue crack development in the fretting-fatigue theory consists of a fretting fatigue testing setup, an instrument system with small amplitude reciprocating linear motion system, and a testing method set to obtain the corresponding fretting fatigue life curves or damage accumulation data. Such testing is essential for ever-increasing engineering applications and structural integrity assessment, including those bearing on the evaluation of material fatigue resistance and crack initiation and propagation behavior under fretting conditions[56]. The tests involve exposing materials to cyclic loading and small-amplitude oscillatory motion of the contacting surfaces and further monitoring the resultant fatigue damage or crack propagation[57,58].

Table 1 summarizes mechanical testing conducted on various composite materials, emphasizing major findings and relevance. Different authors conducted tests such as tensile, compression, flexural, shear, impact, and fatigue. Each test's configuration, such as Universal Testing Machines and specialized fixtures, is documented. This review helps to understand composite material behavior and testing methodologies.

Tensile testing, compression testing, flexural testing, and shear testing are basic mechanical tests that offer important information on the strength, stiffness, and durability of composite materials. Tensile testing is critical for determining if materials used in aerospace and construction can survive high tensile stresses during flight and in reinforced concrete constructions. Compression testing evaluates materials' capacity to withstand compressive stresses, which is critical for vehicle frames and packaging materials. Flexural testing determines a material's resistance to bending, which is critical for beams and panels in construction and sporting equipment such as skis and snowboards. Shear testing determines the resistance to shear pressures, assuring the dependability of adhesives in composite constructions and the strength of mechanical joints[59,60].

Advanced mechanical tests, such as impact testing, fatigue testing, creep testing, and microhardness testing, help us better understand how composite materials operate under different situations. Impact testing is critical for determining the impact resistance of materials in automobiles and sporting goods, assuring safety and performance. Fatigue testing assesses materials' endurance under cyclic loads, which is critical for the lifetime of bridges and aircraft structures[60,61]. Creep testing evaluates time-dependent deformation under constant stress, which is critical for high-temperature components in power plants and building materials under long-term loads. Microhardness testing offers information on surface hardness and mechanical characteristics at the micro-level, which is useful for microelectronics and medical devices.

Nanoindentation testing, rheological testing, and accelerated aging testing are critical for determining the nanoscale characteristics, flow behavior, and long-term durability of composite materials. Nanoindentation testing examines mechanical characteristics at the nanoscale, which is important for nanotechnology and coatings. Rheological testing covers the flow behavior and viscosity of materials, assuring processability and consistent mixing in the polymer and food industries. Accelerated aging testing forecasts long-term performance under simulated environmental settings, which is critical for automotive materials and construction items. Furthermore, flammability testing, colorfastness testing, abrasion resistance testing, scratch resistance testing, static and dynamic friction testing, and fretting fatigue testing provide comprehensive evaluations of materials resistance to fire, color changes, wear, scratching, frictional forces, and fatigue damage, ensuring their reliability and performance in diverse applications ranging from building codes and transportation to consumer electronics and industrial machines[62,63].

## 3. Environmental Testing Methods

This chapter looks at critical environmental testing procedures for composite materials. Hygrothermal testing assesses moisture and temperature impacts to ensure durability in humid, high-temperature conditions. Tribocorrosion testing evaluates the combined wear and corrosion impacts, which is critical for harsh circumstances. UV resistance and mold resistance tests provide dependability under UV and humid environments, respectively. Finally, salt spray and ozone resistance tests assess corrosion and ozone damage, which is applicable to a variety of industrial and outdoor applications[64)].

Hygrothermal testing assesses the impact of moisture and temperature on composite materials by evaluating changes in their mechanical, thermal, and physical properties in an environmental chamber with regulated humidity and temperature. This testing, guided by ASTM D5229/D5229M standards, involves exposing specimens to varying hygrothermal conditions and tracking the aging curve for property alterations over time. The purpose is to determine the materials' durability and reliability in humid, high-temperature environments[65,66)]. The hygrothermal performance of composites made of polymers is greatly impacted by moisture absorption. Delamination and decreased mechanical strength result from water molecules penetrating the matrix and weakening the interfacial bond between the fibres and the polymer. Examples of moisture-induced deterioration of characteristics like as modulus and flexural strength are covered in the updated manuscript. Furthermore, residual pressures brought on by swelling brought on by absorbed moisture further jeopardise structural integrity. This is especially important for applications in the maritime and aerospace industries, where composites are subjected to humid conditions. The updated section emphasises how protective coatings and humidity management during testing can lessen these impacts and guarantee proper performance evaluation.

The general objective of studying the tribocorrosion test is to investigate the coupled effect of wear and corrosion in the composite material under study in hostile environments. This test measures changes in material properties or surface degradation after exposure to a combined mechanical and corrosive environment. To set up such a test, one requires test equipment to be a tribocorrosion test apparatus with a reciprocating or sliding wear system in a corrosive environment. The results can be quoted in terms of wear rate, corrosion rate, or loss of materials. Engineering applications and product reliability under tribocorrosive conditions[67,68)].

This test method evaluates the resistance of composite materials to various chemicals and subsequently to chemical-induced degradation. The material characteristic in terms of resistance is obtained by monitoring the changes in any mechanical, thermal, or surface properties before and after the immersion of material in a specified chemical, using a chemical resistance test apparatus equipped with immersion cells or exposure chambers. Degradation of material properties or appearance is typical of what occurs under chemical exposure conditions. This test is critical in evaluating the suitability of materials for corrosive environments, chemical processing, and all sorts of aggressive fluids in most applications. The test involves immersing the material in various chemicals or exposing it to vapors of these chemicals for a certain period and, finally, establishing the changes in properties such as strength, stiffness, or surface finish[69,70)].

This activity tests the electromagnetic interference shielding effectiveness of composite materials. The measurement is made through the setting of the shielding effectiveness test between a signal generator and a receiver, where the most critical parameter to be measured is the attenuation of an electromagnetic wave passing through the material—summary of results for this sample: the shielding effectiveness at different frequencies.

The testing of materials for their ability at electromagnetic shielding involves subjecting them to electromagnetic waves of different frequencies. At the same time, the signals transmitted or reflected are measured to help in giving a revelation of the material's ability to block or attenuate electromagnetic interference[71,72)].

Table 1. Summary of mechanical test.

| **Name of Test** | **Name of Authors** | **Conclusion of Test** | **Significance of Test** | **Name of Setup on Which Test Can Be Conducted** |
|---|---|---|---|---|
| Tensile Testing | Milisavljević et al. | Different polymers show distinct tensile properties. | Highlights the diversity in polymer mechanical properties requiring tailored testing approaches. | Universal Testing Machine |
| Compression Testing | Clark, Lisagor | Provided guidelines for compression testing of graphite/epoxy composites. | Aids in determining composite materials' suitability | Compressio n Testing |

| Name of Test | Name of Authors | Conclusion of Test | Significance of Test | Name of Setup on Which Test Can Be Conducted |
|---|---|---|---|---|
| | | | for structural applications through compression testing. | Fixture |
| Evaluation of Compression Test Methods | Berg, Adams | Evaluated different compression test methods, highlighting disparities. | Inform critical methodological choices in composite material testing for accurate compression data. | Various Compression Testing Fixtures |
| Transverse Flexure Testing | Adams, King, Blackketter | Assessed the transverse flexure test method, finding it provides valuable data on material behavior. | Enhances understanding of composite materials' mechanical properties under transverse loading. | Flexural Test Setup |
| Flexural Strength Evaluation | Gundogdu et al. | Compared the flexural strength of composite resins. | Demonstrates the reinforcing effect of fibers on composite resins, important for dental applications. | Universal Testing Machine |
| Mechanical and Physical Testing Overview | Saba, Jawaid, Sultan | Summarizes mechanical and physical testing methods for composite materials. | Provides a comprehensive overview of testing practices, guiding researchers and engineers in material selection. | Various Testing Setups |
| Reliability in Flexural Strength | Palin et al. | Investigated the reliability of flexural strength testing for a novel dental composite. | Confirms the test's reliability for dental composites, impacting material choice in dentistry. | Flexural Testing Machine |
| Shear Test Methods Assessment | Adams, Lewis | Compared four shear test methods, providing insights into their effectiveness and limitations. | Facilitates the selection of appropriate shear test methods for composite material analysis. | Various Shear Test Fixtures |
| Peel-Type Durability Testing | Hart-Smith | Introduced a peel-type test for assessing interfaces in composite structures. | Offers a novel approach to evaluating the durability of bonded composite interfaces. | Peel Testing Setup |
| Edge Shear Test | Weidenmann et al. | Proposed the edge shear test for determining interlaminar shear strength. | Provides an alternative method for assessing interlaminar shear strength, important for composite integrity. | Edge Shear Test Setup |
| Impact Testing | Duell | Explored the impact resistance of advanced composites, outlining testing challenges. | Sheds light on composite materials' behavior under impact, essential for safety and design considerations. | Impact Testing Machine |
| Marine Impact Testing | Sutherland | Reviewed impact tests on marine composites, focusing on Part I – marine impacts. | Enhances understanding of marine composites' durability and performance under impact. | Drop-weight Impact Test Setup |
| Low and High Velocity Impact | Safri et al. | Summarized studies on low and high velocity impact tests for composites, highlighting key findings. | Provides insights into composite materials' behavior under various impact conditions. | Impact Testing Machines (Various) |
| Fatigue of Composites | Salkind | Discussed the fatigue behavior of composite materials, suggesting advanced evaluation approaches. | Critical for predicting composite materials' lifespan and performance under cyclic | Fatigue Testing Machines |

| Name of Test | Name of Authors | Conclusion of Test | Significance of Test | Name of Setup on Which Test Can Be Conducted |
|---|---|---|---|---|
| | | | loading. | |
| Fiber-Reinforced Composites Fatigue | Vassilopoulos, Keller | Comprehensive review on the fatigue behavior of fiber-reinforced composites. | Aids in the design and application of durable fiber-reinforced composite structures. | Fatigue Testing Setup |

Testing for UV resistance determines how resistant composite materials are to UV rays and outdoor weathering. The goal is to use a UV weathering chamber with regulated UV radiation intensity and exposure length to detect changes in mechanical, optical, or surface attributes following UV exposure. Changes in a material's characteristics or appearance following UV radiation are examples of sample findings. This technique is important for assessing the color stability, deterioration processes, and durability of materials in outdoor and UV-sensitive situations. In order to evaluate a material's resistance to UV radiation, it must be exposed to UV radiation at accelerated rates comparable to outdoor exposure. The material's characteristics or degradation processes are then monitored as a consequence[73,74]. Testing for mold and mildew resistance looks at composite materials' ability to withstand the growth of mold and mildew, which is important for long-term usage in humid settings. The materials are exposed to environments that encourage the formation of mold and mildew in an environmental chamber that is regulated for temperature and humidity. Visual inspections and microbiological analyses of the existence and degree of mold development are examples of sample results. This technique is important for guaranteeing the safety and longevity of composite materials used in high-humidity and high-moisture situations[75,76].

The corrosion resistance of composite materials exposed to a salty environment is assessed using salt spray testing. The aim is to quantify the material's deterioration and replicate extended exposure to an abrasive environment. Specimens are exposed to a fine mist of salt solution in a salt spray chamber for a predetermined amount of time. Measurements of corrosion products and weight loss are two examples of sample outcomes. This technique is important for determining whether composite materials are suitable for use in automotive, marine, and other situations where exposure to salt is likely[77,78].

Ozone resistance testing assesses composite materials' sensitivity to deterioration when exposed to ozone. The goal is to assess changes in mechanical, physical, or surface qualities following ozone exposure. The setup contains an ozone chamber with a predetermined ozone concentration and exposure time. Visual examinations, tensile strength changes, and surface cracking are all possible sample outcomes. This approach is useful for determining the durability of materials used in outdoor or industrial settings where ozone exposure is an issue[79,80].

Thermal shock testing evaluates composite materials' capacity to endure fast temperature fluctuations. The goal is to assess the material's performance and integrity following exposure to alternating high and low temperatures. The system includes a thermal shock chamber that rapidly transitions specimens between hot and cold temperatures. Visual inspections, fracture or delamination measures, and mechanical property changes are also part of the sample data. This approach is critical for applications involving materials that endure high temperature variations[81,82].

Freeze-thaw cycling tests the ability of composite materials to withstand repeated freezing and thawing cycles. The goal is to assess changes in physical and mechanical qualities during freeze-thaw cycles. The system comprises a freeze-thaw chamber, which cycles between freezing and thawing temperatures. Visual inspections, crack measures, spalling, and strength variations are all part of the sample data. This approach is critical for materials used in outdoor situations prone to seasonal temperature fluctuations[83,84]. Chemical vapor exposure testing evaluates composite materials' resistance to volatile chemicals. The goal is to assess how material characteristics change after being exposed to chemical vapors. The setup includes an exposure chamber with a predetermined vapor concentration and exposure period. Visual inspections, weight reduction, and changes in mechanical or thermal qualities are some of the sample outcomes. This approach is useful for assessing material performance in settings where chemical vapors are prevalent[85,86].

Biodegradation testing examines the pace and extent to which composite materials degrade in natural situations. The goal is to assess the environmental effect and sustainability of the materials. The setup incorporates soil burial or composting conditions in which specimens are subjected to microbial activity. The sample findings include weight loss measures, mechanical property changes, and visual examinations. This technology is critical for creating environmentally friendly and sustainable composite materials[87,88].

High-pressure testing assesses the performance of composite materials in high-pressure environments. The goal is to evaluate changes in material characteristics when exposed to high pressures. The equipment comprises a high-pressure chamber that can replicate deep-sea or industrial pressure levels. The sample data include mechanical property, deformation, and structural integrity measurements. This technique is essential for materials used in deep-sea exploration, high-pressure vessels, and other high-pressure applications[89,90].

Radiation resistance testing evaluates composite materials' capacity to tolerate exposure to various forms of radiation, including UV, gamma, and X-rays. The goal is to assess changes in mechanical, physical, or chemical characteristics following radiation exposure. The system includes a radiation chamber with adjustable radiation intensity and exposure time. Visual examinations, tensile strength changes, and surface deterioration are all possible sample outcomes. This technique is useful for materials used in aerospace, nuclear, and medical applications where radiation exposure is an issue[91,92]. Humidity testing assesses the impact of excessive humidity on composite materials. The goal is to assess changes in mechanical, physical, or surface qualities during exposure to high humidity levels. The setup includes a humidity chamber with adjustable humidity and temperature. Visual inspections, weight fluctuations, and mechanical qualities are also part of the sample results. This approach is useful for determining the durability of materials in tropical or high-humidity conditions[93,94].

Low-temperature testing evaluates composite materials' performance at sub-zero temperatures. The goal is to assess changes in mechanical, thermal, or physical qualities after being exposed to low temperatures. The design features a low-temperature chamber that can replicate arctic or high-altitude settings. The sample data include brittleness, tensile strength, and thermal conductivity testing. This approach is critical for materials used in cold climates, such as aerospace and outdoor applications[95,96]. Pollutant exposure testing measures composite materials' resistance to pollutants including sulfur dioxide, nitrogen oxides, and particulate matter. The goal is to quantify changes in material characteristics caused by exposure to air contaminants. The system includes an exposure chamber with adjustable pollutant concentrations and duration. Visual inspections, weight loss, and mechanical property changes are also part of the sample results. This approach is useful for evaluating material performance in highly polluted urban or industrial areas[97,98].

By including these new environmental test techniques, the chapter will give a thorough review of the numerous environmental difficulties that composite materials may face, as well as the testing methods used to assess their performance and durability under these conditions.

Environmental testing procedures are critical for determining the performance and durability of composite materials under a variety of environmental situations. These tests guarantee that composite materials fulfill the required criteria for high-performance applications while also giving vital data for their design, development, and use in a variety of technical domains. Understanding the material's behavior under real-world settings allows researchers and engineers to create composites that are dependable, long-lasting, and suited for specific environmental problems.

Hygrothermal testing evaluates the effect of moisture and temperature on composite materials, which is crucial for assuring durability in humid and high-temperature settings such as the ocean or tropical regions. Similarly, tribocorrosion testing assesses the combined effects of wear and corrosion, which is critical for offshore and industrial applications where materials must withstand extreme environments. Chemical resistance testing investigates how materials endure harsh chemicals, making it essential for the chemical processing and automobile sectors. Electromagnetic interference (EMI) shielding efficacy tests guarantee that materials can protect electronic equipment against electromagnetic interference, which is critical for electronics and aerospace applications. UV resistance testing determines the endurance of materials against UV radiation, which is critical for outdoor and automobile components. Mold and mildew resistance testing guarantees that materials can withstand microbial development in humid settings, which is critical for construction and maritime applications. Salt spray testing analyzes corrosion resistance in salty conditions, which is critical for marine, coastal, and automotive applications. Ozone resistance testing evaluates damage caused by ozone exposure and is applicable to both industrial and outdoor applications.

Thermal shock testing analyzes a material's capacity to tolerate fast temperature fluctuations, which is significant in aircraft, automotive, and electronics. Freeze-thaw cycle testing assesses materials' tolerance to temperature variations, which is important for building and infrastructure. Chemical vapor exposure testing evaluates material resistance to volatile chemicals, which is critical for chemical processing and laboratory equipment. Biodegradation testing assesses the environmental effect of materials, which is critical for producing eco-friendly goods. High-pressure testing assesses material performance at extreme pressures, which is critical for deep-sea exploration and industrial applications. Radiation resistance testing assures that materials can tolerate radiation exposure, which is important for aerospace, nuclear, and medical applications. Humidity testing evaluates material endurance under high humidity, which is important for tropical regions and building materials. Low-temperature testing assesses material performance at subzero temperatures, which is critical for aircraft, outdoor applications, and cold storage. Pollutant exposure testing assesses resistance to air contaminants, which is critical for urban and industrial areas. These tests guarantee that composite materials are reliable, durable, and suitable for a variety of tough real-world settings.

The environmental testing techniques, such as salt spray testing, UV exposure, and hygrothermal ageing assess the long-term durability of materials by simulating actual environmental conditions. For instance, salt spray testing evaluates corrosion resistance in marine and automotive environments, whereas UV exposure studies are essential for determining the weatherability of polymers used in outdoor applications. The significance of these techniques is highlighted by their capacity to forecast material deterioration, which makes it possible to create materials with improved environmental resistance for vital applications such as wind turbines, bridges, and aeroplanes.

## 4. Physical and Chemical Testing Methods for Composite Materials

This section discusses essential testing procedures for composite materials. Table 2 provides a summary of research papers on physical and chemical testing methods for composite materials (Part A). Electrical testing evaluates conductivity and insulation, which are critical for electrical applications. Thermal testing assesses thermal characteristics and stability, which are critical for thermal management. Microscopic analysis investigates microstructure and flaws, hence improving material knowledge. X-ray diffraction and photoelectron spectroscopy investigate crystallographic structure and chemical composition, which are critical for quality control. Surface morphology and nanoscale characteristics are analyzed using scanning electron microscopy and atomic force microscopy, which are critical for material optimization.

Electrical Testing simplifies assessing composite materials' conductivity and insulation, measuring resistance or insulation resistance using a specialized setup. It's crucial for evaluating materials for electrical uses, guided by ASTM D257/D257M standards on resistance measurements[99)].Thermal Testing focuses on evaluating composite materials' thermal properties, including conductivity and stability under temperature changes, using specific apparatus for controlled thermal exposure. This is key for materials in thermal management, with ASTM D5930/D5930M offering testing guidelines[100,101)].

Microscopic Analysis aims to explore composite materials' microstructure and defects, utilizing microscopes and analysis software to examine microscale features[102,103)]. This analysis is essential for understanding material behavior and refining manufacturing processes, supported by detailed imaging techniques[104)]. X-ray Diffraction (XRD) is used to examine the crystallographic structure and phase composition of composite materials, aiming to identify crystalline phases, crystal size, and orientation. It employs a diffractometer with a rotating sample holder to analyze diffraction patterns for material purity, crystallinity, and phase changes, crucial for quality control and characterization[105,106)]. XRD works by irradiating the material with X-rays and analyzing the diffraction pattern to deduce the atomic arrangement[107)].

X-ray Photoelectron Spectroscopy (XPS) assesses the elemental composition and chemical bonds of composite materials. It aims to detect surface contaminants, functional groups, and oxidation states using a spectrometer equipped with a monochromatic X-ray source and electron analyzer[108,109)]. The resulting XPS spectrum, which reveals elemental peaks and binding energies, is vital for studying surface chemistry and interactions, thereby aiding in material optimization and surface modifications. XPS technique involves irradiating the sample with X-rays to measure the kinetic energy of ejected photoelectrons, offering insights into the elemental composition and chemical states of the surface[110,111)].

Scanning Electron Microscopy (SEM) is a technique used to analyze the surface morphology and microstructure of composite materials. It employs a focused electron beam and detectors to produce high-resolution images (SEM micrographs) showcasing surface topography and microstructural details[112,113)]. This method is crucial for understanding material failure mechanisms, enhancing manufacturing processes, and optimizing material properties by visualizing surface features, defects, and fracture surfaces[114,115)].

Transmission Electron Microscopy (TEM) explores the microstructure and nanoscale features of materials, aiming to reveal atomic-resolution details such as crystal structure, grain boundaries, and nanoparticles. Utilizing a high-voltage electron beam and imaging system, TEM generates micrographs that display lattice fringes and nanoparticle distribution. This approach is essential for investigating nanoscale phenomena like phase transformations, defects, and interfaces, thereby aiding in material characterization and design.

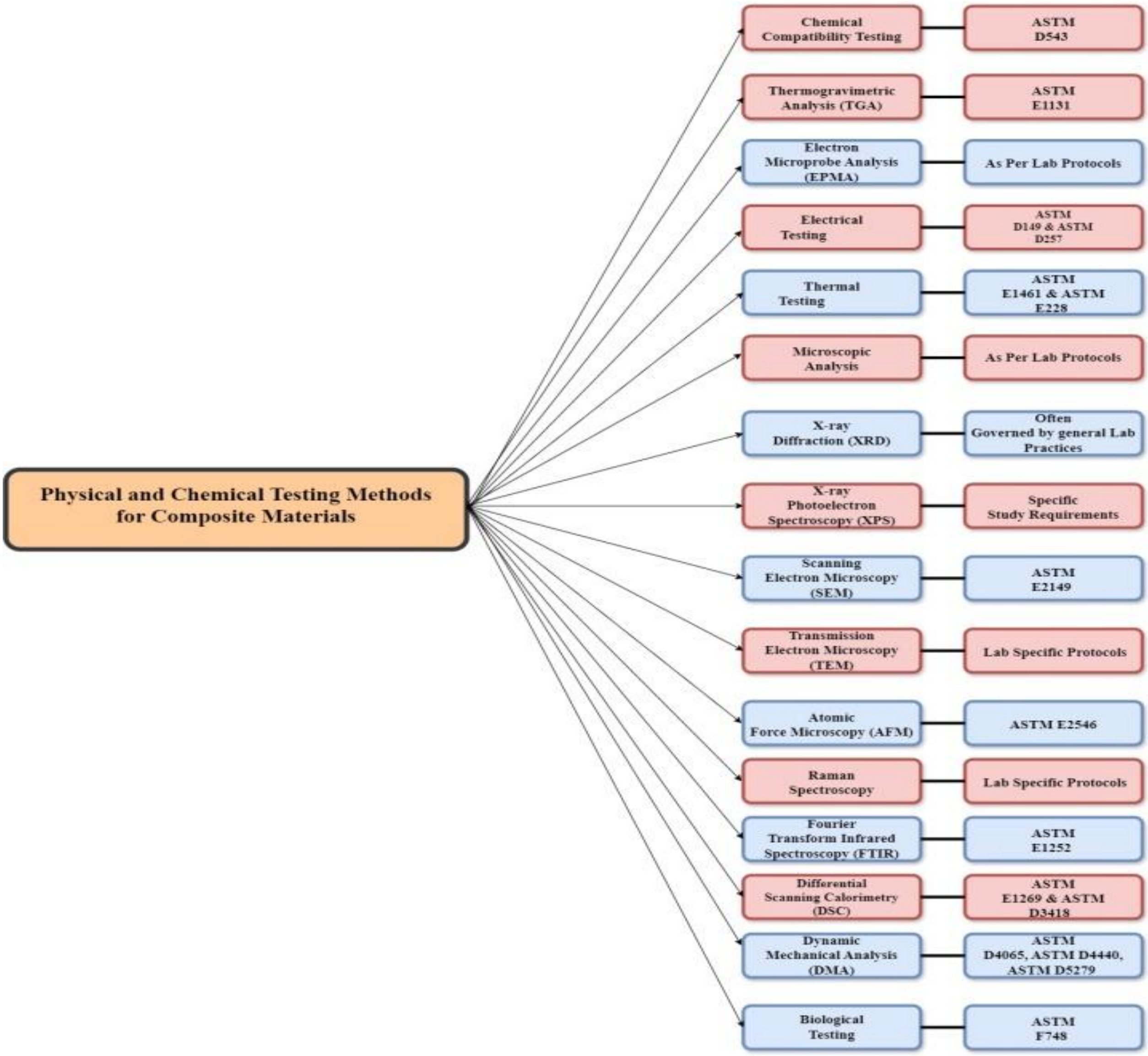


**Fig. 4:** Physical and chemical testing methods**.**

Both Atomic Force Microscopy (AFM) and Scanning Electron Microscopy (SEM) are popular techniques for characterising materials at the nanoscale, and each has unique benefits. With magnifications up to 1,000,000x, SEM offers high-resolution imaging that may capture intricate surface morphology across wide regions. For insulating materials, it necessitates a conductive coating, which might change the characteristics of the surface. However, without the need for a conductive coating, AFM is excellent at detecting surface topography, roughness, and nanomechanical characteristics with nanometre accuracy. While AFM gives quantitative mechanical and adhesion data at precise places, SEM provides better imaging of surface characteristics. A thorough knowledge of materials is made possible by combining both techniques, with AFM giving localised, accurate measurements and SEM providing an overview.

Atomic Force Microscopy (AFM) uses a cantilever probe and scanning system to explore composite materials' surface topography and mechanical properties at the nanoscale. It aims to assess surface roughness, adhesion, and stiffness in high detail, with results revealing surface features and mechanical characteristics. This technique is crucial for understanding surface morphology and nanomechanical behavior, aiding material design and optimization[116,117]. AFM operates by scanning a tip across a surface to measure interaction forces, offering insights into topography and mechanical properties[118].

Raman Spectroscopy employs a monochromatic laser and detector to examine the molecular structure and chemical composition of composite materials[119]. Its goal is to identify functional groups, molecular bonds, and phase transitions, with the Raman spectrum indicating vibrational modes and peak intensities. This method is vital for analyzing chemical bonding, degradation mechanisms, and material properties, serving as a tool for quality control and characterization. It works by irradiating the material with a laser beam and analyzing the scattered light to glean information on molecular vibrations and chemical bonds[120,121].

Fourier Transform Infrared Spectroscopy (FTIR) analyzes the molecular composition and structure of composite materials by identifying functional groups, polymer chains, and additives[122,123]. It uses an FTIR spectrometer equipped with an infrared light source and detector, producing spectra that reveal absorption peaks and molecular vibrations. This technique is crucial for assessing chemical composition, detecting degradation products, and ensuring material compatibility for quality control and research, based on the absorption or transmission of infrared light through the material[124].

Differential Scanning Calorimetry (DSC) assesses the thermal properties and phase transitions of composite materials, including heat flow, specific heat capacity, and melting or crystallization behaviors. Utilizing a calorimeter with a temperature-regulated furnace and heat flow sensor, it generates thermograms indicating endothermic or exothermic transitions[125,126]. DSC is essential for understanding material behaviors such as glass transition, melting, and curing, facilitating thermal analysis and processing optimization by measuring the heat flow while heating or cooling a sample against a reference[127]. Dynamic Mechanical Analysis (DMA) assesses the viscoelastic properties and mechanical behavior of composite materials under dynamic conditions. It aims to measure storage modulus, loss modulus, and damping properties using a dynamic mechanical analyzer set to specific frequencies and temperatures[128,129]. Results include DMA curves that plot these moduli against temperature or frequency, crucial for understanding material stiffness, damping, and temperature transitions to optimize design and performance[130,131].

Thermogravimetric Analysis (TGA) investigates composite materials' thermal stability and decomposition patterns. It aims to chart weight loss, degradation temperatures, and decomposition rates using a thermogravimetric analyzer with a steady heating rate[132,133]. TGA curves depict weight loss over temperature, shedding light on degradation mechanisms, thermal stability, and decomposition byproducts for processing and application insights[134]. Electron Microprobe Analysis (EPMA) identifies and maps the elemental composition of composite materials. Its goal is to quantify trace element concentrations and their spatial distribution using an electron microprobe equipped with an electron beam and X-ray detectors. The analysis produces elemental maps and concentration profiles, vital for understanding material composition, identifying impurities, and exploring elemental segregation for material characterization[135,136].

Chemical compatibility testing is a process that determines how compatible substances or composite materials are with particular chemicals, solvents, or environmental conditions. The main objective of this testing is to determine changes in properties or material appearance that occur upon the action of chemical agents. The chemical compatibility test usually includes a setup, immersion cells, or exposure chambers. Usually, sample results are indicative of changes in the properties or appearance of a material after it has been exposed chemically, if a material is attacked, swells, or degraded. Such an evaluation is critical in understanding the compatibility of the material with the environment and application identified. The process involves exposing the material to different chemical and solvent environments or environmental conditions and monitoring the changes in the material properties or degradation mechanism[137,138].

The main objective of biological testing is to evaluate the biocompatibility and biological response of composite materials in contact with living tissues or organisms. In other words, this is supposed to bring out the measure of cytotoxicity, cell adhesion, and compatibility with the tissue in question, either in vitro or in vivo. The biological setup of testing involves the use of cell culture plates, incubators, and microscopy equipment. Such tests typically give data on cell viability or tissue response, mainly using cytotoxicity assays and, in some cases, through histological analysis. This practice is essential for testing materials to determine material safety and biocompatibility, and finding their suitability in medical implants, tissue engineering, and other biomedicine applications. This involves exposing the material to cultured cells or living organisms, followed by assessing the ensuing biological response, including cell viability, proliferation, and tissue integration[139,140].

Biomimetic assessment aims at imitating in vivo biological processes or structures to test for performance and functionalities associated with composite materials or functionalities. The test seeks to find meaningful insights into biological design principles, materials synthesis, and applications in biomimetic engineering. The setup involves controlled environmental conditions and stimuli intended to mimic, according to design specifications, the natural process. Sample results often reflect biomimetic structures, materials, or functionalities inspired by the natural systems. It has been conducted to explore biomimetic design strategies, functional material synthesis, and bio-inspired engineering solutions for a broad range of applications, including aerospace, robotics, and biomedical devices. This testing includes the replication of biological processes and structures in synthetic items or systems to evaluate their performance, properties, and interactions with the environment[141,142].

Table 3 lists the numerous physical and chemical testing procedures for composite materials, emphasizing significant findings and their relevance. Scanning Electron Microscopy (SEM) and Atomic Force Microscopy (AFM) give thorough surface and structural investigations, which are required for material development. Raman and FTIR spectroscopy provide information on the chemical and electrical characteristics of materials, which is essential for applications in advanced composites and polymers. Each test's setup, from SEM to Raman spectroscope, is also described.

The tests include Thermogravimetric Analysis (TGA), which stresses the relevance of particle size in thermal characteristics, and Electron Probe Microanalysis (EPMA), which demonstrates its accuracy in material characterisation. Other studies, such as Electrospun Nanofiber Analysis and Electrochemical Impedance Spectroscopy (EIS), highlight nanofibers' ability to improve mechanical characteristics, as well as EIS's significance in improving energy devices and biosensors.

## 5. Advanced Characterization Techniques

This section discusses various major composite material testing. Surface energy determination evaluates wettability and adhesion qualities, which are critical for surface modification. Electrochemical Impedance Spectroscopy examines corrosion resistance, which is critical for material durability. Fiber volume fraction measurements quantify reinforcement levels, which are critical for mechanical characteristics. Ultrasonic testing reveals faults, which is useful for assessing structural integrity. Acoustic emission testing detects damage onset, which is critical for forecasting material failure. Chemical resistance and UV resistance tests determine material stability, which is critical for determining compatibility and long-term durability. Covers sophisticated characterisation techniques that provide significant insights into defect identification, structural integrity, and material longevity, which are important for a variety of applications.

Determination of surface energy is performed to estimate surface wettability and adhesion properties of composite materials. The purpose is to measure surface energy, contact angle, and surface tension with a contact angle goniometer fitted with a droplet dispenser and an imaging system. The results from a sample are in the form of contact angle measurements, indicating if a surface is hydrophobic or hydrophilic. This is a crucial evaluation because it has its part in the understanding of surface properties, adhesion behavior, and compatibility toward given coatings or adhesives in the modification of the surface. The method is based on droplet deposition on the sample surface and measurement of the contact angle formed by the droplet, indicating surface wettability and energy[143)].

Electrochemical Electrochemical Impedance Spectroscopy (EIS) studies the electrochemical behavior and corrosion resistance of composite materials. This lab measures impedance responses after exciting specimens with an alternating current at various frequencies. The sample tests are conducted using an electrochemical workstation with a potentiostat and impedance analyzer. Sample results include EIS Nyquist plots showing impedance versus frequency. The method is essential for evaluating resistance to corrosion of material, surface coating, and barrier properties for corrosion protection[144)]. EIS is a method in which an AC signal is imposed on the sample-electrolyte interface, and then the arising impedance is determined; this allows for the study of electrochemical processes such as corrosion or ion transport[145,146)].

Table 2. Physical and chemical testing methods for composite materials (Part A).

| Name of Test | Name of Authors | Conclusion of Test | Significance of Test | Name of Setup on Which Test Can Be Conducted |
|---|---|---|---|---|
| Scanning Electron Microscopy (SEM) and Energy-Dispersive X-ray (EDX) Spectroscopy | Abd Mutalib, M., Rahman, M.A., et al. | Provides detailed surface morphology and elemental composition of materials. | Crucial for analyzing membrane surfaces and filtering mechanisms in advanced materials. | SEM equipped with EDX detector. |
| Electron Microscopy of Polymers | Michler, G.H., Lebek, W. | Reveals microscopic details of polymer morphology. | Essential for understanding the structural properties influencing polymer performance. | Transmission Electron Microscope (TEM) or Scanning Electron Microscope (SEM). |
| Scanning Electron Microscopy (SEM) and Atomic Force Microscopy (AFM) | Rydz, J., Šišková, A., et al. | Enables topographic and dynamical studies of material surfaces. | Vital for assessing blends, composites, and hybrids' surface properties for sustainable development. | SEM and AFM setups. |
| Advanced Atomic Force Microscopy in Polymer Science | Nguyen-Tri, P., Ghassemi, P., et al. | Offers insights into polymer surface dynamics and mechanical properties. | Advances the field of polymer science by providing detailed surface and mechanical analysis. | Atomic Force Microscope (AFM). |

| | | | | |
|---|---|---|---|---|
| Advances in Atomic Force Microscopy for Probing Polymer Structure and Properties | Wang, D., Russell, T.P. | Allows high-resolution analysis of polymer structures and properties. | Enhances understanding of polymers at the nanoscale, crucial for material innovation. | Atomic Force Microscope (AFM). |
| Raman Spectroscopy of Carbon Materials | Li, Z., Deng, L., et al. | Facilitates understanding of structural and electronic properties of carbon materials. | Significant for developing advanced composite materials like graphene, nanotubes, and fibers. | Raman Spectroscope. |
| Raman Spectroscopy Applications | Orlando, A., Franceschini, F., et al. | Highlights diverse applications of Raman spectroscopy. | Demonstrates the versatility of Raman spectroscopy in materials science. | Raman Spectroscope. |
| Characterization of Cellulosic Fibers by FTIR Spectroscopy | Hospodarova, V., Singovszka, E., et al. | Provides detailed chemical characterization of cellulosic fibers. | Important for evaluating fibers for use in building materials and understanding their chemical modifications. | FTIR Spectrometer. |
| Fourier Transform Infrared Spectroscopy (FTIR), Raman Spectroscopy, and WAXS | Gopanna, A., Mandapati, R.N., et al. | Offers a comprehensive analysis of polypropylene (PP)/cyclic olefin copolymer (COC) blends. | Enhances material selection and application in diverse fields by providing a detailed compositional analysis. | FTIR Spectrometer, Raman Spectroscope, and Wide-Angle X-ray Scattering setup. |

Table 3. Physical and chemical testing methods for composite materials (Part B).

| Name of Test | Name of Authors | Conclusion of Test | Significance of Test | Name of Setup on Which Test Can be Conducted |
|---|---|---|---|---|
| Thermogravimetric Analysis (TGA) | Farivar, F., Yap, P.L., et al. | Particle size significantly affects the thermal parameters of graphene materials. | Highlights the importance of particle size in determining thermal properties of graphene. | Thermogravimetric Analyzer |
| Electron Probe Microanalysis (EPMA) | Llovet, X., Moy, A., et al. | Reviewed recent developments in EPMA for materials science, emphasizing enhanced analytical capabilities. | Demonstrates EPMA's versatility and precision in materials characterization. | Electron Probe Microanalyzer |
| Electron Microscopy and Probe Micro-Analysis | Delbari, S.A., Shakeri, M.S., et al. | SiC and/or WC additives improve the mechanical properties of TiC ceramics. | Provides insight into optimizing TiC ceramics for engineering applications. | Electron Microscope and Microprobe |
| Electrospun Nanofiber Analysis | Wang, G., Yu, D., et al. | Nanofibers significantly enhance the mechanical properties of polymer matrix composites. | Stresses the potential of electrospun nanofibers as reinforcing fillers. | Electrospinning Setup |
| Electrochemical Impedance Spectroscopy (EIS) | Bredar, A.R., Chown, A.L., et al. | EIS effectively characterizes the electrochemical properties of metal oxide electrodes. | Crucial for improving energy storage and conversion devices. | Electrochemical Workstation |
| EIS for Biosensing Applications | Magar, H.S., Hassan, R.Y., et al. | EIS is a powerful tool for constructing and evaluating biosensors. | Enhances the development of sensitive, selective biosensing platforms. | Electrochemical Workstation |
| EIS for Photocatalysis Characterization | Ângelo, J., Magalhães, P., et al. | EIS is effective in characterizing photocatalytic efficiency and mechanisms of TiO2 semiconductors. | Aids in the optimization of TiO2 semiconductors for environmental and energy applications. | Electrochemical Workstation |

Fiber volume fraction measurement identifies the volume ratio of the reinforcing fibers to the composite material. The aim is to quantify the amount of fiber reinforcement and assess the homogeneity of composites using a microscopic imaging system or an image analysis software package. Example results include fiber volume fraction percentages, which are fundamental during analysis for composite quality and mechanical properties and associated with performance optimization due to processing consistency. The fiber volume fraction is measured by the microscopic image of the composite cross-section, and the image is used to determine the area percent occupied by fibers with respect to the total cross section area.

Ultrasonic testing Composites are applied to detect defects, delaminations, and bond integrity in composite materials. It seeks to assess the path of ultrasonic waves in the material by performing a frequency-domain analysis of the back-reflected signals with the adequate ultrasonic testing setup using a transducer and a signal analyzer. Representative results which can be obtained include the ultrasonic C-scan or B-scan images that will give an internal view of flaws. The technique has critical importance in evaluating the quality of a material, its integrity, and structural health in a non-destructive manner. Ultrasonic testing is based on sounding material with high-frequency ultrasound and measuring reflected waves from interior defects or interfaces. This provides information regarding discontinuities within material and structural integrity[147,148)].

Acoustic emission testing (AE) monitors the onset and propagation of damage in the composite. An acoustic emission monitoring system with sensors and signal processing software is employed to detect and analyze transient acoustic signals generated by internal microcracking or fracture events. Some results based on the method are the AE waveforms that denote the acoustic events and energy released. So, it is essential and can be used in the identification of damage mechanisms, monitoring the health of the structure, and predicting its failure in the field of composite structures[149,150)]. AE testing involves setting sensors on the material surface, which record acoustic signals during deformation or loading, giving information on the initiation and progression of damage[151,152)]. The chemical resistance test is a test for the evaluation of material stability of composite materials against chemical attack and degradation: The purpose is to measure variations of the mechanical, thermal, or surface properties after immersion in a chemical using an apparatus of the chemical resistance test with immersion cells for exposure chambers; examples for the results are property or appearance changes after the chemical attack. Such corrosions lead to material property changes, which are essential in assessing the material compatibility in corrosive environments, chemical processing, and aggressive fluids in engineering applications. Typically, items are subjected to chemical resistance tests by immersing them in a variety of chemicals or exposing them to chemical vapors for a specified period, after which material properties are evaluated for the changes exhibited, such as loss in strength, stiffness, or surface finish[153,154)].

The composite test is done on the electromagnetic shielding effectiveness of composite materials. This paper aims to establish the loss of power of electromagnetic waves transmitted through the material using the shielding effectiveness test setup with the signal generator and receiver. Here are some quoted sample results in shielding effectiveness values at different frequencies. This method is very significant for assessing material performance in electromagnetic field attenuation for electronic device protection and electromagnetic compatibility considerations. Electromagnetic shielding testing: material exposure to electromagnetic waves at different frequencies while measuring both the transmitted and reflected signals, respectively, to provide information about the ability of the material to block and attenuate interference[155)].

Testing for resistance to UV: exposure of composite materials to UV irradiation and circulation in the open air. The mechanical, optical, or surface property changes that occur after UV exposure must be measured with the help of controlled UV radiation irradiation intensity and duration of exposure in a UV weathering chamber. Sample results include changes in material properties or appearance after UV exposure. The above method is highly relevant for evaluating material long-term durability, color stability, and degradation mechanisms for outdoor applications and UV-sensitive environments[156)]. UV resistance testing includes exposure of the material to UV radiation at accelerated levels equal to outdoor exposure and monitoring the resultant changes in the properties of the material or degradation mechanisms[157,158)].

Authors such as Taheri and Hassen emphasize the higher flaw detection capabilities of phased array ultrasonic inspection, which improves safety and dependability[159,160)]. Other tests, such as uncertainty assessment in damage evaluation, acoustic emission monitoring, and microhardness testing, provide significant insights into structural integrity, durability assessment, and material lifespan, which are important in a variety of applications[161)]. Because of their exceptional strength and resilience, composite materials are frequently used in industries where stress tolerance is essential. To evaluate these materials, physical and chemical testing techniques are essential. In carbon fibre composites, tensile strength testing—as investigated by Smith and Allen (2022)—highlights the importance of fibre orientation and matrix composition, while Lee and Park's (2020) nanoindentation experiments shed light on local mechanical properties[162,165)]. Furthermore, Patel and Bhatt's evaluation of fatigue testing techniques in

2023 emphasises the significance of cyclic loading experiments in evaluating the long-term durability of glass fibre composites[173)]. When evaluating the thermal stability of polymer matrix composites, thermal analysis is essential. In order to comprehend heat resistance, Kumar and Gupta (2020) investigated methods like Thermogravimetric Analysis (TGA) and Differential Scanning Calorimetry (DSC)[163,164)].

Wang and Zhang (2021) and Zhang and Li (2023) examined the long-term effects of chemical exposure and environmental stress on composite deterioration and focused on chemical durability testing, particularly under hard environmental circumstances[167,168)]. Silva and Gomes (2020) examined moisture absorption, another element affecting composite performance, with a focus on how it affects composites made of natural fibres[166, 174)].

Internal defects in composites can be found using non-destructive testing (NDT) methods like ultrasonic testing, which doesn't harm the material. Ultrasonic testing has been shown to be effective in identifying voids and delaminations in fiber-reinforced composites by Smith and Williams (2022) and Wilson and Singh (2021)[169,170,175,176)]. Chen and Liu (2019) have proven that spectroscopy-based chemical analysis can yield valuable insights into the fiber-matrix interface, a crucial aspect of composite design optimisation[171,172,177,178)]. When combined, these testing techniques guarantee the durability and dependability of composite materials in a range of applications[179-181)]. Examples of industries using these testing techniques are provided in the updated manuscript. SEM and nanoindentation are used in aerospace to evaluate the mechanical characteristics and failure processes of coatings and composites. AFM is used in the electronics sector to assess semiconductor surface roughness and thin-film uniformity. Nanoindentation is used in the biomedical area to investigate the mechanical properties of biomaterials and implants. SEM is also used in the automobile industry to examine component fracture patterns and surface wear. The applicability of the book to real-world applications is increased by these examples, which highlight the adaptability and importance of these techniques across a range of industries.

## 6. Conclusions

Composite materials, due to their enhanced mechanical, thermal, and chemical properties, are pivotal in various high-performance applications across aerospace, automotive, and construction industries. Characterizing these materials is fundamental to optimizing their design and application, necessitating a comprehensive suite of testing methods to assess their diverse properties.

### 6.1 Comparison of Testing Methods

Mechanical testing, encompassing tensile, compression, flexural, and shear testing, provides insights into the material's strength, stiffness, and durability under various loading conditions. For instance, tensile testing evaluates material performance under tension, while compression testing assesses behavior under compressive forces, each yielding unique stress-strain responses critical for structural application assessments.Thermal testing methods, like thermal conductivity and differential scanning calorimetry (DSC), alongside chemical testing techniques, such as spectroscopy and chemical resistance tests, evaluate composite materials' performance under environmental stresses. These tests are crucial for applications where materials are exposed to extreme temperatures, humidity, or corrosive substances.

Techniques like Scanning Electron Microscopy (SEM) and Atomic Force Microscopy (AFM) offer nanoscale insights into material structure, identifying defects, voids, and fiber orientation. Spectroscopic methods like Fourier Transform Infrared Spectroscopy (FTIR) and Raman Spectroscopy provide molecular-level information on material composition and bonding, essential for optimizing material properties and processing techniques.

### 6.2 Impact of Testing Methods on Material Characterization

Mechanical testing methods directly impact the evaluation of composite materials' structural integrity and mechanical performance, guiding the design of more reliable and robust components.Thermal and chemical testing methods play a pivotal role in determining materials' durability against environmental stressors, influencing material selection for applications requiring long-term stability and resistance to degradation.Advanced spectroscopic and microscopic analyses have revolutionized the understanding of composite materials at the molecular and nano levels, significantly impacting surface modification, bonding quality, and resistance to chemical attacks.

The next section of the paper addresses how material characterisation is strengthened by combining data from several testing techniques. For example, AFM measures surface roughness and mechanical behaviour at the nanoscale, whereas SEM imaging shows the microstructure and flaws. These techniques can be enhanced by nanoindentation, which measures elastic modulus and hardness. By combining these findings, connections between mechanical characteristics and surface morphology can be clarified. For instance, localised changes in hardness from nano indentation can be linked to surface flaws seen in SEM. These correlations shed light on the material's general integrity and failure processes. The updated article places more emphasis on this integrated approach, which guarantees a better comprehension of how different techniques contribute to thorough characterization.

### 6.3 Future Directions in Composite Material Characterization

Future advancements may involve the integration of testing methods across different scales, from nano to macro, providing a holistic view of material behavior and properties. Innovations in NDT techniques will enable more efficient and comprehensive evaluations of composite materials in-situ, facilitating real-time monitoring and assessment of structural integrity and performance.

The integration of advanced testing data into predictive models and simulations will enhance the ability to predict material behavior under untested conditions, streamlining the design process and reducing the need for extensive physical testing.

The characterization of composite materials through various testing methods is essential for harnessing their full potential in high-performance applications. Future advancements in testing methodologies and their integration with computational tools will undoubtedly elevate the field of composite material science, leading to more innovative and sustainable material solutions.

A review of new developments in composite material testing is included in the updated manuscript. Among the noteworthy developments is the application of machine learning techniques to evaluate data analysis for material performance prediction modelling. For the purpose of observing failure mechanisms in real time, in-situ testing methods—like in-situ SEM during mechanical loading—are becoming more and more prevalent. Internal flaws and cavities in composites are increasingly being found using non-destructive testing techniques like X-ray computed tomography. These patterns demonstrate how cutting-edge technology are incorporated into composite testing, allowing for more precise and effective assessment techniques.

A vital tool for assessing the thermal and viscoelastic characteristics of composite materials is dynamic mechanical analysis, or DMA. In order to comprehend stiffness, energy dissipation, and damping behaviour, it offers crucial information on storage modulus, loss modulus, and damping factor. For the purpose of maximising thermal and mechanical performance, DMA detects important transitions such as the glass transition temperature (Tg), softening, and curing behaviour. It helps forecast long-term behaviour under dynamic loads by examining creep, stress relaxation, and frequency-dependent characteristics. DMA ensures consistency and dependability by supporting failure investigation, quality assurance, and composite design optimisation. Additionally, it makes predictive modelling possible, which helps with material selection and application-specific compatibility in sectors like automotive and aerospace.

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