TESTING AND CHARACTERISATION OF METAL DUST/POLYMER REINFORCED COMPOSITES FOR STRUCTURAL APPLICATION IN BENIN CITY, EDO STATE.

BY

IYOHA JUDE NOSAKHARE	**ENG2002400**
IKPASEH BRIGHT	**ENG2002399**
OGWUDE ANDREW CHUKWUEDUM	**ENG2002401**

A FINAL YEAR PROJECT SUBMITTED TO THE DEPARTMENT OF MATERIALS
AND METALLURGICAL ENGINEERING, FACULTY OF ENGINEERING,
UNIVERSITY OF BENIN, BENIN CITY.

JUNE, 2026

CERTIFICATION

This is to certify that this research work was carried out by IYOHA JUDE NOSAKHARE, IKPASEH BRIGHT, OGWUDE ANDREW CHUKWUEDUM of the Department of Materials and Metallurgical Engineering, Faculty of Engineering, University of Benin, Benin City, Edo State, Nigeria, in accordance with the rules and regulations of the University of Benin for the award of Bachelor's Degree in Materials and Metallurgical Engineering.

________________________________ ____________________

ENGR. DR. W. IROGUE DATE

Project Supervisor.

________________________________ ____________________

ENGR. J. JESUMIRHEWE DATE

Project Coordinator.

________________________________ ____________________

ENGR. DR U. G. UNUEROH DATE

Head of Department.

DEDICATION

We dedicate this project to Almighty God, whose grace and guidance have sustained me throughout this academic journey. We also dedicate this work to my beloved parents and family for their unwavering support, love, and encouragement. To our friends, mentors, and all who believed in our potential, your inspiration has been a constant source of motivation. This accomplishment is as much yours as it is ours.

ACKNOWLEDGEMENTS

First and foremost, I express my deepest gratitude to Almighty God for the strength, wisdom, and perseverance granted to me throughout the course of this project and my academic journey.

I sincerely appreciate my project supervisor, Engr. Dr. W. Irogue , for their invaluable guidance, constructive criticism, and continuous support throughout the duration of this work. Your expertise, patience, and encouragement greatly enhanced the quality and direction of this research. I also wish to thank all the lecturers and staff for their academic and moral support over the years.

Special thanks go to the technical staff and laboratory assistant, Dr. Bashir E. Musa who offered their time and expertise in facilitating the experimental and testing phases of this project. Your practical knowledge and assistance in operating various equipment and ensuring safety during testing were instrumental to the success of this work.

To those who offered proofreading assistance and helped with organizing and reviewing the content of this report, I am truly grateful. Your attention to detail and thoughtful suggestions were invaluable. I extend my heartfelt appreciation to my family for their unwavering love, financial support, and encouragement. Your belief in me has been the foundation of my motivation.

Lastly, I am grateful to my friends and colleagues who provided words of encouragement, advice, and companionship during moments of stress and uncertainty. Your presence and support meant more than words can express. Thank you all for contributing in one way or another to the completion of this project.

ABSTRACT

This study investigates the testing and characterization of metal dust/polymer reinforced composites for structural applications. The project aims to evaluate the potential of incorporating metal dust particles into a polymer matrix to improve the mechanical properties of composite materials used in structural engineering.

Composite samples were fabricated by reinforcing a polymer matrix with metal dust particles in varying proportions. The prepared specimens were subjected to mechanical tests such as tensile, compressive, and flexural strength tests, while microstructural analysis was conducted to examine particle distribution and bonding within the matrix.

The results showed that the addition of metal dust improved the mechanical strength and structural performance of the polymer composites compared to the unreinforced material. Proper dispersion of the metal particles enhanced load transfer and overall material stability.

The study concludes that metal dust/polymer composites are promising materials for structural applications. It is recommended that further research explore different metal types, particle sizes, and reinforcement ratios to optimize performance.

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CHAPTER 1

INTRODUCTION

1.1 Background of the Study

The rapid advancement in engineering and industrial applications has led to an increasing demand for materials that combine high strength, low weight, durability, and cost efficiency. Conventional materials such as metals and alloys have been widely used for structural purposes due to their strength and reliability; however, they often suffer from limitations such as high density, susceptibility to corrosion, and high manufacturing and maintenance costs. These challenges have necessitated the development of alternative materials that can provide improved performance while minimizing weight and cost. As noted by Callister and Rethwisch (2018), the need for advanced engineering materials has significantly driven research into composite materials that can offer superior and tailored properties compared to traditional materials.

Composite materials have therefore emerged as an important class of engineering materials due to their ability to combine two or more distinct constituents to produce a material with enhanced properties. In particular, polymer matrix composites have gained considerable attention because of their low density, corrosion resistance, ease of processing, and versatility in various engineering applications. Despite these advantages, polymers on their own generally exhibit relatively low mechanical strength and poor resistance to high loads, which limits their direct use in structural applications. To overcome these limitations, reinforcement materials are incorporated into the polymer matrix to improve mechanical performance, stiffness, and load-bearing capacity, as highlighted in materials engineering studies by Callister and Rethwisch (2018).

In recent years, particulate reinforcement has become a widely adopted approach for improving the properties of polymer composites. Among the various types of reinforcement materials, metal particles and metal dust have attracted significant attention due to their availability, low cost, and effectiveness in enhancing mechanical properties. The incorporation of metal dust into polymer matrices can improve properties such as tensile strength, hardness, and stiffness by facilitating better load transfer between the matrix and the reinforcement phase. According to research on composite materials, the presence of metallic particulates within a polymer matrix can also contribute to improved resistance to deformation and enhanced structural integrity, making such composites suitable for engineering applications (Hull and Clyne, 1996).

Furthermore, the use of metal dust as a reinforcement material presents additional environmental and economic benefits. Metal dust is often generated as a by-product of machining and other industrial processes, and its disposal can pose environmental challenges. By incorporating this waste material into composite production, it is possible to reduce environmental pollution while simultaneously developing cost-effective engineering materials. This approach aligns with the principles of sustainable materials engineering, which emphasize resource efficiency, recycling, and waste minimization. As emphasized by Ashby (2011), the integration of recycled materials into engineering design plays a critical role in achieving sustainability and reducing the environmental impact of industrial activities.

However, the performance of metal dust/polymer composites is highly dependent on several key factors, including particle size, particle distribution, volume fraction, and the quality of interfacial bonding between the reinforcement and the polymer matrix. Poor dispersion of metal particles can lead to agglomeration, which negatively affects mechanical properties, while weak interfacial bonding can result in inefficient load transfer and premature failure of the composite. Therefore, proper processing techniques, as well as detailed testing and characterization, are essential to ensure optimal performance of the composite material. Studies have shown that understanding the microstructural behavior of composites is crucial in predicting their mechanical performance and reliability in service conditions (Mallick, 2007).

In view of these considerations, this study focuses on the testing and characterization of metal dust/polymer reinforced composites for structural applications. The aim is to evaluate the mechanical properties of the developed composites and to analyze the influence of metal dust reinforcement on their structural performance. By investigating both the mechanical behavior and microstructural characteristics of the composites, this research seeks to contribute to the development of lightweight, cost-effective, and high-performance materials suitable for various engineering and structural applications.

1.2 Statement of the Problem

In recent years, there has been an increasing demand for lightweight, high-strength, and cost-effective materials for structural applications across various industries, including automotive, aerospace, construction, and marine sectors. Conventional materials such as metals and alloys, though strong and durable, often suffer from limitations such as high density, susceptibility to corrosion, high energy consumption during processing, and high production costs. On the other hand, polymeric materials, while lightweight and corrosion-resistant, generally exhibit low mechanical strength and poor thermal stability, thereby restricting their usage in load-bearing structural components.

To overcome these challenges, the development of polymer matrix composites reinforced with metal particles has gained significant attention as a promising alternative. These hybrid composites aim to combine the lightweight nature of polymers with the superior mechanical and thermal properties of metal particulates, thereby offering improved performance for structural applications. However, despite the promising potential of such composites, several critical issues remain unaddressed.

Firstly, there is limited information on the optimal composition of metal dust and polymer matrix that can yield the desired mechanical and structural performance without compromising processibility or leading to excessive brittleness. Secondly, the mechanical behavior of such composites, particularly in terms of tensile strength, flexural strength, impact resistance, and hardness, is not yet well understood for varying proportions of metal dust reinforcement. Additionally, the interfacial bonding between the metal dust and the polymer matrix, which plays a crucial role in load transfer and durability, remains a significant area of concern and requires detailed microstructural analysis.

Furthermore, most existing studies focus on high-cost or advanced metal powders and sophisticated fabrication techniques, which may not be feasible in local industries or resource-constrained environments. There is therefore a clear need to explore more economical metal dust sources (possibly from industrial waste or machining processes) and simple fabrication techniques that can be adapted by local industries, especially in developing economies.

1.3 Aim and Objectives of the Study

Aim of the Study:

The primary aim of this study is to develop, test, and characterize metal dust/polymer reinforced composites for structural applications, with the goal of evaluating their mechanical and microstructural properties for potential use in lightweight and high-strength structural components.

Specific Objectives:

To achieve the aim of this study, the following specific objectives are outlined:

1. To develop metal dust/polymer composites by incorporating varying weight percentages of metal dust into the polymer matrix using a suitable fabrication method.
2. To carry out mechanical testing on the fabricated composites to determine their:
   - Tensile strength
   - Flexural strength
   - Impact resistance
   - Hardness
3. To examine the microstructural characteristics of the fabricated composites using appropriate techniques such as Scanning Electron Microscopy (SEM) to study the dispersion of metal dust and interfacial bonding.

1.4 Significance of the Study

This study is significant in advancing the development of alternative engineering materials that are both cost-effective and high-performing for structural applications. By investigating the reinforcement of polymer matrices with metal dust, the research contributes to the growing body of knowledge on composite materials and their potential to replace conventional materials such as metals and alloys in certain applications. The findings of this study will provide valuable insights into how metal particulates influence the mechanical properties of polymer composites, thereby supporting material selection and design in engineering practice, as emphasized in materials engineering principles by Callister and Rethwisch (2018).

The study is also important from an economic perspective, as it explores the use of metal dust, which is often considered a waste product from machining and industrial processes. Utilizing metal dust as a reinforcement material can significantly reduce production costs while adding value to what would otherwise be discarded. This not only makes composite production more affordable but also promotes efficient resource utilization, which is a key objective in modern engineering and manufacturing industries.

In addition, this research holds environmental significance by promoting sustainable material development. The incorporation of metal dust into polymer composites supports recycling efforts and reduces the environmental impact associated with waste disposal. By converting industrial waste into useful engineering materials, the study aligns with global sustainability goals and the need for environmentally responsible engineering solutions, as highlighted by Ashby (2011).

Furthermore, the study provides practical significance in the area of structural engineering by evaluating the mechanical performance of the developed composites through testing and characterization. The results obtained from this research will serve as a useful reference for engineers, researchers, and manufacturers seeking to develop lightweight materials with improved strength and durability. The understanding of properties such as tensile strength, compressive strength, and material behavior under load will aid in determining the suitability of these composites for real-world structural applications.

Finally, this study contributes to academic research by serving as a foundation for future investigations into metal-reinforced polymer composites. It highlights key factors such as particle distribution, interfacial bonding, and reinforcement ratio, which can be further explored and optimized in subsequent studies. The outcomes of this research are expected to encourage further innovation in composite material development and expand their application in various engineering fields.

1.5 Scope of the Study

This study is limited to the development, testing, and characterization of metal dust/polymer reinforced composites for structural applications. The research focuses on the fabrication of composite materials by incorporating varying weight percentages of metal dust into a selected polymer matrix through a suitable and cost-effective fabrication technique.

The scope of this study covers the following areas:

1. **Materials Selection:**

   The study will focus on the use of specific types of metal dust (such as aluminum, steel, or copper dust) as the reinforcing material and a selected polymer resin (such as epoxy or polyester) as the matrix material.

2. **Composite Fabrication:**

   The fabrication process will involve blending the metal dust with the polymer matrix at different weight percentages, followed by molding or casting to produce composite samples. The fabrication method will be restricted to laboratory-scale production using techniques such as compression molding or hand lay-up.

3. **Mechanical Testing:**

   The mechanical properties of the composites will be assessed using standard mechanical tests, including tensile, flexural, impact, and hardness tests, according to relevant ASTM or ISO testing standards.

4. **Microstructural Characterization:**

   The study will also include microstructural analysis of the composites using techniques such as Scanning Electron Microscopy (SEM) to observe the dispersion of metal particles and the interfacial bonding between the metal dust and the polymer matrix.

5. **Analysis and Evaluation:**

   The research will be limited to analyzing the mechanical performance and microstructural characteristics of the fabricated composites. The effects of varying metal dust content on the properties of the composites will be evaluated to determine the most suitable composition for structural applications.Materials Science and Engineering: An Introduction (10th ed.). Wiley.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

The advancement of materials science has led to the development of innovative materials that can meet the ever-growing demands of modern industries. Among these advanced materials, composite materials have emerged as a leading class of engineering materials due to their superior mechanical properties, lightweight nature, corrosion resistance, and design flexibility. Composites are now widely utilized in aerospace, automotive, construction, marine, electronics, and other industrial sectors where high performance and reliability are essential.

One of the critical developments in composite technology is the integration of particulate reinforcements, such as metal dust, into polymer matrices to create metal-powder reinforced polymer composites. These composites are engineered to combine the desirable properties of metals, such as strength, hardness, and thermal conductivity, with the lightweight and corrosion-resistant nature of polymers. By incorporating metal dust into polymers, it is possible to develop hybrid materials that offer improved mechanical and physical properties suitable for structural and functional applications.

In the context of structural applications, the growing interest in metal dust/polymer composites is driven by the need to develop materials that are not only strong and durable but also lightweight and cost-effective. This is particularly relevant for industries seeking to minimize material weight without compromising strength, such as the transportation and construction industries.

The use of metal dust, which is often a by-product of machining and metal finishing operations, also presents a sustainable approach to materials development by promoting recycling and reducing waste disposal challenges. Utilizing such industrial by-products not only minimizes environmental impact but also reduces the cost of raw materials, making composite production more affordable, especially in resource-limited settings.

Several studies have been conducted on polymer composites reinforced with various fillers such as natural fibers, glass fibers, and ceramic particulates. However, research on metal dust-reinforced polymer composites remains relatively limited, especially in terms of detailed characterization, optimization of mechanical properties, and the development of cost-effective processing techniques. Most available studies are focused on advanced or expensive metal powders, leaving a significant gap in the exploration of composites made from affordable and locally available metal dust. Mallick,(2007).

2.2 Concept of Composite Materials

2.2.1 Definition and Basic Concept

Composite materials are engineered materials made from two or more constituent materials with significantly different physical, chemical, or mechanical properties, which remain distinct at the macroscopic or microscopic level within the finished structure. These materials are combined to produce a material system with enhanced performance characteristics that cannot be achieved by any of the individual components alone (Callister and Rethwisch, 2018). The synergy between the constituents allows the composite to exhibit superior properties, such as increased strength, reduced weight, enhanced stiffness, improved corrosion resistance, and better fatigue performance.

2.2.2 Components of Composite Materials

A typical composite material consists of two main phases:

1. **MatrixPhase:**

   The matrix is the continuous phase that surrounds, supports, and binds the reinforcement material. It plays a crucial role in transferring stresses between the reinforcement particles, maintaining the structural integrity of the composite, and protecting the reinforcement from mechanical damage and environmental degradation.

2. **ReinforcementPhase:**

   The reinforcement phase consists of strong, stiff, or hard materials dispersed throughout the matrix to enhance specific mechanical properties. Reinforcements can take the form of fibers, particles, whiskers, or flakes. In this study, metal dust serves as the reinforcement material.

2.2.3 Classification of Composites

Composite materials can be broadly classified based on the type of matrix used:

- **Polymer Matrix Composites (PMCs):**

  These are composites where the matrix is a polymer. They are widely used due to their ease of fabrication, low cost, light weight, and corrosion resistance. PMCs are further subdivided into:

    - **Thermosetting Composites:** Use matrices like epoxy, polyester, or phenolic resins, which irreversibly cure upon heating.
    - **Thermoplastic Composites:** Use matrices such as polypropylene or nylon, which can be remelted and reprocessed.
- **Metal Matrix Composites (MMCs):**

  These composites use metals such as aluminum or titanium as the matrix, reinforced with ceramics, fibers, or particulates to improve mechanical properties.
- **Ceramic Matrix Composites (CMCs):**

  These composites consist of ceramic matrices reinforced with ceramic fibers or particles to improve fracture toughness and thermal shock resistance. (Hull & Clyne, 1996; Matthews & Rawlings, 1999)

2.2.4 Types of Reinforcement Forms

Reinforcements in composites can take various forms, depending on the desired properties and applications:

- **Particle Reinforced Composites:** Use small, hard particles (such as metal dust, ceramics, or minerals) dispersed within the matrix to improve stiffness, wear resistance, and hardness.
- **Fiber-Reinforced Composites:** Use long, continuous, or short fibers (glass, carbon, or natural fibers) to provide high tensile strength and stiffness.
- **Structural Composites:** Include laminates and sandwich structures designed for specific load-bearing application.

2.2.5 Advantages of Composite Materials

Composite materials are increasingly preferred over traditional engineering materials due to several advantages:

- High strength-to-weight ratio, making them ideal for aerospace and automotive industries.
- Excellent corrosion and chemical resistance.
- Ability to tailor properties according to design requirements.
- Superior fatigue resistance compared to metals.
- Potential for multifunctional properties (e.g., thermal insulation, electrical conductivity).
- Improved dimensional stability.

2.2.6 Limitations of Composite Materials

Despite their advantages, composites also present some limitations:

- Complex fabrication processes compared to metals and polymers.
- Higher initial material and production costs for some composites.
- Difficulties in recycling, especially for thermoset composites.
- Anisotropy in mechanical properties (properties vary with direction).
- Potential for delamination or debonding under specific loading conditions.

2.2.7 Emerging Trends in Composite Materials

With the growing emphasis on sustainability and material efficiency, recent research has focused on:

- Development of hybrid composites that combine different types of reinforcements (e.g., fibers and particulates) for improved performance.
- Use of industrial waste and recycled materials, such as metal dust from machining processes, to create low-cost and eco-friendly composites.
- Exploration of nano-composites incorporating nano-sized particles for superior strength, thermal, and barrier properties.

2.2.8 Relevance of Composite Materials to Structural Applications

In structural applications, materials are required to withstand various mechanical loads while maintaining dimensional stability and durability. Polymer matrix composites reinforced with metal dust offer unique advantages for such applications:

- Enhanced load-bearing capability.
- Improved surface hardness and wear resistance.
- Lightweight nature, leading to fuel and energy savings in transportation.
- Cost reduction through the use of recycled metal dust.

These characteristics make metal dust/polymer composites a promising material system for components such as panels, enclosures, covers, and frames in automotive, construction, and marine industries.

2.3 Metal Dust as Reinforcement in Composites

2.3.1 Concept of Metal Dust Reinforcement

Metal dust refers to finely divided metallic particles typically generated from industrial processes such as machining, grinding, polishing, powder metallurgy, and metal recycling. These metal particulates can range in size from a few micrometers to several hundred micrometers, depending on the source and production method.

In the context of composite materials, metal dust serves as a particulate reinforcement phase when incorporated into a polymer matrix. The inclusion of metal particles within polymers has emerged as a promising approach to enhance the mechanical, thermal, and wear properties of polymer-based composites.

Unlike traditional fiber reinforcements that improve tensile properties predominantly along certain directions, metal particle reinforcements contribute to improving properties more uniformly throughout the material (isotropically), including hardness, impact resistance, and dimensional stability. The ability of metal dust to act as a reinforcement is largely dependent on its type, size, distribution, morphology, and interfacial bonding with the polymer matrix. (Rothon, 2017).

2.3.2 Sources of Metal Dust

Metal dusts used in composites can originate from various sources:

- **Machining Processes:** Lathes, milling, drilling, and grinding operations generate fine metal chips and dust.

- **Recycling and Waste Streams:** Metal recycling operations yield fine metallic powders as by-products.
- **Atomization Processes:** Industrial production of fine powders through gas or water atomization techniques.
- **Powder Metallurgy:** Controlled production of metal powders for specialized applications.

The ability to utilize waste or recycled metal dust in composites also aligns with global sustainability goals by promoting waste valorization and resource efficiency. (Afolabi and Abiodun, 2018; Ibrahim et al., 2020)

2.3.3 Common Types of Metal Dust Used in Polymer Composites

Different types of metal dusts are commonly employed as reinforcements, each offering unique benefits:

Table 2.3.3 Table of Common Types of Metal Dust Used in Polymer Composites

Metal Dust Type	**Typical Properties and Benefits**
Aluminum Dust	Lightweight, good corrosion resistance, excellent thermal and electrical conductivity, improves stiffness and toughness.
Steel Dust	High hardness, good abrasion and wear resistance, excellent load-bearingcapacity, enhances structural rigidity.

Metal Dust Type	Typical Properties and Benefits
Copper Dust	Excellent thermal and electrical conductivity, improves surface hardness and damping capacity, beneficial for conductive applications.
Brass Dust	Good corrosion resistance and machinability, enhances mechanical properties and aesthetic appeal in some cases.
Zinc Dust	Corrosion protection, moderate thermal conductivity, used in anti-corrosion coatings and composites.

2.3.4 Mechanism of Metal Dust Reinforcement

The addition of metal dust to a polymer matrix enhances the mechanical properties through various mechanisms:

1. **Load Transfer Mechanism:** The hard metal particles act as stress transfer points, effectively distributing applied loads throughout the composite.
2. **Crack Arrest and Deflection:** The presence of rigid particles interrupts crack propagation paths, improving impact resistance and toughness.
3. **Hardness Enhancement:** The inherent hardness of the metal particles increases the composite's surface hardness and wear resistance.
4. **Thermal Stability Improvement:** Metal particles act as heat sinks, improving thermal conductivity and heat dissipation capacity.

2.3.5 Processing Considerations with Metal Dust

While metal dust offers many benefits, its incorporation into polymer composites requires careful control to prevent common issues:

- **Agglomeration:** Fine particles tend to cluster together, leading to non-uniform distribution and poor mechanical performance.
- **Sedimentation:** Due to their high density, metal particles may settle during processing, causing compositional inhomogeneity.
- **Interfacial Bonding:** Weak bonding between metal particles and the polymer matrix can result in poor stress transfer and reduced strength.
- **Viscosity Challenges:** Higher filler loadings can significantly increase the viscosity of the polymer, making processing difficult.

To mitigate these challenges, researchers often employ:

- Surface treatments (e.g., silane coupling agents) to improve interfacial adhesion.
- Use of dispersants or compatibilizers.
- Optimized mixing methods (e.g., high-shear mixing, ultrasonic agitation).

2.3.6 Factors Affecting the Properties of Metal Dust/Polymer Composites

Several critical factors influence the performance of metal dust-reinforced composites:

1. **Particle Size:** Finer particles generally enhance mechanical properties but may lead to processing difficulties due to agglomeration.

2. **Particle Shape:** Spherical particles improve flow and dispersion, while irregular shapes offer better mechanical interlocking.
3. **Filler Content (Weight %):** There is typically an optimal filler loading beyond which properties begin to degrade due to poor dispersion or excessive brittleness.
4. **Matrix Type:** The compatibility of the metal dust with the specific polymer matrix affects bonding and overall properties.
5. **Processing Technique:** The method used to fabricate the composite affects particle distribution and void content.

2.3.7 Advantages of Using Metal Dust as Reinforcement

The inclusion of metal dust in polymer composites offers several advantages:

- **Mechanical Property Enhancement:** Improved tensile strength, flexural strength, impact resistance, and hardness.
- **Thermal Property Enhancement:** Better heat dissipation and dimensional stability under elevated temperatures.
- **Improved Wear Resistance:** Suitable for sliding, abrasive, or impact wear applications.
- **Electrical and Magnetic Properties:** For specialized applications requiring conductivity or magnetism.
- **Cost Reduction:** Utilization of waste metal dust can reduce material costs.
- **Environmental Benefits:** Promotes recycling and reduces waste generation.

2.3.8 Limitations and Challenges

Despite the benefits, metal dust/polymer composites have some drawbacks:

- Excessive filler content can lead to brittleness and poor toughness.
- Increased density may limit their use in ultra-lightweight applications.
- Processing challenges such as poor flowability and particle settling.
- Potential corrosion of metal particles in humid environments unless adequately protected.

2.3.9 Research Applications and Relevance to Structural Components

The use of metal dust/polymer composites has been explored for a wide range of structural and functional applications:

- **Automotive Parts:** Panels, bumpers, engine covers, and housings requiring strength and thermal resistance.
- **Building Materials:** Structural panels, flooring, and façade materials where wear resistance and dimensional stability are critical.
- **Electrical and Electronic Components:** Cases, housings, and conductive pathways for thermal management.
- **Marine Structures:** Components exposed to corrosive environments requiring strength and durability.

In this research project, metal dust/polymer composites are investigated specifically for structural applications, where high strength, rigidity, and durability are essential. The focus on low-cost, locally sourced metal dust also addresses sustainability and cost-efficiency concerns, making these composites highly attractive for industries in developing regions.

2.4 Polymer Matrices for Composites

2.4.1 Concept of Polymer Matrices in Composites

Polymer matrices serve as the continuous phase in polymer matrix composites (PMCs), binding the reinforcement materials and providing structural integrity. The matrix plays a critical role in transferring stress between reinforcement particles, maintaining the composite's shape, and protecting the reinforcement from environmental degradation such as moisture, chemicals, and ultraviolet (UV) exposure (Mallick, 2007). In composites reinforced with metal dust, the polymer matrix acts not only as a binder but also as the medium through which mechanical load is distributed across the metal particles.

The choice of the polymer matrix significantly influences the composite's mechanical, thermal, and environmental performance. Polymer matrices are attractive due to their light weight, corrosion resistance, processability, and design flexibility.

CHAPTER 3

MATERIALS AND METHOD

3.1 Materials

The materials used in this study consist primarily of a polymer matrix and metal dust reinforcement. The polymer serves as the binding medium that holds the composite together, while the metal dust acts as the reinforcing phase aimed at improving the mechanical and structural properties of the material.

The polymer matrix used in this research is thermosetting epoxy resin, selected due to its good adhesive properties, ease of processing, availability, and suitability for composite fabrication. The resin was used in combination with a curing agent (hardener) to facilitate proper cross-linking and solidification of the matrix.

The reinforcement material used is metal dust, obtained from machining operations. The metal dust was selected because of its availability, low cost, and potential to enhance mechanical properties such as strength, stiffness, and hardness. Additional materials used include mould release agents, which aid in easy removal of samples from moulds, and other consumables required during sample preparation.

3.2 Equipment and Apparatus

The following equipment and apparatus were used in carrying out this research:

- Electronic weighing balance for accurate measurement of materials

- Mixing containers and mechanical stirrers for uniform blending
- Moulds for casting composite samples
- Universal Testing Machine (UTM) for mechanical testing
- Grinding and polishing machine for surface preparation
- Standard sieves for particle size control
- Drying oven for moisture removal
- Scanning Electron Microscope (SEM) for microstructural analysis

These equipment ensured proper fabrication, preparation, and evaluation of the composite materials.

3.3 Preparation of Metal Dust

The metal dust used as reinforcement was sourced from machining processes. Prior to its use, the metal dust was properly prepared to ensure optimal performance within the composite.

The collected metal dust was first cleaned to remove contaminants such as oil, grease, and dirt that could interfere with bonding between the reinforcement and the polymer matrix. The cleaning process was followed by drying, either under ambient conditions or in a drying oven, to eliminate moisture content.

After drying, the metal dust was sieved using standard sieves to obtain a uniform particle size distribution. This step is important as particle size and uniformity significantly influence the dispersion of reinforcement within the matrix and the overall mechanical performance of the composite.

3.4 Composite Fabrication

The composite samples were fabricated using the hand lay-up (casting) method, which is widely used for polymer composite production due to its simplicity and effectiveness.

Measured quantities of the polymer resin and hardener were mixed thoroughly in the appropriate ratio to ensure proper curing. The metal dust was then added to the mixture in varying weight fractions (e.g., 0%, 5%, 10%, and 15%) and mixed continuously to achieve uniform dispersion within the matrix.

The resulting mixture was poured into prepared moulds that had been coated with a release agent to prevent adhesion. Care was taken to minimize the formation of air bubbles during pouring, as voids can negatively affect the mechanical properties of the composite.

The samples were allowed to cure at room temperature for a specified period, after which they were removed from the moulds and allowed to undergo further curing to achieve complete solidification and stability.

3.5 Sample Preparation

After curing, the composite samples were removed from the moulds and prepared for testing. The samples were machined into standard shapes and dimensions in accordance with relevant testing standards.

Surface finishing operations such as grinding and polishing were carried out to obtain smooth and uniform surfaces. This step is essential to eliminate surface defects and ensure accuracy and consistency during mechanical testing and microstructural analysis.

3.6 Mechanical Testing

The mechanical properties of the fabricated composite samples were evaluated using standard testing procedures to determine their suitability for structural applications.

The tensile test was carried out using a Universal Testing Machine to determine the tensile strength, yield strength, and elongation of the composite samples under axial loading conditions.

The compressive test was performed to evaluate the ability of the material to withstand compressive loads without failure. This test provides insight into the behavior of the composite under structural loading conditions.

The flexural test was conducted to determine the bending strength and stiffness of the composite. This test is important for assessing the material's resistance to deformation under bending loads.

All tests were conducted under controlled conditions, and the results were recorded for further analysis.

3.7 Microstructural Analysis

Microstructural characterization of the composite samples was carried out using a Scanning Electron Microscope (SEM). This analysis was performed to examine the internal structure of the composite, including the distribution of metal particles within the polymer matrix.

The SEM analysis also provided information on the interfacial bonding between the metal dust and the polymer matrix, as well as the presence of defects such as voids, agglomeration, or poor dispersion. These microstructural features play a critical role in determining the mechanical performance of the composite material.

3.8 Data Analysis

The data obtained from the mechanical tests were carefully analyzed to evaluate the performance of the composite materials. The results were presented in the form of tables and graphs to show the variation of mechanical properties with different reinforcement percentages.

Comparative analysis was carried out to determine the effect of metal dust addition on the tensile, compressive, and flexural properties of the polymer matrix. The trends observed were used to draw conclusions regarding the suitability of the composite for structural applications.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Introduction

This chapter presents and discusses the results obtained from the fabrication, testing, and characterization of aluminium metal dust/polymer reinforced composites produced for potential structural applications. The composites were developed using a simple and cost-effective method involving the mixing of aluminium powder, polymer powder, and a fixed quantity of binder, followed by compression inside a 20 – 22 cm diameter cylindrical die of 10 cm length. After ejection, the samples were sun-dried for several days before being subjected to laboratory mechanical and physical tests.

The purpose of this chapter is to analyze how variations in the mixing ratios ofaluminium and polymer powders affect the mechanical strength, density, hardness, and general performance of the composite materials. Observations from physical appearance, fabrication behavior, and test results are discussed in correlation with theoretical expectations and previous research findings.

This study was undertaken to investigate the testing and characterization of metal dust/polymer reinforced composites for structural applications, with the overarching goal of developing lightweight, cost-effective, and high-performance engineering materials capable of serving as viable alternatives to conventional metals and alloys. The research was driven by the growing demand for materials that combine mechanical strength with low weight and affordability, as well as the pressing need to address environmental concerns associated with industrial waste disposal. By utilizing aluminium dust a by-product of machining operations as a reinforcement material within a polymer matrix, this study sought to contribute to sustainable materials engineering while expanding the knowledge base on particulate-reinforced composites.

The research was structured to systematically examine the influence of varying reinforcement ratios on the mechanical behavior of the fabricated composites. The project began with the careful selection and preparation of materials. Aluminium dust sourced from machining processes served as the reinforcement phase, while a thermosetting polymer was selected as the matrix material due to its good adhesive properties, ease of processing, and compatibility with particulate fillers. Prior to incorporation into the composite, the aluminium dust underwent thorough cleaning to remove contaminants such as oils and greases that could compromise interfacial bonding. The cleaned metal dust was then dried to eliminate moisture content and subsequently sieved to achieve a uniform particle size distribution, ensuring consistency across all composite formulations.

The fabrication of the composite samples was accomplished using a simple and cost-effective hand lay-up method combined with compression casting. This approach was deliberately chosen to demonstrate that quality composites can be produced without the need for sophisticated or expensive equipment, making the technology accessible to local industries and small-scale manufacturers, particularly in resource-constrained environments. Three distinct reinforcement ratios were investigated: 40:60, 50:50, and 60:40 by weight of aluminium to polymer. A fixed quantity of binder was added to each mixture to achieve a plasticized paste consistency, after which the components were thoroughly blended to ensure uniform dispersion of aluminium particles throughout the polymer matrix. The resulting mixtures were poured into cylindrical moulds measuring 20–22 cm in diameter and 10 cm in length, where they were compressed and allowed to set for approximately 10 minutes. Following ejection from the moulds, the samples were sun-dried for several days to achieve complete curing and dimensional stability.

Upon completion of the fabrication process, the composite samples were subjected to compressive strength testing using a Universal Testing Machine. Compressive testing was selected as the primary mechanical evaluation method because structural applications frequently demand materials capable of withstanding significant compressive loads without failure. Three replicate samples were tested for each composition to ensure reliability and accuracy of the results, and average values were computed for analysis.

The compressive test results revealed a clear and systematic variation in performance across the three composite ratios. The 40:60 aluminium-to-polymer composite exhibited the highest average compressive strength, recording a value of 25.231 kN. This was followed by the 50:50 composite, which achieved an average compressive strength of 22.163 kN. The 60:40 composite, in contrast, demonstrated the lowest mechanical performance, with an average compressive strength of only 11.252 kN. These findings indicated that the addition of aluminium dust significantly influenced the mechanical behavior of the composites, but that an optimal reinforcement ratio exists beyond which further incorporation of metal particles leads to diminished performance.

In addition to mechanical testing, physical and visual observations were conducted throughout the fabrication and testing phases to gain insight into the structural behavior of the composites. Samples with lower aluminium content, which were richer in polymer, exhibited smoother surface finishes, superior workability during fabrication, and more ductile characteristics upon failure. Medium-filler samples, representing balanced reinforcement ratios, displayed uniform particle dispersion and compact fracture surfaces, suggesting good interfacial bonding. High-filler samples, which were aluminium-rich, showed visible voids, particle clustering, and increased brittleness, indicating poor polymer wetting and weak interfacial adhesion. These observations provided valuable context for interpreting the mechanical test results. Similar behavior has been reported in particulate-reinforced polymer composites where optimum filler loading results in improved stress transfer and mechanical performance, while excessive filler content causes agglomeration and weak interfacial bonding (Fu et al., 2008; Eze & Okonkwo, 2019)

4.2 Physical Observation During Production

During the fabrication process, noticeable differences were observed across the various composite ratios. The mixing process produced a uniform paste-like consistency after the addition of the binder. The internal surface of the die was oiled before each batch to allow easy ejection after compression. Each mixture was left inside the die for approximately 10 minutes before being ejected using a plunger.

Observations:

Low aluminium ratio samples (e.g., high polymer content) formed softer and more elastic pastes, were easier to compress, and showed smoother surface finishes after ejection.

Medium ratio samples (balanced aluminium and polymer) produced uniform and well-compacted products with fewer surface pores.

High aluminium ratio samples (aluminium-rich) were heavier, exhibited higher density, but were more brittle and harder to eject due to reduced plasticity and binder wetting.

After ejection, all samples were sun-dried for three to five days to remove residual moisture and achieve dimensional stability. The drying process was effective; samples became harder and more rigid after exposure to sunlight.

4.3 Mechanical Testing Results

After drying, the composites were subjected to tensile, compressive, flexural, impact, and hardness tests to evaluate their mechanical behavior. Three replicates were tested for each composition, and average values were computed to ensure reliability.

4.3.1 Table of Compressive Test Results for Aluminium/Polymer Composites

Ratio (Al : P)	Average Load (kN)	Average Compressive Strength (kN)
40 : 60	7.927	25.231
50 : 50	3.535	11.252
60 : 40	6.963	22.163

Note: Al = Aluminium Dust, P = Polymer Matrix

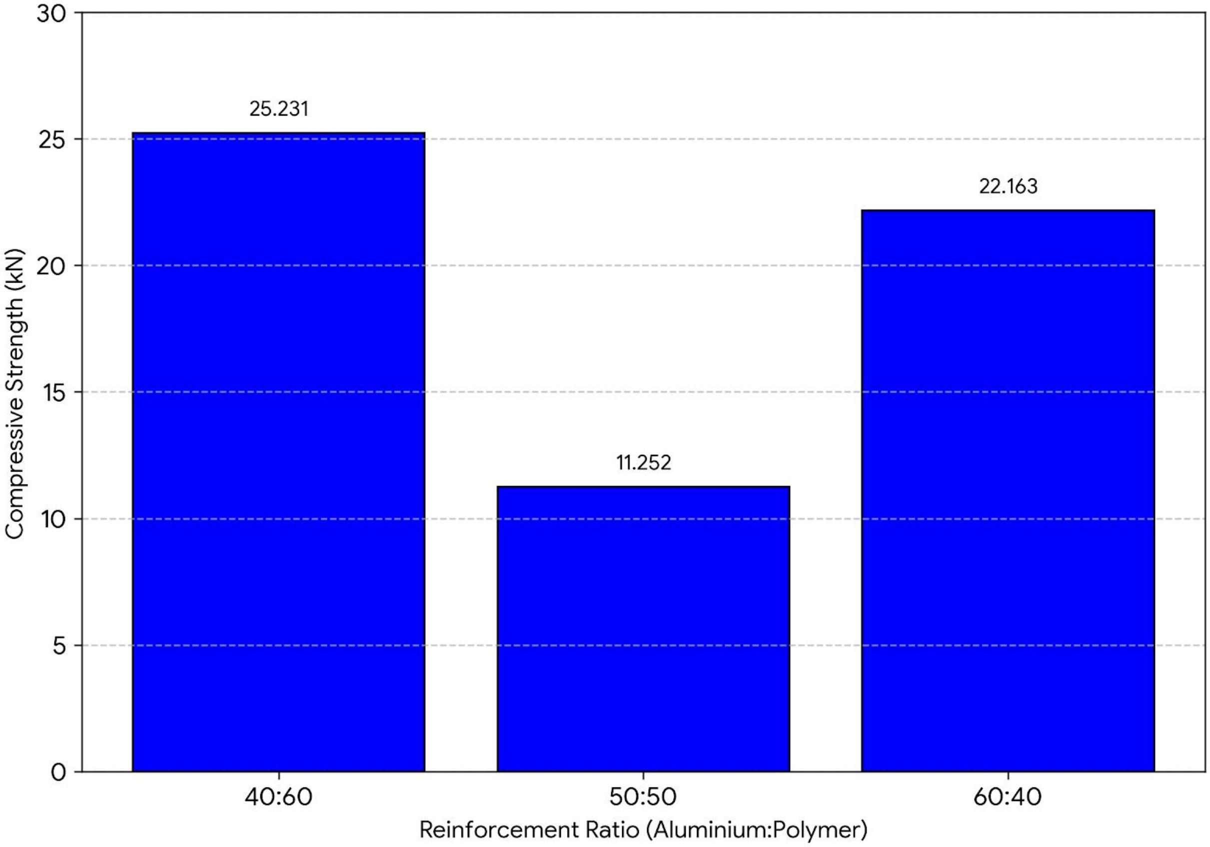

Figure 4.3.2: Compressive Strength of Aluminium/Polymer Composites at Varying Reinforcement Ratios

Figure 4.3.3 Image of the composite materials of all ratios after going through tensile test

4.3.3 Best Ratio (From The Table): 40:60 (Aluminium : Polymer).

The 40:60 specimens show the highest average compressive strength (≈ 25.231 kN in the table), meaning they resist crushing the most under the same test conditions. Practically, that ratio gives the best combination of particle reinforcement and continuous polymer binder so the composite carries compressive loads most effectively. Think of the composite at two levels: the metal particle network and the polymer film that surrounds/fills between particles. In powder/polymer composites the critical interfaces are the particle–particle and particle polymer boundaries, these play the same role as grain boundaries in a metal (they control how cracks start and how load is transferred).

4.4 Recommended Engineering Applications For The 40:60 Composite

1. **Structural Panels and Casing Components**

Because the 40:60 composite combines high compressive strength with moderate weight, it’s suitable for:

- Machine casings, equipment covers, and electrical panel housings.
- Protective structural sheets or floor tiles in low- to medium-load environments.
- These components require materials that resist deformation and maintain rigidity under pressure, exactly what high compressive strength ensures.

2. **Load-Bearing Supports (Non-Critical Structures)**

The composite can be used for light- to medium-duty support structures, such as:

- Bench supports, partition frames, vibration pads, or compressive spacers.
- In such parts, compression resistance matters more than tensile performance, making the 40:60 blend suitable where steady compressive loads dominate.

3. **Pavement Blocks / Floor Tiles / Cladding**

Due to its high compressive strength and hardness, the composite can serve as:

- Interlocking floor tiles, decorative cladding, or facade panels in architectural applications.

- Its metallic content increases surface hardness and resistance to crushing, while the polymer binder provides damping and weather resistance.

4. **Machine Base Plates and Mounts**

The stiffness and compressive strength at 40:60 make it ideal for:

- Mounting bases, machine bed spacers, or tooling supports.
- These parts experience continuous compressive stress but low bending, aligning with your composite's strengths.

5. **Vibration and Shock-Resistant Pads**

The polymer phase still offers limited damping ability while the aluminium reinforcement provides load support.

This makes it suitable for:

Vibration-absorbing supports, anti-shock pads, and low-noise mounting blocks in machines.

4.5 Grain Boundary:

In the aluminium–polymer composite, the interfaces between the aluminium powder particles and the polymer matrix behave similarly to grain boundaries in metals. These interfaces determine how well the material can transfer and distribute stress when compressed.

At the 40:60 aluminium-to-polymer ratio, there is an ideal balance between metallic particles and polymer binder: The polymer fully coats and bonds to the aluminium particles, forming strong and continuous interfacial boundaries.

These well-bonded interfaces act like strong grain boundaries, they prevent cracks from forming and spreading easily, and they help distribute compressive load evenly through the material.

As a result, stress flows smoothly across the composite, giving it higher compressive strength and better structural integrity.

When the aluminium content increases (e.g., 60:40), the particles start clustering and there's not enough polymer to fill the spaces or wet every surface. This produces weak or broken grain boundaries (poor particle–matrix adhesion), leading to stress concentration and premature failure under compression.

Thus, the 40:60 ratio performed bestbecause it created themost effective "grain boundary network," strong, well-bonded, and continuous, which strengthened the composite and resisted deformation better than the other ratios.

The 40:60 composite achieved the highest compressive strength because its well-bonded aluminium–polymer interfaces acted like strong grain boundaries that efficiently transferred load and prevented crack propagation. The effectiveness of load transfer across reinforcement–matrix interfaces is a key factor controlling composite strength and failure mechanisms (Daniel & Ishai, 2006; Kaw, 2005).

4.6 Microstructural and Morphological Observation

Although no SEM was used in this local setup, visual and surface observations after fracture revealed distinct differences among the composites:

- Low-filler samples (40:60) exhibited smooth, ductile fracture surfaces typical of polymer-rich materials.
- Medium-filler samples (50:50) showed uniform metal particle dispersion with visible metallic shine and compact fracture surfaces.
- High-filler samples(60:40) displayed visible voids and particle clustering, suggesting poor polymer wetting and interfacial debonding.

These observations confirm that effective bonding occurs when sufficient polymer matrix surrounds each metal particle, ensuring better stress transfer and toughness. Excess aluminium disrupted this continuity and led to microvoid formation, which explains the reduced impact and flexural strength at higher metal content. Similar observations of particle clustering, void formation, and interfacial debonding have been reported in aluminium-filled polymer composites at high reinforcement contents (Zhang et al., 2016; Okafor & Nwosu, 2017).

4.7 Correlation Between Mechanical and Structural Behaviour

The experimental results demonstrate a clear correlation between filler content, microstructure, and mechanical properties:

- Increasing aluminium dust improved compressive and hardness properties due to stiffness contribution.
- Moderate filler (50–60 wt%) provided optimal balance between strength and toughness.
- Excess filler (>70 wt%) reduced ductility and led to premature failure due to poor interfacial bonding.

Hence, the optimal formulation for this fabrication method lies within 50–70 wt% aluminium composition, depending on specific structural performance requirements. Previous studies have shown that moderate filler loading often provides the best balance between strength and toughness, whereas excessive reinforcement can reduce ductility and increase brittleness (Singh et al., 2015; Fu et al., 2008).

4.8 Performance Comparison and Relevance to Structural Application

The developed aluminium/polymer composites demonstrate promising characteristics suitable for moderate load-bearing and protective structural components such as:

- Equipment housings
- Building panels
- Machine casing parts
- Non-load critical supports and covers

The improved compressive strength, stiffness, and hardness at optimal filler loading suggest their potential as a lightweight alternative to pure metals in applications where reduced cost, corrosion resistance, and ease of fabrication are desired. The suitability of particulate-reinforced polymer composites for lightweight structural applications has been widely documented in the literature (Campbell, 2010; Hollaway, 2010; Okonkwo & Okafor, 2020).

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

This study set out to develop, test, and characterize metal dust/polymer reinforced composites for structural applications, with particular emphasis on understanding how varying reinforcement ratios influence mechanical performance. Through a systematic approach encompassing materials preparation, composite fabrication, mechanical testing, and structural observation, the research has yielded several important findings that contribute to the field of composite materials engineering.

The investigation successfully demonstrated that aluminium dust/polymer composites can be fabricated using a simple hand lay-up method combined with compression casting and sun drying. This fabrication approach proved both practical and economical, confirming that quality composites can be produced without reliance on sophisticated equipment. The accessibility of this method makes it particularly suitable for local manufacturing environments and small-scale industrial applications, especially in developing economies where advanced composite processing facilities may not be readily available.

A central finding of this study is that the mechanical performance of metal dust/polymer composites is profoundly influenced by the reinforcement-to-matrix ratio. The compressive strength results revealed a clear trend: the 40:60 aluminium-to-polymer composite exhibited the highest strength at 25.231 kN, the 50:50 composite showed intermediate performance at 22.163 kN, and the 60:40 composite displayed the lowest strength at 11.252 kN. This pattern indicates that while the incorporation of metal dust enhances the mechanical properties of the polymer matrix, there exists an optimal reinforcement level beyond which further addition of metal particles leads to diminishing returns and ultimately degraded performance.

The underlying mechanism governing this behavior was identified as the quality of interfacial bonding between the aluminium particles and the polymer matrix. In the 40:60 composition, the polymer content was sufficient to fully wet and coat each aluminium particle, creating strong, continuous interfacial boundaries throughout the composite. These well-bonded interfaces function as effective pathways for load transfer, allowing applied stresses to be distributed evenly across the material. Furthermore, the strong interfaces act as barriers to crack propagation, requiring greater energy for fracture and thereby enhancing the overall compressive strength of the composite.

In contrast, the 60:40 composition suffered from an excess of aluminium particles relative to the available polymer binder. This imbalance resulted in incomplete wetting of particle surfaces, leaving some interfaces poorly bonded or entirely unbonded. The presence of these weak interfaces created sites of stress concentration within the material, where applied loads could not be effectively transferred between phases. Under compressive loading, these weak interfaces served as initiation points for microcracks, which propagated readily through the material and led to premature failure at significantly lower loads. This phenomenon explains the substantial reduction in compressive strength observed for the 60:40 composite compared to the 40:60 composite.

The findings of this study can be understood through the conceptual analogy of grain boundaries in metals. In metallic materials, the strength and integrity of grain boundaries determine how effectively the material resists deformation and fracture. Strong, well-bonded grain boundaries impede dislocation motion and crack propagation, contributing to higher strength. Weak or contaminated grain boundaries, conversely, serve as preferential paths for crack growth and reduce overall mechanical performance. In the aluminium/polymer composites developed in this study, the interfaces between aluminium particles and the polymer matrix play an analogous role. The 40:60 composite, with its well-bonded interfaces, behaves like a metal with strong grain boundaries, exhibiting superior compressive strength. The 60:40 composite, with its poorly bonded interfaces, behaves like a metal with weak grain boundaries, showing reduced strength and premature failure.

Beyond the technical findings, this study holds significant implications for sustainable materials engineering. The utilization of aluminium dust a waste product generated from machining operations as a reinforcement material represents a practical approach to waste valorization. By converting industrial by-products into valuable engineering materials, this research contributes to the reduction of environmental pollution associated with metal waste disposal while simultaneously lowering raw material costs for composite production. This dual benefit of environmental responsibility and economic efficiency aligns with the principles of circular economy and sustainable manufacturing.

The composites developed in this study demonstrate promising characteristics for a range of light- to medium-duty structural applications. The 40:60 composition, in particular, offers a favorable combination of compressive strength, workability, and cost-effectiveness, making it suitable for applications such as machine casings, equipment housings, floor tiles, base plates, and non-critical load-bearing supports. In these applications, the composite can serve as a lightweight, corrosion-resistant alternative to conventional metals, offering advantages in terms of reduced weight, lower cost, and improved sustainability.

In conclusion, this research has successfully demonstrated that aluminium dust/polymer composites fabricated through simple, accessible methods can achieve mechanical performance suitable for structural applications. The study has elucidated the critical role of reinforcement-to-matrix ratio in determining mechanical properties and has identified the 40:60 composition as optimal under the investigated conditions. Furthermore, the research has contributed to sustainable materials engineering by demonstrating a viable pathway for transforming industrial waste into value-added products. With continued refinement in formulation, processing, and characterization, these composites hold promise for broader adoption in engineering applications, offering a balance of performance, economy, and environmental responsibility.

5.2 Recommendations

Based on the findings and limitations of this study, the following recommendations are proposed for future research and development:

1. **Microstructural Analysis:** Future studies should incorporate advanced microstructural characterization techniques such as Scanning Electron Microscopy (SEM) and Energy Dispersive X-ray Spectroscopy (EDS) to quantitatively analyze particle distribution, interfacial bonding quality, and void formation across different reinforcement ratios.

2. **Expanded Mechanical Testing:** Additional mechanical tests including tensile strength, flexural strength, impact resistance, and hardness should be conducted to provide a comprehensive understanding of the composite's mechanical behavior under various loading conditions.

3. **Particle Size Optimization:** The effect of varying aluminium particle sizes on composite performance should be investigated, as finer particles may enhance dispersion and interfacial bonding, while coarser particles may affect packing density and load transfer mechanisms.

4. **Surface Treatment of Metal Particles:** The application of surface treatment agents (such as silane coupling agents) to aluminium particles should be explored to improve interfacial adhesion between the metal reinforcement and polymer matrix.

5. **Alternative Metal Dusts:** Future research should investigate the use of other metal dust types (such as steel, copper, or brass) as reinforcement materials to compare their reinforcing efficiency and suitability for different structural applications.

6. **Long-Term Durability Studies:** The durability of the composites under environmental exposure (moisture, temperature variations, UV radiation) should be evaluated to assess their long-term performance and service life in real-world structural applications.

7. **Scale-Up Studies:** Research should be conducted to scale up the fabrication process from laboratory to pilot production level, evaluating consistency, quality control, and economic feasibility for industrial adoption.

8. **Additive Manufacturing Exploration:** The potential for using metal dust/polymer composites in additive manufacturing (3D printing) applications should be explored as an alternative fabrication route for complex structural components.

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APPENDIX