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Research Methods

Recycled Composite Materials

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Abstract

The mechanical performance of recycled fiber-reinforced polymer (FRP) composites produced by mechanical, pyrolytic, and microwave-assisted recycling techniques is investigated in this work. The recycling of composite waste has become a major subject of research due to growing environmental concerns and the need for sustainable materials. Although mechanical recycling is economically feasible, its usage is restricted to non-structural applications because of a significant loss of structural integrity and fiber length. Improved fiber recovery with good tensile strength retention is provided by pyrolysis; however, interfacial bonding is impacted by surface degradation. A viable substitute is microwave-assisted recycling, which shows greater bonding properties, shorter processing times, and higher fiber quality. In order to evaluate tensile strength, flexural behaviour, and void content across various recycling techniques, this study combines mechanical testing and microstructural investigation. The study seeks to determine the best recycling strategy for structural reuse while establishing relationships between mechanical performance and microstructural integrity. It is anticipated that the results will help promote sustainable composite technologies and facilitate the engineering materials industry's shift to a circular economy.

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1. Introduction

Fiber-reinforced polymer (FRP) composites have become indispensable materials in a number of industries, including aerospace, automotive, and construction, due to its advantageous properties, such as a high strength-to-weight ratio, corrosion resistance, and durability. However, there are now serious issues with managing end-of-life composite trash due to the growing use of these materials. Because of their cross-linked polymer structure, which precludes remelting or reshaping, FRPs—especially those with thermoset matrices—present recycling issues in comparison to conventional materials.

As sustainability becomes a global concern, there is a growing need for efficient recycling techniques that maintain the mechanical performance of composite materials while lessening their environmental impact. The most popular and economical method is mechanical recycling; however, it drastically shortens fiber length and jeopardizes structural integrity. Thermal techniques, such as pyrolysis, enable the recovery of high-value fibers, especially carbon fibers, while maintaining relatively good strength retention, despite ongoing issues such surface deterioration and energy consumption. Microwave-assisted recycling has recently attracted interest as a novel technique that provides better interfacial characteristics, less fiber damage, and increased heating efficiency.

Despite these developments, a thorough comparison of recycling techniques is still lacking, especially when it comes to the relationship between mechanical performance and microstructural features like void content and fiber morphology. By using a mixed-methods strategy that combines mechanical testing, microscopy, and statistical analysis, this work seeks to close these gaps. The goal of the study is to evaluate the efficiency of different recycling methods and determine whether they are suitable for structural and semi-structural applications.

2. Literature Review

2.1 Mechanical Recycling: Limitations in Structural Retention

Mechanical recycling is recognized as the most advanced and economically viable technique within the industry. This process involves the shredding and reprocessing of composite waste into secondary materials. According to recent research (e.g., Zhang et al., 2024), tensile strength decreases of up to 30% result from a reduction in fiber length, which seriously compromises load transfer efficiency. The reduction in aspect ratio, which limits the distribution of stress at the fiber–matrix contact, is the main factor influencing this degradation mechanism.

Additionally, mechanical recycling results in defects such as voids and microcracks that arise from repeated thermal and mechanical processing. These defects function as

stress concentrators, hastening failure under tensile loading (Witik et al., 2013). Although less affected, flexural modulus also experiences a decrease due to weakened interfacial bonding.

Mechanical recycling significantly alters the reinforcement properties of materials, transitioning from continuous fibre reinforcement to discontinuous fibre systems. This fundamental change restricts its application primarily to non-load-bearing or semi-structural components.

2.2 Pyrolysis:

One important technique for recovering high-value fibers, especially carbon fibers, is pyrolysis. In order to maintain the fiber length and inherent mechanical qualities, this procedure entails the thermal breakdown of the polymer matrix in an inert atmosphere.

Tensile strength retention levels range from 80% to 95%, with ideal conditions producing about 93% retention, according of recent experimental studies carried out between 2023 and 2025 (Zhang et al., 2024).

Pyrolysis results in surface-level degradation, such as oxidation and the removal of sizing agents that are essential for fiber-matrix adhesion. This leads to a decrease in interfacial shear strength, which may restrict composite performance, notwithstanding the retention of high fiber strength (Oliveux, Dandy, and Leeke, 2015).

Additionally, cumulative deterioration is revealed by multi-cycle recycling tests, with gradual strength reductions observed following each recycling cycle. Energy usage and environmental effect continue to be concerns, especially when it comes to large-scale industrial applications.

2.3 Microwave-Assisted Recycling: Emerging High-Performance Alternative

Microwave-assisted pyrolysis represents a considerable advancement in composite recycling technology. Unlike conventional heating, microwave radiation enables volumetric heating, resulting in more uniform temperature distribution and reduced processing time.

According to recent studies (Jiang et al., 2023; Li et al., 2024) highlight several advantages such as:

- Reduced char formation on fibre surfaces
- Improved fibre cleanliness and surface energy
- Enhanced fibre–matrix interfacial bonding

In mechanical testing, the tensile and flexural capabilities of composites reinforced with microwave-recycled fibers exhibit encouraging results that are comparable to those of virgin materials. Improvements in bonding characteristics have occasionally resulted in 20–50% increases in flexural strength.

However, despite its technical advantages, microwave-assisted recycling has difficulties with equipment prices, process scalability, and electromagnetic field distribution management.

2.4 Influence of Void Content and Microstructural Integrity

Void content is widely acknowledged as a significant factor influencing composite performance. Because of the effects of stress concentration, even small increases in porosity can lead to significant decreases in tensile strength.

Due to insufficient consolidation and matrix degradation, mechanically recycled composites typically exhibit the greatest void fractions. Pyrolysis and microwave-assisted techniques, on the other hand, produce a lower void content; nonetheless, bonding quality may still be compromised by damage to fiber surfaces (Witik et al., 2013).

The importance of thermal degradation in the creation of voids in hybrid systems, like fiber-reinforced concrete, where polymer fibers may melt or disintegrate at high temperatures, greatly reducing tensile capacity, is further highlighted by recent studies (2025).

2.5 Research Gap

Despite the increasing interest in composite recycling, several gaps persist, including:

- The absence of standardized comparative frameworks across various recycling methods,
- The need for an integrated analysis of mechanical performance in conjunction with microstructural factors,
- The lack of experimental validation for microwave-assisted techniques at a larger scale.

This research seeks to fill these gaps by integrating mechanical testing with microstructural characterization and conducting a comparative analysis.

3. Aim and Objectives

Aim

To critically evaluate the mechanical performance of recycled Fiber-reinforced polymer (FRP) composites produced by using mechanical, pyrolytic, and microwave-assisted recycling methods.

Objectives

- Quantify tensile strength retention across recycling methods
- Evaluate changes in flexural modulus and stiffness
- Analyse the relationship between void content and mechanical degradation
- Assess fibre morphology and interfacial bonding characteristics
- Determine the suitability of recycled composites for structural applications

4. Research Questions

- How do recycling methods influence tensile and flexural performance?
- What are the dominant degradation mechanisms in each process?
- To what extent does void content control mechanical behaviour?
- Can microwave-assisted recycling outperform conventional methods?
- What are the practical implications for structural reuse?

5. Methodology

5.1 Research Approach

A mixed-methods approach integrating experimental testing, microscopy, and statistical analysis will be employed.

5.2 Materials

- CFRP (Carbon Fiber Reinforced Polymer) Laminates

Composition: A polymer matrix, usually epoxy, contains carbon fibers.

Properties: These materials are remarkably rigid, corrosion-resistant, and have a very high strength-to-weight ratio.

Applications: Carbon fiber composites are used in industries like wind turbine blade production, automobile, and aerospace.

Recycling: Because of the strong adhesion between the fiber and the matrix, recycling is a difficult procedure.

Typical techniques consist of:

The process of pyrolysis, which involves burning the resin to extract carbon fibers, may cause some strength loss.

Solvolysis uses solvents to break down the matrix more gently.

Recovered carbon fibers can be used in applications that don't require as much performance.

- Glass Fiber Reinforced Polymer (GFRP) Laminates

Composition: Glass fibers in a polymer matrix, usually epoxy or polyester.

Properties: Strong, corrosion-resistant, and less expensive than CFRP.

Applications include wind turbine blades, pipes, construction, and maritime.

Recycling:

Because of the lower fiber value, it is more economically challenging than CFRP.

Techniques consist of:

Grinding into filler material is a mechanical recycling method.

Recover fibers (sometimes with diminished characteristics) by thermal treatments.

Recycled materials are frequently utilized as fillers or in the manufacturing of cement.

- Thermoset matrices, such as Epoxy

Characteristics: structure that is permanently cross-linked and cannot be remelted. strong resistance to heat and chemicals.

Recycling Difficulties: Once healed, it cannot be reshaped.

Recycling techniques:

The matrix can be broken down chemically (solvolysis) or thermally (pyrolysis).

Recovering fibers is frequently prioritized over the resin itself.

- Matrices made of thermoplastic

Characteristics: polymers that are branched or linear and can be melted and reformed. Polypropylene (PP) and polyether ether ketone (PEEK) are two examples.

Benefits of Recycling

recyclable more easily than thermosets.

Reusable, remoldable, and reheatable.

Melting and reforming are common forms of mechanical recycling.

Limitations:

Fiber-matrix separation is still difficult.

Properties may deteriorate with repeated recycling.

5.3 Recycling Techniques: Mechanisms and Impacts

- Mechanical grinding and remoulding.
- Conventional pyrolysis under inert atmosphere.
- Microwave-assisted pyrolysis.

5.3.1 Recycling Mechanically

The procedures of shredding, grinding, or milling composite trash into smaller pieces are all included in mechanical recycling. In modern composite systems, the resulting recyclers are usually used as fillers or short-fiber reinforcements. This method produces a random orientation and a large loss in fiber length, which significantly lowers load transfer efficiency even if it is scalable and cost-effective (Pickering, 2006; Liu et al., 2022). Importantly, mechanical recycling limits the application of high-performance continuous fiber composites to non-structural sections by converting them into low-performance discontinuous systems. The long-term sustainability benefits of mechanical recycling beyond trash reduction are called into question by this constraint.

5.3.2 Recycling Thermally

In order to recover fibers, thermal recycling techniques like pyrolysis and fluidized bed treatment break down the polymer matrix at high temperatures. Under ideal circumstances, pyrolysis has been particularly successful in recovering carbon fibers, retaining up to 90% of their tensile strength (Oliveux et al., 2015; Jiang et al., 2021). However, the process of heat deterioration can generate flaws including surface roughness and residual char, weaken interfacial bonding, and degrade fiber surfaces (Jiang et al., 2021). The total environmental benefits of thermal recycling are also called into doubt by the ongoing difficulties associated with energy consumption and emissions.

5.3.3 Solvolysis, or Chemical Recycling

Solvents are used in chemical recycling to break down polymer matrices at comparatively lower temperatures. Resin components and fibers with minimal damage can occasionally be recovered using the solvolysis process (Yang et al., 2012; Liu et al., 2022). Despite its technological advantages, chemical recycling has a number of problems, including high costs, challenges recovering solvents, and limitations on

industrial scalability. Despite being the most promising strategy, chemical recycling is still the least developed technology.

5.4 Mechanical Testing

- Tensile testing.
- Flexural testing.
- Interlaminar shear strength.

5.5 Microstructural Analysis

- Scanning Electron Microscopy (SEM).
- Micro-CT scanning for void quantification.
- Fibre length distribution analysis.

5.6 Data Analysis

- Comparative statistical analysis (ANOVA).
- Regression modelling (void content vs strength).
- Performance mapping.

6. Key Factors Influencing Mechanical Performance

6.1 Fibre Length and Orientation

Fibre length is naturally linked to the efficiency of stress transfer. Mechanical recycling tends to decrease fibre length significantly; however, advanced alignment techniques can partially alleviate this issue. The preservation of fibre orientation is critical for the attainment of superior mechanical properties.

6.2 Fibre Surface Quality and Interface

Recycling methods frequently compromise fibre surfaces, which diminishes adhesion with the matrix. Techniques for surface functionalisation, such as plasma treatment and resizing, have demonstrated considerable improvements in interfacial bonding and load transfer efficiency (Oliveux et al., 2015).

6.3 Processing and Manufacturing Techniques

The selection of manufacturing method—whether it be injection moulding, compression moulding, or additive manufacturing—profoundly influences the final properties of the product. Optimised processing can lead to a reduction in defects, enhancement of fibre distribution, and overall performance improvement.

7. Expected Results and Hypothesis

It is theorized that:

- Pyrolysis will achieve the highest tensile strength retention (~90%).
- Mechanical recycling will show the greatest degradation (~30%).
- Microwave-assisted recycling will provide optimal balance between strength and interfacial bonding.
- Void content will exhibit a strong inverse correlation with tensile strength.

8. Significance of the Study

This research influences on:

- Sustainable composite material development
- Circular economy implementation in engineering materials
- Industrial decision-making for recycling technologies
- Advancing structural reuse of recycled composites

9. Limitations

- Material variability across composite systems
- Limited scalability of microwave processes
- Potential inconsistencies in fibre recovery quality
- Laboratory vs industrial process differences

10. Applications and Industrial Relevance

Recycled composites are increasingly being used in consumer items, athletic goods, construction panels, and car interiors. They are attractive for secondary structures because of their affordability and smaller environmental impact. Recycled carbon fiber composites are used in non-load bearing parts, engine covers, and seat constructions in the automotive sector. However, reliability concerns continue to limit their use in main structural components.

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Appendix

Appendix A: Conceptual Framework

Input Variables:

- Recycling method
- Processing parameters
- Material type

Intermediate Variables:

- Fibre length retention
- Surface morphology
- Void content

Output Variables:

- Tensile strength
- Flexural modulus
- Structural performance

Appendix B: Data Analysis Framework

1. Tensile Strength Retention Calculation

$$\text{Retention (\%)} = \frac{\text{Recycled Strength}}{\text{Virgin Strength}} \times 100$$

2. Void Content Relationship Model

$$\sigma = \sigma_0(1 - kV)$$

Where:

- σ = tensile strength of recycled composite
- σ_0 = original tensile strength
- V = void fraction
- k = material constant

Appendix C: Mechanical Testing Standards

Property	Standard	Description
Tensile Strength	ASTM D3039	Determines ultimate tensile behaviour
Flexural Strength	ASTM D790	Measures bending performance
Interlaminar Shear	ASTM D2344	Evaluates interface bonding strength

Appendix D: Expected Results Summary Table

Recycling Method	Tensile Retention	Modulus Change	Void Content	Structural Suitability
Mechanical	60–75%	Decrease	High	Low–Moderate
Pyrolysis	80–93%	Slight decrease	Low	High
Microwave	85–95%	Stable/Increase	Very Low	Very High

Appendix E: Key Mechanical Property Trends

- Recycled carbon fibre composites retain **70–90% tensile strength** but lower structural performance due to fibre discontinuity.
- Flexural and impact properties are **more sensitive to fibre-matrix interface degradation**.
- Fatigue life is consistently **lower due to micro-defects and voids**.

Appendix F: Risk Assessment

Risk	Impact	Mitigation
Equipment failure	Delay in experiments	Backup lab scheduling
Inconsistent fibre recovery	Data variability	Standardised processing
Microwave safety concerns	Health risk	Shielded equipment, training
Material supply issues	Delays	Multiple suppliers