Developing and Investigating a Polyester Resin Polymer Matrix Composite, Reinforced with E-Glass, Aluminum Oxide (Al_2O_3), and Coffee Husk as Reinforcement

Lelisa Tesfaye Gejo

A Thesis Submitted to the Department of Mechanical Engineering

College of Mechanical, Chemical, and Material Engineering

Presented in Partial Fulfillment of the Requirement for the Degree of Master's in Manufacturing Engineering

Office of Graduate Studies

Adama Science and Technology University

June, 2025

Adama, Ethiopia

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Major Advisor

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DECLARATION

I hereby declare that this Master Thesis entitled "**Developing and Investigating a Polyester Resin Polymer Matrix Composite, Reinforced with E-Glass, Aluminum oxide (Al_2O_3), and Coffee Husk as Reinforcement**" is my own work. That is, it has not been submitted for the award of any academic degree, diploma or certificate in any other university. All sources of materials that are used for this thesis have been duly acknowledged through citation.

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Therefore, I recommend the submission of a revised version of the thesis to the department, following the applicable procedures.

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Title of work	Developing and Investigating a Polyester Resin Polymer Matrix Composite, Reinforced with E-Glass, Aluminum oxide (Al_2O_3), and Coffee Husk as Reinforcement
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Dr. Moera Gutu Jiru	____________________	__________________
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LIST OF ACRONYMS AND DESCRIPTION

Acronyms	Description
Al_2O_3	Aluminum oxide
ASTM	American Society for Testing of Materials
BM	Bending Modulus
BMC	Bulk Molding Compound
BS	Bending Strength
CaCO3	Calcium Carbonate
CMCs	Ceramic Matrix Composites
DOE	Design of Experiment DOE
DOF	Degree of Freedom
EB	Elongation at Break
GF	Glass Fiber
GRA	Grey relational analysis
IS	Impact Strength
MMCs	Metal Matrix Composites
MWCNTs	Multi Walled Carbon Nano Tubes
NaOH	Sodium Hydroxide
NFs	Natural Fibers
OM	Optical Microscope
OA	Orthogonal Array
PMCs	Polymer matrix composites
SEM	Scanning Electron Microscope
SMCs	Sheet Molding Compound
TM	Tensile Modulus
TS	Tensile Strengths
TMCs	Thick Molding Compound
TiO2	Titanium oxide

NOMENCLATURE

Abbreviation	Description
$\mathcal{P}_{Al2O3}$	Density of aluminum oxide
$\mathcal{P}g$	Density of E-glass
$\mathcal{P}_{CH}$	Density of coffee husk
$\mathcal{P}_{P}$	Density of polyester resin
$\mathcal{P}c$	Composite's density
Mc	Composite's mass
Wa	Composite's weight in air
Ww	Composite's weight in water
V_C	Composite's volume
W_g	Weight fraction of E-glass
W_{CH}	Weight fraction of coffee husk
W_P	Weight fraction of polyester
W_{Al2O3}	Weight fraction of aluminum oxide
Wt. %	Weight Percentage
W_{D1}	The dry specimen's weight
W_{M2}	The wet specimen's weight

ABSTRACT

Nowadays, increased demand has arisen for structural materials that are lightweight with superior strength. Additionally, to reduce costs, weight, and environmental pollution, several companies are looking for more durable, sustainable, and environmentally friendly materials. The inexpensive cost, plenty, renewable, and biodegradable nature of agro waste-based materials make them attractive for use agro waste based composite. This study's primary goal was to create and examine polyester resin reinforced with E-glass, aluminum oxide, and coffee husk to fabricate lightweight, high-strength, biodegradable, low-cost, and eco-friendly materials. This composite was created using the hand layup technique and evaluated through a series of mechanical tests, including tensile strength testing, flexural strength testing, impact strength testing, hardness, water absorption, density, porosity, and SEM analysis. The experimental design used Taguchi method with a focus on optimization of reinforcement ratios using gray relational analysis. The results confirmed that the optimal composition of 20 wt.% E-glass, 2.5 wt.% aluminum oxide, and 20 wt.% coffee husk achieved the highest tensile strength of 101.1 MPa, flexural strength of 480.27 MPa, impact strength of 33.9 kJ, and hardness of 144.5. At the optimal composition water absorption tests revealed the addition of aluminum oxide and coffee husk significantly improves polyester resin composite's mechanical qualities by lowering the matrix's moisture absorption. Density and porosity tests showed low porosity because of the optimal composition's excellent interfacial bonding between the reinforcement and matrix. SEM analysis revealed well-defined features with good orientation and dispersion of reinforcing materials in the matrix. The results of this investigation show that the inclusion of E-glass, aluminum oxide, and coffee husk successfully improves the mechanical behavior of polyester resin composites. The test formulations with higher E-glass content exhibited improved tensile and flexural strength, while the incorporation of aluminum oxide assisted in improving hardness, impact strength, and physical properties.

Key words: *Polyester resin, Coffee husk, Aluminum oxide, Hand layup, Mechanical tests*

CHAPTER ONE

INTRODUCTION

1.1 Introduction to Composite Materials

Recently, great interest has developed in the pursuit of composite material development by various industries in finding new solutions to conventional material problems. Increased demand has arisen for structural elements that are lightweight with superior strength; thus, motivating researchers to study substitute materials that provide high performance at a lesser cost. With metals and woods becoming scarcer and thus more expensive, it becomes necessary now to develop composite materials whose desirable strength and durability meet economic and viable requirements. A general trend manifested here in the case of composite materials involves the desire within materials science to move towards sustainable and efficient product development. A composite is made up from different basic material components having different properties. In this regard, the mechanical, electrical, and thermal qualities of the composite formed are significantly superior to those of the original constituent components. The most commonly encountered example of composites is that of reinforced plastics, in which polymers are combined with fibrous materials for strength and rigidity. Due to such a combination of materials, composites manage to reach a combination of performance characteristics unreachable by conventional materials (Etri et al., 2024).

Composites are divided into three according to reinforcement. These are: fiber-reinforced which include glass, carbon, or natural fibers, these materials have high strength and stiffness; particle-reinforced which utilize gravel or metal powders for wear resistance and structural integrity, such materials can be used for paving roads or making concrete; and sheet-sourced which use sheet molding compounds, with long glass fibers and thermosetting resins. Such composites have exceptional strength-to-weight ratios ideal for big structural parts. Based on matrix, composite are classified into polymer matrix composite, ceramic matrix composite and metal matrix composite (Rajak, Pagar, Kumar, et al., 2019).

Polymer matrix composites (PMCs) are composites made up of two separate phases. These are polymer matrix and dispersive fibers or particles, where the polymer matrix is the active phase and the fibers or particles are either the second or scattered stage. The polymer matrix maintains the shape and structure, while reinforcing fibers (carbon or glass fibers) enhance tensile strength and thermal stability. This properties enables PMCs to perform better than traditional materials across different sectors, where lightweight are highly needed (Hsissou et al., 2021). The modulus of elasticity, resistance to wear, impact strength, and mechanical strength are all significantly improved over the base material. Polymer matrix composites' specific strength and modulus make them a great choice for many applications.

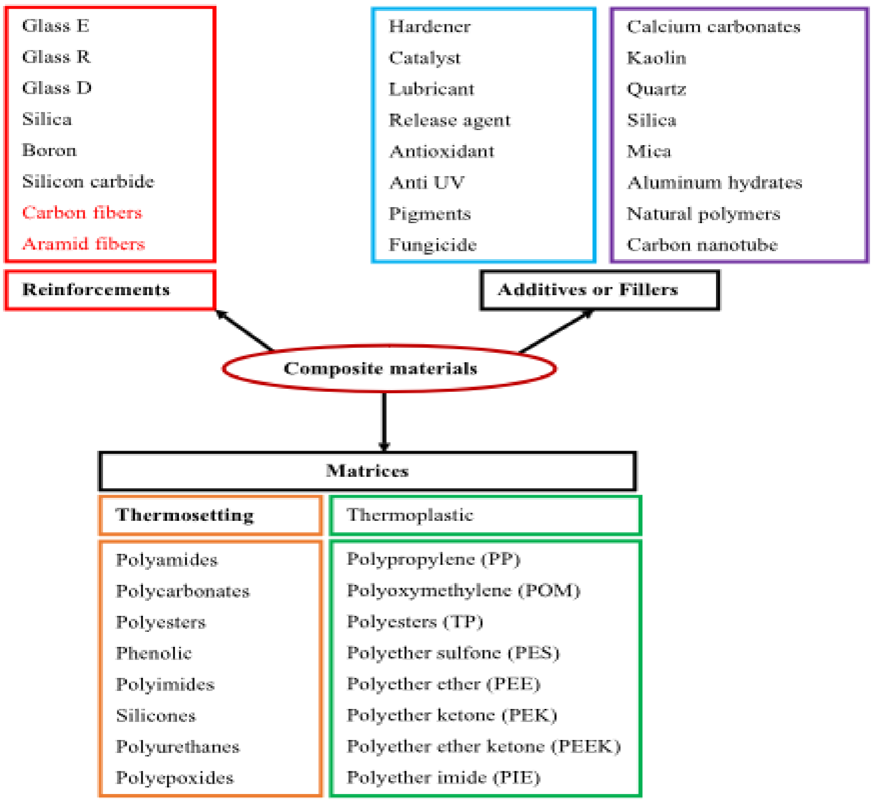


Figure 1.1 Polymer matrix composite formulation (Hsissou et al., 2021)

Polymer based materials are now commonly used instead of traditional materials like aluminum, zinc, and copper across different sectors such as automobiles, construction, sporting, household appliances, and the like. This shift is mainly due to the many advantages that these composites provide, such as easy production, process ability, high strength and stiffness. Manufacturers can alter the properties of such substances to satisfy the particular needs by combining various polymer matrixes with different fibers. Polymer matrix composites usually contain different types of inorganic fillers like silicon carbide, aluminum oxide, silica, magnesium hydroxide, and zinc oxide that are used to improve mechanical qualities. These fillers will be able to enhance certain properties like hardness, stiffness, temperature of thermal distortion, and toughness (Kiran et al., 2018).

The production of composites based on polymers using residue from agriculture is now becoming very popular because it not only adds value to the strength properties but also promotes environmental sustainability. One of the potential applications of recycled agricultural by-products, such as coffee husk, rice husks, wheat straw, and corn stalks for cost-effective reinforcements, is that using them will result in such benefits as increased tensile strength, flexural strength, and the ability to withstand impact. Manufacturers can make things lighter by choosing these plant fibers as an alternative to the traditional non-biodegradables, thus reducing usage of fossil fuels and emissions of greenhouse gases of a product. Adding agricultural waste to polymer-based composites contributes to their biodegradability, which helps solve one of the biggest problems with plastic waste: pollution and piling up (Jaramillo et al., 2021).

Besides natural reinforcement, synthetic fiber reinforcement has also been a subject of vast research. Of all the synthetic fibers the most widely used type of fiber is E glass. It provides good mechanical characteristics, involving tensile strength, flexural strength, impact strength, modulus, and resistance to chemical attack as a result of improved stress distribution between the fiber and matrix as a result of greater bonding between the polyester matrix and glass fiber (Morampudi et al., 2020).

1.2 Statement of Problem

The pursuit of innovative materials by the engineering community highlights the need for affordable, durable, biodegradable, and lightweight material alternatives. Most of the highly used polyester resin based composites in construction and automotive applications fall short in mechanical property, thermal stability, and environmental sustainability. Addition of reinforcement materials is highly important to improve these properties; specifically, by the addition of E-glass, aluminum oxide, and coffee husk, this shortcoming can be improved. This research aims to develop a composite substance that maintains the benefit of being lightweight, biodegradable, and cost-effective while also achieving higher strength, durability, and eco-friendly. This is essential since synthetic and natural based polymer composites are highly substituting convectional materials like metals and wood in different sectors, where a high strength-to-weight ratio and improved performance are crucial.

In addition, the massive amounts of waste generated by the disposal of coffee husks during the coffee processing process worsen land degradation and increase waste production as the world's coffee consumption increases. Burning and landfilling methods of disposal of coffee husk have been found to be particularly damaging to aquatic habitats and contaminate water supplies. Reusing the coffee husk as filler in unsaturated polyester resin composite is one such opportunity in Ethiopia that may arise out of waste from the shell of the coffee. It would support environmental sustainability, reduce waste, and decrease the production cost.

1.3 Objectives of the Studies

1.3.1 General objective

The general objective of this thesis is to develop and investigate a polyester resin polymer matrix composite, reinforced with E-glass, aluminum oxide (Al_2O_3), and coffee husk as reinforcement, which is manufactured utilizing the hand-layup technique.

1.3.2 Specific objectives

Specifically, the goals of this study are:

1. Developing polymer composites reinforced with E-glass, Al2O3, and coffee husk (as a reinforcement) samples, with varying weight percentage ratios, employing the hand lay-up technique.
2. Testing the developed composite's mechanical characteristics, including its tensile, impact, hardness, and flexural strengths.
3. Examining the generated composite's physical characteristics, such as its density, void contents, and water absorption.

4. Investigating the morphological structure of the product using SEM.
5. Optimizing the outcome of mechanical and physical testing using gray relational analysis.

1.4 Significance of the Study

The usage of polymer composite reinforced with E glass, aluminum oxide, and coffee husk in this study provides the following advantages:

- The study incorporates agro wastes, one of which is the coffee husk, to develop degradable composites. This meets the global challenge of limiting plastic waste and other hazardous wastes that affect the environment.
- The investigation contributes toward improving the mechanical properties of polymer composite so as to result in stronger, tougher composites appropriate for demanding applications in different sectors.
- Addition of aluminum oxide and coffee husk adds outstanding hardness and thermal stability, this very useful in improving the polyester composite's mechanical and thermal characteristics.
- A composite development based on this work may result in inexpensive materials that help in reducing manufacturing cost with enhanced product performance.
- By offering useful information and insights for further investigation, this study also advances the scientific understanding of composite materials.

1.5 Scope

The scope of the study was to develop and test polymer matrix reinforced with E glass, aluminium oxide, and coffee husk as reinforcement. Using the hand lay-up technique, the specimen was prepared by adjusting the weight percentages of the fillers and reinforcements. Coffee husk served as environmentally friendly filler, while the combination of aluminum oxide and E-glass gave the product more strength.

The research included mechanical properties of the composite through a number of trials in order to evaluate its performance. Tests involved the measurement of tensile strength, which is the maximum amount of pulling force a material can bear, and flexural strength, which shows the resistance of the material to bending. The test was done on a universal testing machine for accuracy. Also impact strength which measures toughness of the material, and vicker hardiness test which is employed to measure the material's resistance to indentation, was done. Besides the mechanical testing, we are doing physical tests, such as water absorption, density and porosity to find out the ability of the composite to resist water absorption and crack initiation. Finally, the morphology of the composites would be characterized using SEM techniques. This characterization will enable us to know more about the properties of the material and how those different components will interact.

1.6 Limitation of the Study

The following limitations were noticed during the development and testing of the polymer composite reinforced with E-glass, aluminum oxide, and coffee husk filler in this study;

- Some of the laboratories utilized for this task are located in different cities across the country, which wastes time.
- The lack of supply of silicon carbide in Ethiopia. Because of this, aluminum oxide is used in place of silicon carbide.
- The process of fabricating composite by hand layup is quite challenging.
- Financial matter.

1.6 Research Motivation

The development and investigation of polyester resin matrix reinforced with E glass, aluminum oxide, and coffee husk as reinforcement are motivated by the current surge in demand for ecologically friendly and high-performance materials across different industries. Recently, the need for sustainable and materials with superior performance in various industries has been very high. The present research focused on the manufacturing of sustainable, ecologically degradable, and superior performance composite by incorporating coffee husk, E glass, and aluminum oxide into the polyester resin. This dual focus on sustainability and performance is very important to address both environmental issues and the need for advanced material in applications such as construction, automotive, aerospace, etc.

1.7 Thesis Organization

There are five chapters in this research work. Introduction of the study, statement of problem, objectives, significance, scope, research motivation, and research limits were all introduced in chapter one. An overview of previous research and the literature on polymer composite materials was presented in the second chapter. Materials, sample preparation procedures, and test setup for the mechanical and physical testing of a polyester resin matrix reinforced with E-glass, aluminum oxide, and coffee husk were covered in the third chapter. Results and discussion of experimental tests were covered in the fourth chapter. Conclusions, suggestions, and future work were presented in chapter five.

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

This section offers a review of the literature with the goal of covering the previous and current state of prior research on polyester resin reinforced with natural and synthetic fibers, the impact of filler and reinforcement on polymer matrix composites, the manufacturing and application of composite based on polymer matrix, as well as alternative methods of enhancing physical and mechanical characteristics of polymers reinforced with natural and synthetic fibers using fillers.

2.2 Composite Materials

Composite is a substance that combines different materials with significantly differing physical or chemical characteristics to create a material with special attributes. Embedment of reinforcement in a matrix is a common feature of composite materials. During the embedment, the matrix keeps the reinforcement to give it the necessary shape and distributes applied loads to the fibers, keeps the fibers together as a structural unit, and, frequently, adds necessary properties like electrical insulation, ductility, or toughness. For a strong interface bond to be formed, the matrix and the fiber must be able to join mechanically or chemically. In a composite material, reinforcing serves primarily to enhance the overall mechanical properties of the matrix. There are several different forms of reinforcement, including flakes, short fibers, continuous fibers, whiskers, and particles. Each of the various fibers used in composites as reinforcement has unique qualities that influence the composite’s characteristics. Composites are superior to traditional materials because they are lightweight, biodegradable, inexpensive, widely accessible, renewable, low density, and highly strong (Egbo, 2021; Nagavally, 2016).

The base and filler ingredients that make up a composite material determine its classification. According to their structure or filler, composites fall into three major types. These include sheet-molded, particle-reinforced, and fiber-reinforced composite materials (Rajak, Pagar, Menezes, et al., 2019).

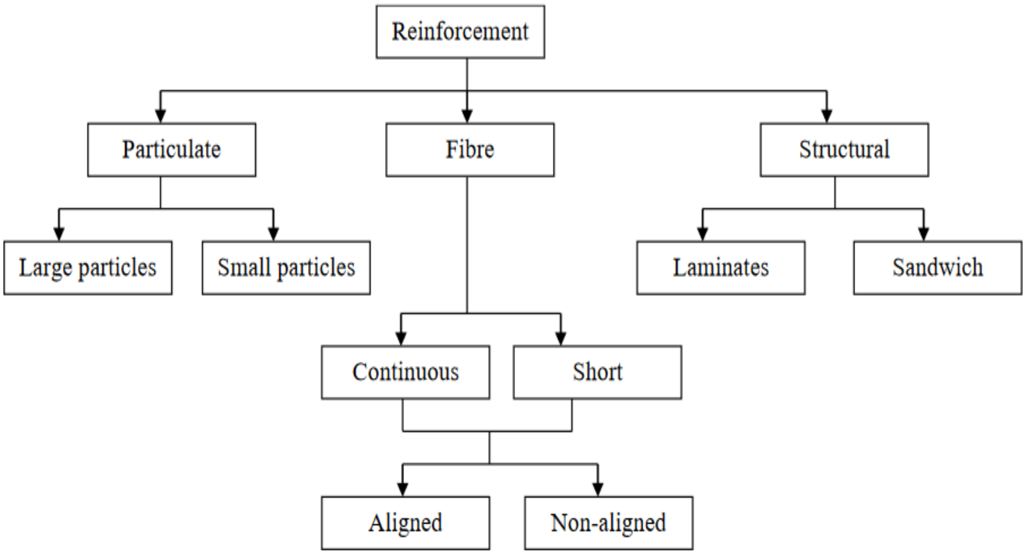


Figure 2.1 Classifications of composite according to reinforcement (Madueke et al., 2022)

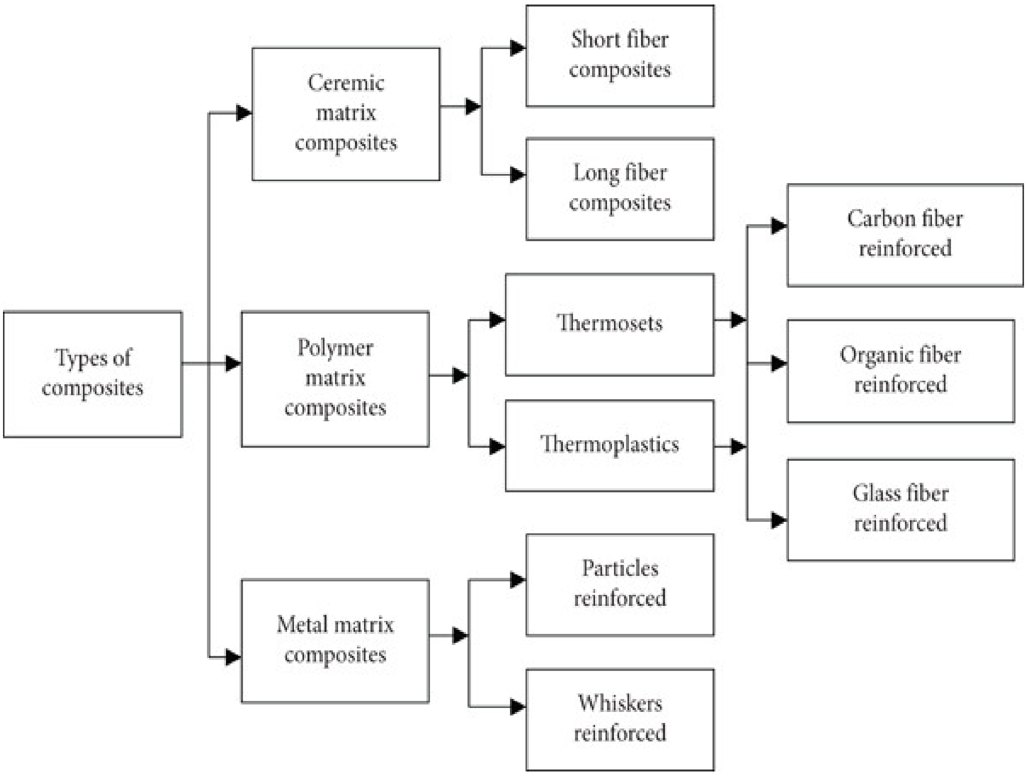


Figure 2.2 Classifications of composite according to matrix (Dhanasekar et al., 2022; Sumithra et al., 2023)

Depending on the foundation or matrix constituents, composite materials can be classified as metal matrix composites, ceramic matrix composites, or organic matrix composites

(Sumithra et al., 2023). Metal Matrix Composites are commonly acknowledged as cutting-edge material. MMCs have superior mechanical and thermal qualities over traditional materials, such as high wear resistance and superior thermal conductivity. Currently, magnesium, nickel, aluminum, and titanium are utilized as matrix materials (Singh et al., 2020). CMCs are a family of materials that are greatly needed for use in various industries. Fibers, whiskers, and graphene are some examples of reinforcing substance in ceramic matrix composites. These composites provide outstanding strength and resistance to wear, good fracture toughness, stability at high temperatures, and exceptional resistance to thermal shock in addition to functionality (Gavalda Diaz et al., 2019).

PMCs' exceptional strength-to-weight ratio makes them one of the materials that are most frequently used in place of conventional materials. PMCs are classified as either particle-reinforced composites or fiber-reinforced composites. Carbon and E glass fiber reinforced polymers are further classifications for fiber reinforced composites. Polymer matrix composite are made of polymers (thermosets and thermoplastics) plus a range of continuous and discontinuous fillers or reinforcements to enhance the materials' performance. Polymer matrix composites (PMC) have long used synthetic fiber as a reinforcing agent to create lightweight materials with enhanced stiffness, strength, and modulus (Begum et al., 2020).

2.3 Effect of Reinforcement on Polymer Matrix Composite

2.3.1 Fiber

Composite materials based on fibers are attracting a lot of attention due to their excellent durability, strength, low weight, and resistance to corrosion. Through functional modification of the fiber materials, fiber-based composite materials can modify the shortcomings of any individual material while yet retaining their original qualities (Yang et al., 2019). Composites reinforced with fibers have the key advantage of having high modulus and strength that are superior to many conventional polymer materials. These composites are significantly better than polymer materials because of their significant weight to modulus ratios, low specific gravity, and great strength. The two primary categories of fiber are natural and synthetic fiber (Maiti et al., 2022).

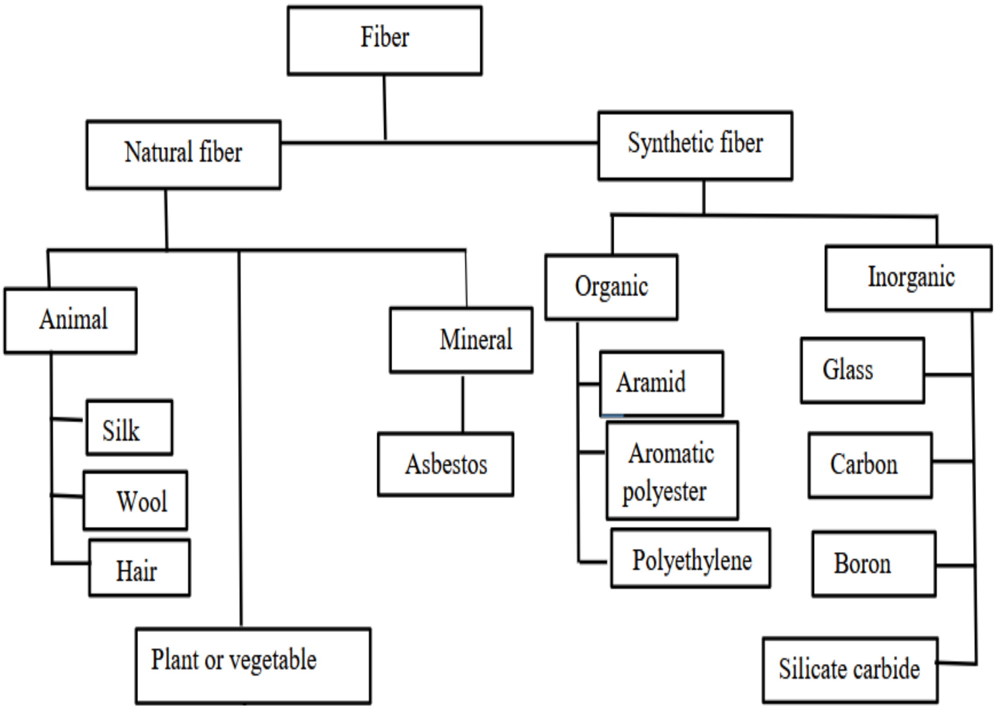


Figure 2.3 Classification of fiber (Elanchezhian et al., 2018).

Natural fiber

Natural fibers are derived mostly from animals, minerals and plants. They have the ability to be spun into yarn, used to make fabric, or used in other industrial processes. The major elements of naturally occurring fibers are cellulose, pectin, hemicellulose, and trace amounts of extractives (Karthi et al., 2020).

Natural fiber composite materials are increasingly being used in various industries due to rising need for lighter, safer, and more fuel efficient vehicles. However, there are several difficulties that require attention when employing natural fibers, including poor fiber-matrix adhesion, durability, and moisture absorption. Poor interface in the matrix, and inconsistent fiber quality are the primary issues that must be improved for better performance and consequently increased use in industry. Moreover, the utilization of natural fibers will contribute the achievement of the country's sustainable development , which include establishing sustainable cities and societies, encouraging sustainable industrialization, eliminating poverty, and ensuring responsible material production and consumption (Naik et al., 2022).

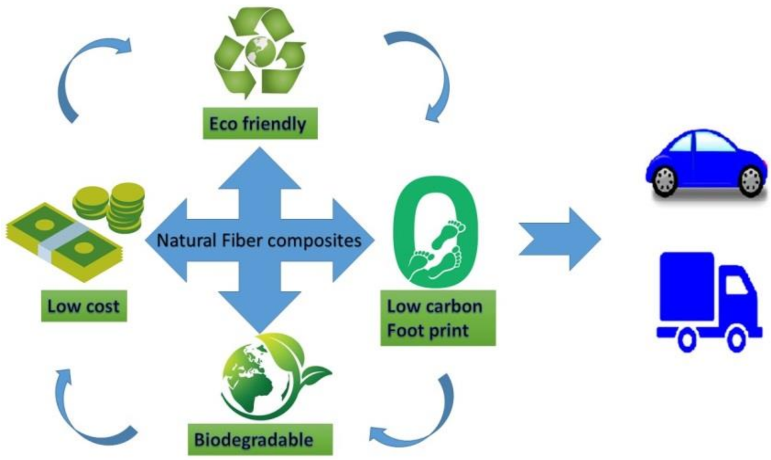


Figure 2.4 Natural fiber composites' sustainability and potential in the automobile industry (Naik et al., 2022)

Synthetic fiber

The most often utilized synthetic reinforcements are E glass, boron, and carbon fibers, which are known as artificial fibers and have better mechanical qualities than natural fibers but are not considered to be biodegradable and threaten to pollute the environment, and they are also more expensive than natural fibers.

Composites reinforced with synthetic fibers have excellent strength, resistance to wear, and corrosion. These features guarantee that fiber materials can withstand hostile environments and meet the demands of contemporary constructions with high strength, light weight, and large loads. They can also satisfy the needs of contemporary industrial building. From their early use in the aerospace sector to their current uses in shipbuilding, construction, and recreation, composite materials made from synthetic fiber had advanced quickly. High mechanical strength, superior insulation, and resistance to heat and corrosion are all attributes of GF. Its composite materials are employed in hydraulic and subterranean constructions, as well as in the construction of bridges and highways and marine-related industries. PBO fibers' primary characteristics include high strength, high modulus, and superior heat resistance. It performs exceptionally well in heat-resistant filter textiles, fire service uniforms, anti-cut protective apparel, and missile and bullet protection gear. High-performance composites are currently made by combining several performance fiber materials with a base material (Yang et al., 2019).

Mohan Kumar et al., (2018) fabricated polymer matrix bonded with woven E-glass to study characterization and processing using the hand layup method. The composite specimens are created utilizing a polyester resin matrix phase and a volume fraction of 60, 65, and 70% of E glass as reinforcement using a modified hand lay-up approach. The project's aim is analyzing the maximal yield strength, impact resistance, hardness, and flexural strength of polyester composites. This investigation demonstrates that a 70% volume percent of reinforcement yields improved tensile characteristics, hardness values, and flexural strengths when compared to 60 and 65% reinforcement ratios. The new hybrid composite containing E glass fibers as reinforcements offers good tensile properties as compared to pure matrix material.

Islam et al., (2019) developed unsaturated polyester resin reinforced with E-glass fiber utilizing the manual layup technique. According to this study, the percentage of E-glass fiber by weight ranged from 5% to 50%. The produced composites' mechanical characteristics, including their tensile and bending strength, were examined. The composites with 5% and 50% fiber reinforcement had respective tensile strengths (TS) of 32 MPa and 72 MPa. It proved that when the E-glass fiber content increased, the composites' mechanical qualities significantly improved.

Engineering & College (2018) had considered the mechanical behavior of polyester composites reinforced with E-glass and S-glass. The results showed, the mechanical characteristics of the composites are significantly enhanced by the addition of glass fibers, and this improvement is particularly noticeable when both E-glass and S-glass fibers are included.

El-wazer et al., (2017) produced an E-glass fiber reinforced polymer composite with randomly oriented fiber percentages of 20%, 30%, 45%, and 60% using a hand lay-up process. The findings demonstrated that adding more glass fiber significantly improved the manufactured composite's mechanical qualities. Best mechanical qualities were achieved at 60% glass fiber weight.

Yakoub, (2022) investigated the mechanical features of polyester resin reinforced with E-glass fiber and multi-walled carbon nanotubes (MWCNTs). In this case, polyester resin and MWCNT nanoparticles are mixed in various percentage fractions of 0.1, 0.2, 0.4, and

0.6%. Also, E-glass fiber was utilized in several percentage fractions, such as 80 of polyester/20 E-glass wt.%, 70 of polyester/30 of E-glass wt.%, and 50 of polyester/50 of E-glass wt.%. Based on this weight percentage the impact of different E-glass fiber chopped strand is examined and the result showed that adding E glass fiber and multi walled carbon nanotubes (MWCNTs) greatly improve tensile strength and hardness respectively. 50 wt. % E glass fibers showed an increase of about 39.8% in tensile strength.

2.4 The Effect of Filler on Polymer Matrix Composite

2.4.1 Effect of synthetic filler

In composite materials, fillers are substances that have been added to the composite matrix for reasons of improving to its durability, toughness, and thermal stability. Fillers can change the mechanical feature of composites. For matrix fillers, powdered forms of substances such as graphene, Nano clay, finely chopped glass fiber, aluminum oxide, silicon carbide and natural fillers are commonly utilized. Materials' stiffness, electrical conductivity, and thermal conductivity can all be altered with fillers (Balart et al., 2020).

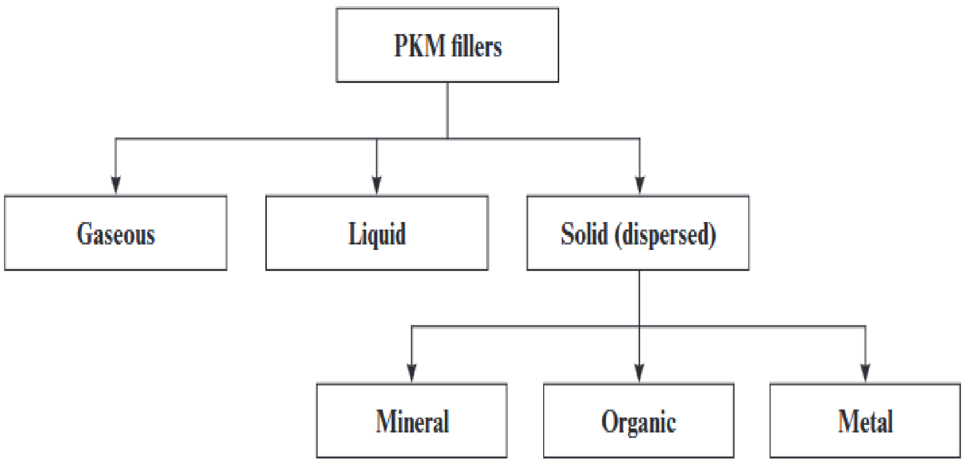


Figure 2.5 Filler category (Mazitova et al., 2022).

Fillers are categorized based on a number of factors. They are divided into three groups; gaseous, liquid, and solid according to the stage of aggregation. By nature, they fall into one of two categories: organic or inorganic. Fillers are used primarily to reduce the finished goods' cost and flammability; however, they can also impart or enhance the following qualities: decreasing the absorption of plasticizer, altering the dielectric characteristics, increasing rigidity and hardness, decreasing the transmission of noise, and decreasing the toxicity of combustion products (Mazitova et al., 2022).

Praveenkum et al., (2021) looked into how synthetic fillers including boron carbide, calcium carbonate, silicon carbide, and aluminum oxide affected polymer matrix composites. This study found that the strong Van der Waals force causes fillers to cluster or agglomerate, which affects the mechanical properties and fiber interface; the filler's concentration and geometry of the filler directly affect how far the clustering can extend. Aluminum oxide is incorporated to boost mechanical strength and thermal conductivity, while silicon carbide improves hardness and reduces wear rates.

Farhan & Hussein, (2020) studied the ceramic fillers effect such as Al_2O_3 particle, silica, and TiO_2. Silica and alumina are powder materials used for reinforcing; according to the study their particle sizes are 53-63 μm and 106-150 μm, respectively, and their weight percentages are 20%, 30%, and 40%. The findings demonstrated that composite materials contain filler exhibited superior flexural strength and hardness than matrix resin, and composites strengthened with Al_2O_3 had great flexural strength and hardness than reinforced composites containing equivalent silica.

Sharma & Sen, (2022) investigated the mechanical performance of epoxy polymer composites reinforced with E-glass fiber and filled with aluminum oxide and silicon carbide. The composites were fabricated using equal proportions of silicon carbide and aluminum oxide at different weight fractions (0, 2, 4, and 6 wt%). Mechanical testing included evaluations of tensile and flexural properties. Results indicated that the composite containing 4 wt% of the fillers exhibited the highest mechanical performance.

2.4.2 Effect of natural filler (Effect of using agro waste as filler)

Coffee husk

One of the world's most consumed beverages is coffee. Some people argue the second most widely consumed liquid globally, following water. Coffee comprises more than half of Ethiopia's annual commodity exports and thus is considered the leading export in the country. The main producing areas are in the south and east of the country, particularly within the Oromia and SNNPR regions, along with major processing facilities. Wollega Zone has acquired fame for producing premium-quality coffee. Currently, there are no economic uses for the coffee husks, which happen to be the main solid waste product arising from handling and processing coffee. One of the big environmental problems is the proper disposal of such husks. The cherry usually contains two coffee beans, each with a flat side facing the other. Every bean is covered by a thin coating of tegument, or Silver's skin. Another skin, which is yellow colored and is attached as light parchment over the bean. Pulp, parchment, and skin all dried make up the husk, or chaff, coffee waste, which is a by-product of the dry process (Oliveira & Franca, 2015).

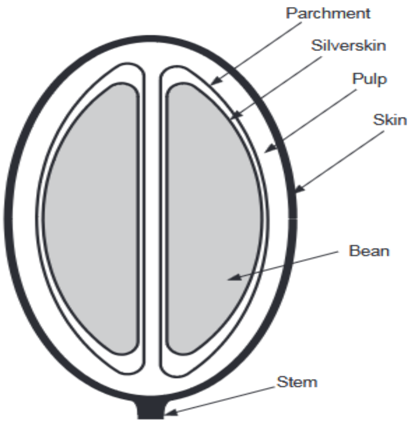


Figure 2.6 A coffee cherry schematic (Oliveira & Franca, 2015)

From an economic and environmental perspective, integrating coffee crop waste products into polymer production should be viewed as a novel way to use them. When these waste products are managed well, they can dramatically lower the production costs of polymers and polymer composites while enhancing their value, improving the economics of coffee production. Additionally, coffee crop by-products have have an interesting benefit over numerous other forms of lignocellulosic substance due to their chemical composition, including the presence of antioxidant chemicals (Hejna, 2021).

Cristina Borghesi et al., (2016) studied the impact of coffee husk filler on poly caprolactone matrix composite. The findings indicated that the inclusion of coffee husk serves several purposes, including acting as organic filler in the polymeric matrix, supporting the adhesion of microorganisms and increasing the rate of polymeric biodegradation.

Yiga et al., (2020) developed fiber-reinforced plastics using rice husk and coffee husk fillers, incorporating filler loadings from 0–20% for rice husks and 0–10% for coffee husks. A polypropylene (PP) matrix was blended with these fillers using a twin-screw extrusion process. Tensile strength and elongation results varied across different filler types and treatments, ranging from 27.4–37.4 MPa and 2.4–70.3% for untreated coffee husks, 31.1–37.4 MPa and 5–70.3% for untreated rice husks, 30.7–37.4 MPa and 5.3–70.3% for treated coffee husks, and 30.7–37.4 MPa and 4.8–70.3% for treated rice husks.

Chemical composition of coffee husk

Among various agro-wastes, coffee husk has unique properties and chemical composition. Unlike other agro-wastes, coffee husk is abundant, particularly in coffee-producing regions, making it a readily available and cost-effective option. This accessibility not only reduces the cost of raw materials but also promotes the recycling of waste, contributing to environmental sustainability (Gonçalves et al., 2021).

Coffee husk has balanced composition elements over other agro-wastes. Cellulose is a natural polymer that provides strength and rigidity to plant materials. Coffee husk contains high contents of cellulose, which contributes significantly to the mechanical properties of the resulting composite. This high cellulose content is advantageous because it enhances the bond between matrix and reinforcement, leading to improved tensile strength and durability when compared to other agro-wastes. Natural cellulose obtained from these types of biomasses can be converted into materials at the micro and nanoscales, producing products like microcrystalline cellulose, micro febrile cellulose, or cellulose nanocrystals with excellent reinforcing qualities (Blinová et al., 2017).

Coffee husk is rich in antioxidants and other bioactive compounds that can add additional properties to the composite. These compounds can increase the durability of the material. Other agro-wastes often lack such beneficial compounds, which can limit their effectiveness as reinforcement materials. The unique chemical profile of coffee husk thus offers a dual advantage strengthening the composite while potentially improving its longevity and performance in various applications (Silva et al., 2021).

Table 2.1 Contents of coffee husk and pulp (Oliveira & Franca, 2015).

Contents	Wt.% of contents in Coffee husk(dry processed)	Wt.% of contents in Coffee pulp(wet processed)
Protein	8-11	4-12
Lipid	0.5-3	1-2
Carbohydrate	58-85	45-89
Minerals	3-7	6-10
Caffeine	1	1
Tannins	5	1-9

Coffee husk is the primary solid leftover from coffee processing, which currently have no commercial use and whose proper disposal poses a serious danger to the environment. The primary by-product of wet or semi-dry processing is coffee pulp (Hejna, 2021).

Table 2.2 Basic components of coffee husk (Nguyen et al., 2023).

Composition	Wt.% in coffee husk
Cellulose	39.2
Hemicellulose	12.6
Klason lignin	23.3
Acid-soluble lignin	2.9
Extractives	8.7
Ash	6-7

Coffee husk, with its notable composition, is a valuable agro-waste among others agro wastes for polymer composites. The table above highlights key components: cellulose (39.2 wt. %), hemicellulose (12.6 wt. %), and lignin (23.3 wt. %), which contribute to the mechanical strength and bonding properties of the composite. The presence of antioxidants in coffee husk enhances durability.

Chemically treating coffee husk can reduce lignin and hemicellulose levels, increasing cellulose content and improving compatibility with polymers. This treatment ultimately enhances the mechanical performance and sustainability of the resulting composites (Amena et al., 2022).

2.5 Fabrication Techniques of Polymer Matrix Composite

There are numerous ways to manufacture composite made of polymer matrix (Chohan et al., 2022; Kangishwar et al., 2023).

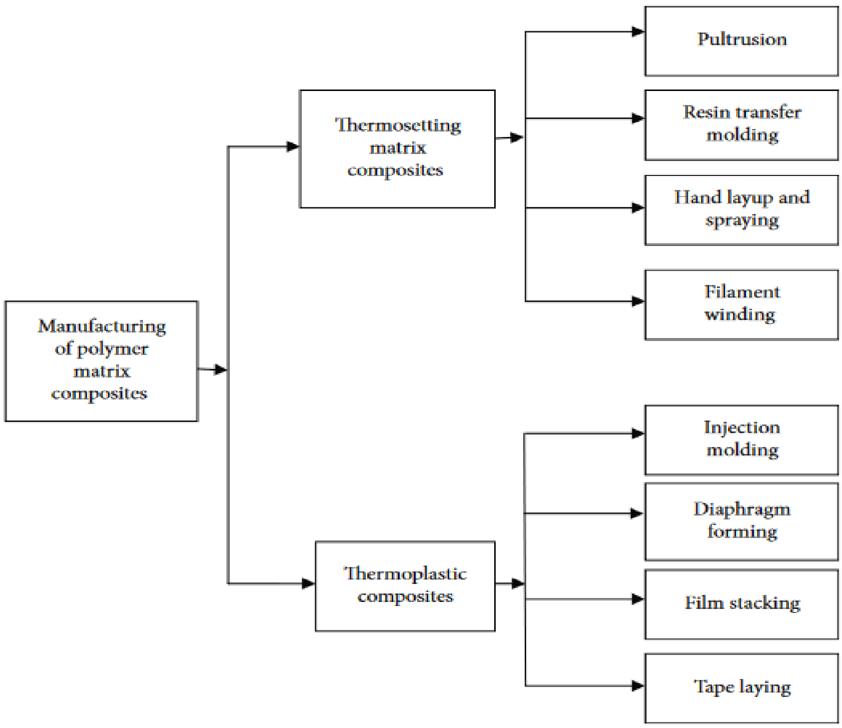


Figure 2.7 Manufacturing technique of composite based polymer matrix (Chohan et al., 2022; Kangishwar et al., 2023).

2.5.1 Pultrasion method

Pultrusion is a production technique for composite based polymer that pulls layers of material soaked in resin via a hot die to produce certain descriptive shapes regardless of length. This method produces excellent quality, rapid composite processing, low material waste, and high productivity. The disadvantages of this approach are improper fiber wet-out, and fiber breakage. Panels, beams, roll-up doors, ladders, insulators, poles, and hand railings can all be made with this technique (Chohan et al., 2022; Kangishwar et al., 2023).

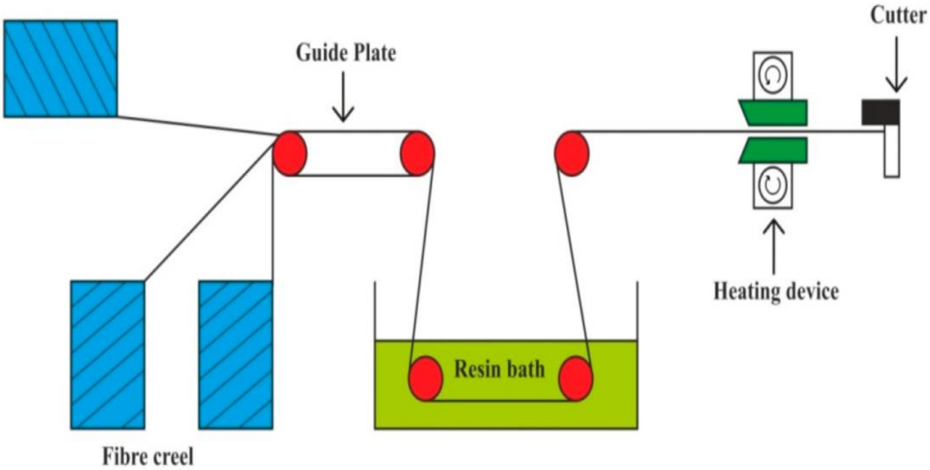


Figure 2.8 Process principle of pultrusion process (Kangishwar et al., 2023; Rajak, Pagar, Menezes, et al., 2019).

2.5.2 Resin transfer molding

Resin Transfer Molding (RTM) is the most prevalent techniques for the manufacture of polymer matrix composites, particularly for those applications needing high strength and rigidity. In this process, the pre-shaped and dried reinforcements are pressed in a heated die mold. Liquid resin is poured to the heated mold for curing of the component, which then closes it. Lastly, the mold is opened in order to extract the piece. This approach has the benefit of providing the automation of large, intricate patterns and curves using skilled labor at a minimal cost (Chohan et al., 2022; Kangishwar et al., 2023; Rajak, Pagar, Menezes, et al., 2019).

2.5.3 Injection molding technique

Injection molding is a highly employed manufacturing procedure when production of components has to be carried out in large quantities, especially when it comes to components made from plastic. The process consists of melting the plastic pellets into a mold with high pressure, and after cooling and solidification of the material, it opens up, and the completed portion is removed. It's quite efficient process that enables the manufacture of complicated shapes with accuracy and reproducibility. Among the different types of injection molding, screw-type injection molding machines are used by most industries. This injection machine can be powered by electricity or hydraulics. (Kangishwar et al., 2023; Kumar Sahu et al., 2024).

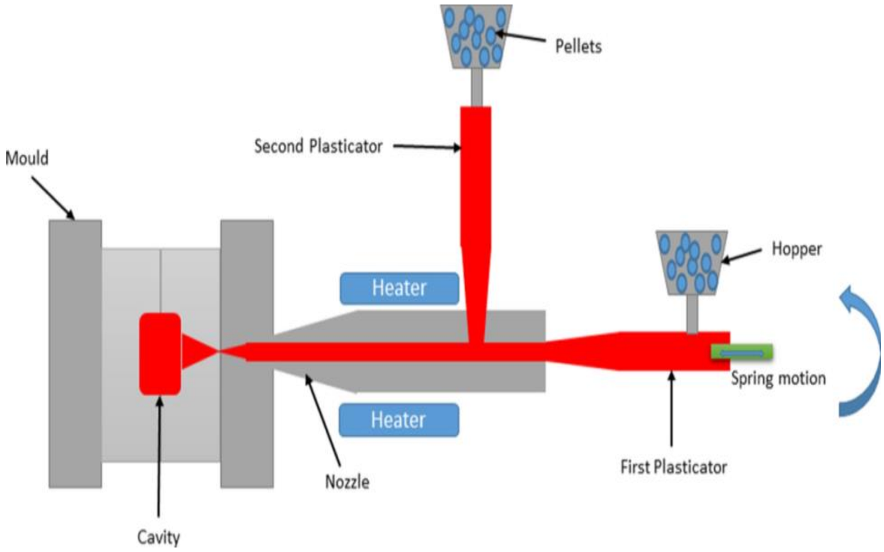


Figure 2.9 Process principle of Injection molding (Kangishwar et al., 2023)

2.5.4 Hand layup technique

The hand lay-up technique is a generally used method in composite manufacturing, especially because of its simplicity and versatility. It basically involves the manual laying of composite materials, usually fiberglass or carbon fiber, with a resin matrix to achieve strong and lightweight structures. In this technique, the procedure starts with applying a release agent to the mold, then carefully placing dry fiber reinforcement. Once the number of layers desired is achieved, resin is applied, usually with the help of brushes or rollers, to impregnate the fibers (D. Kumar et al., 2019).

This process allows excellent control over the orientation and thickness of the fibers, which makes it very well-suited for applications requiring customization, from automotive parts to aerospace components. Among the main advantages of the hand lay-up technique is cost-effectiveness, especially in the case of medium production runs. It requires very minimal equipment, mostly molds and hand tools; hence it is accessible for medium manufacturers and allows for significant design flexibility, which enables the manufacturers to make shapes and structures that may be quite difficult to achieve using automated processes (Adekomaya et al., 2018; Kangishwar et al., 2023).

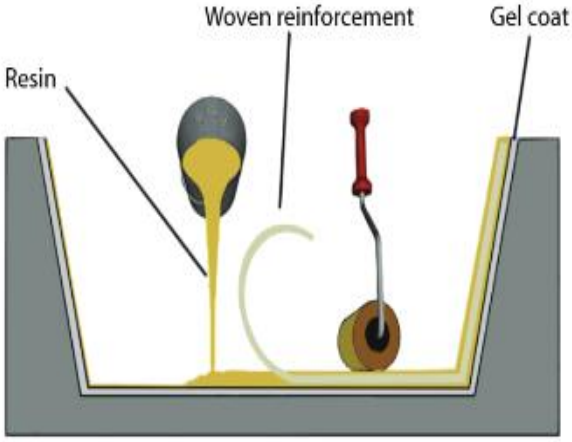


Figure 2.10 Hand layup process (Kangishwar et al., 2023)

2.6 Factors Affecting Polymer Matrix Composite

2.6.1 Length of fibers

Volume percentage and fiber length have an impact on the composites' mechanical qualities. Shrivastava et al., (2017) studied factors affecting mechanical characteristics of the hybrid epoxy resin composite made of glass fiber and coir. According to the study the length of the coir fiber and the fiber loading can measure the composite's mechanical qualities. Fiber length very important, according to the study the mechanical qualities of 10 mm length coir fiber are superior to those of 15 mm fiber. Thus, short coir fiber is preferable over long fiber in order to prevent the curling effect of the fibers.

Khan et al., (2018) examined how the tensile and flexural characteristics of natural fiber reinforced polymer composites were affected by the length and treatment of the fibers. The study found that the combination of long/short fibers and particulates results in good tensile and flexural capabilities because the appropriate length of fiber and particles reduce the gaps between the fiber and matrix. For NFRPCs to have good tensile and flexural qualities, the ideal fiber length is between 20 and 50 mm.

Combining various organic polymers with short or continuous fibers and a variety of reinforcing agents can improve the properties of polymer matrix composites (PMC), including high strength, stiffness, and fracture toughness (Yashas Gowda et al., 2018).

2.6.2 Treatment of fibers

Coffee husk and other natural fibers undergo chemical treatment to eliminate impurities. The chemical most frequently used to bleach and/or clean surfaces made of plant fibers are sodium hydroxide. Various techniques are employed to improve fiber reinforced composite's matrix-fiber bonding. When coffee husk is treated with alkali to modify its surface, its impact and tensile strength are maximized (Amena et al., 2022; Gonçalves et al., 2021). Amena et al., (2022) studied the effects of both treated and untreated coffee husk fiber for composite materials, and found that the treated coffee husk had a balanced level of lignin and hemicellulose. Also compared to untreated coffee husk fiber, treated coffee husk absorbs less water.

The most popular alkali treatment for washing and bleaching the natural outer layer of natural fibers to create high-quality fibers is sodium hydroxide (NaOH). Using a 5 percent of sodium hydroxide (NaOH) solution, the natural fiber had been submerged for a full day in the solution at room temperature. To get rid of the NaOH component and unwanted fiber components, the fiber was continuously cleaned with fresh and distilled water. The alkaline treatment generally had two impacts: It increase the roughness of the fiber surface, which improves interfacial adhesion, and it enhance the exposure of cellulose on the fiber's surface, which raises the quantity of hydroxyl (OH) that was free (Asim et al., 2017; Sonar et al., 2015).

2.6.3 Combination of fibers

Composite made of natural and synthetic fiber have shown their potential as useful materials for structural applications. Shukla & Devnani, (2021) investigated what happens when two distinct fibers are combined in a composite made of polymer matrix. According to the study the mechanical qualities of a polymer matrix containing different fibers are better than those of single fiber reinforcement.

2.7 Application of Hybrid Polymer Matrix Composite

PMCs' excellent strength-to-weight ratio has made them crucial for the development of the automotive parts in automotive industry (Ravichandran et al., 2020).

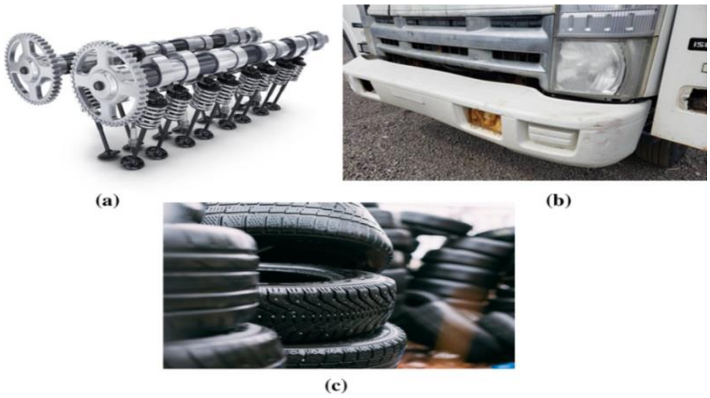


Figure 2.11 Application of polymer matrix composite in automotive (Kangishwar et al., 2023)

Hybrid polymer composite are used in the fabrication of marine components, including Podded propeller, development of hulls and marine craft structures (D. Kumar et al., 2019).

Figure 2.12 Hybrid polymer matrix composite applications in marine (D. Kumar et al., 2019).

In the field of aerospace sciences, polymer matrix composites outperform traditional aluminum-based alloys due to their increased strength and stiffness (Kangishwar et al., 2023).

2.8 Summary of Literature Review

Several investigations have been carried out on the fabrication and characterization of composite made of polymer matrix using different fillers, fabrication techniques, reinforcement types, and reinforcement particle sizes. Among all polymer matrix composite, composite made of polymer matrix reinforced with natural fiber or filled with different agro wastes gotten a lot of interest because of their affordability, low weight, biodegradability, ease of manufacturing, high strength to weight ratio, low production costs, and eco-friendliness. The primary disadvantages of composite made of polymer matrix reinforced with natural fiber or agro wastes are their low mechanical qualities and humidity absorption as a result the hydrophilic features of fibers that are natural. Furthermore, variations in fiber quality, poor matrix interface bonding, and moisture absorption are the main issues that need to be resolved in order to improve performance.

Synthetic fibers are not as difficult to use as fiber that are natural, however, they are more costly and not biodegradable. The primary advantage of using synthetic fiber is to improve the bonding between the matrix and reinforcement, which aids in more effectively distributing tension between the fiber and matrix, so synthetic fiber increases mechanical qualities including impact, flexural, and tensile strength, especially E glass fiber and aluminum oxide (Al2O3) are a synthetic material with favorable electrical, tribological, and mechanical features.

According to the findings of earlier research, combining synthetic fibers and agro waste filler can significantly improve polymer matrix composites (PMCs') mechanical performance, and resistance to moisture.

Table 2.3 Summary of the literature review

Author	Materials used	Method used	Key findings	Applications
(M. N. Islam et al., 2019)	Matrix: polyester resin Reinforcement: E glass fiber	Hand layup method	Polyester resin reinforced with E glass fiber exhibited improved mechanical qualities with increased E-glass fiber amount	Applicable in Construction, automotive industry,

			Percentage of elongation decreased with increased E glass fiber content	marine components,
(Praveena et al., 2022)	Matrix: polyester resin Reinforcement: E glass fiber and Jute fiber Filler: Nano clay	Hand layup method	The incorporation of Jute fiber and E-glass fiber with nanoclay filler into polyester resin, highly improved mechanical properties of the fabricated composite (tensile and flexural strength recorded 69.7 and 90.22). The combination of natural and synthetic fiber reinforced with polyester resin revealed high mechanical qualities compared with single fiber rein forced with polyester resin	Automotive industry, Marine applications
(Mohan Kumar et al., 2019)	Matrix: polyester resin Reinforcement: E glass woven	Hand layup method	The increment of E-glass fiber improved mechanical performance.	Aerspace components, Industrial applications,
(Sharma & Sen, 2022)	Matrix: Epoxy Reinforcement: E-glass fiber Filler: Alumina and silicon carbide	Hand layup method	Composite containing 4 wt% of the fillers (alumina and silicon carbide) exhibited the highest mechanical performance.	Highly applicable in automotive industry

2.9 Research Gap

Epoxy and polyester composites reinforced with E-glass have been extensively studied; however, their ability to degrade, sustainability, and mechanical qualities are inadequate. These properties are highly based on type of reinforcement used and weight percentage of reinforcement employed in the matrix during the mixture. Since no experimental work has been done on polyester composites employing E-glass, aluminum oxide, and coffee husk as reinforcement, a further review of the literature indicates a considerable gap. This is unexpected, in part because of the potential advantages of using agricultural waste materials, such coffee husk, to fabricate sustainable and biodegradable composite materials, additionally the use E-glass and aluminum oxide to enhance mechanical qualities of the composite. There is a great need for more research contributions because the most recent studies do not focus on the principal usage of sustainable materials. Coffee husk powder is one such filler ingredient that could be used to assist reduces production waste and, most likely, improves the composites' overall effectiveness with a combination of E-glass and aluminum oxide. Applying these materials could offer up new possibilities for creating composites with better properties. Research on the physical and mechanical qualities of composite made of polyester combined with these materials is therefore desperately needed. Examining this unique mix could serve as a realistic platform for obtaining suitable, advanced and environmentally friendly materials that satisfy the increasing need for sophisticated composite technology while also satisfying sustainability standards. By creating and examining such a composite, this study seeks to fill this gap.

CHAPTER THREE

METHODOLOGY

3.1 Introduction

The materials and methodological frame work used to fabricate polyester resin reinforced with E-glass, aluminum oxide and coffee husk are described in this chapter. Characterization and experimental methods employed were described in order to produce the necessary output for the problem specified in chapter one. Prior to processing the material, the range of the controllable and variable parameters was ascertained by consulting the literature. This information was then used as an input to generate the output.

3.2 Materials

3.2.1 Polyester resin

Polyester resin having the brand name TOPAZ-1110 was utilized in this investigation. In compared to the epoxy matrix, it possesses good properties, is less expensive, and takes less energy to produce. Since polyester resin is the most extensively used standard and least priced resin in the industry, it was selected as the matrix for this investigation. The outcome is high performance products. Polyester resin is converted to solid by adding 1.5% of hardener (Methyl Ethyl Ketone Peroxide) per 100grams of polyester resin.

Table 3.1 Properties of polyester resins (Reddy Palle et al., 2022)

Properties	Density (g/cm3)	Tensile strength (MPa)	Compressive strength (MPa)	Young Modulus (GPa)	Modulus of elasticity (GPa)
Properties of polyester	1.2-1.5	40-90	60-250	2-4.5	3.23

Figure 3.1 (a) Polyester resin (b) Polyester resin measurement

3.2.2 E glass

Glass fiber is a material that is commonly used as a reinforcing fiber in composite fabrication because it comprises incredibly thin glass fibers with superior strength. E-glass has unique characteristics since it is made of silica, alumina, and other oxides. Its exceptional mechanical qualities, high strength, and affordability make it a popular option. For this investigation, the material had been purchased from World Fiber Glass (WFG) in Addis Ababa, Ethiopia.

Table 3.2 Properties of E-glass (Rana & Purohit, 2017)

Properties	Density (g/cm3)	Tensile strength (MPa)	Compressive strength (MPa)	Young Modulus (GPa)	Modulus of elasticity (GPa)
Properties of E-glass	2.55	3100 – 3800	4000-5000	75 – 78	72

Figure 3.2 (a) Chopped E-glass fiber (b) E-glass fiber measurement

3.2.3 Aluminum oxide (Al_2O_3)

Aluminum oxide is widely used filler during the fabrication of composite and it is also known as alumina. It is a ceramic compound that is suitable for a variety of applications because of its great strength, hardness, and thermal stability. Aluminum oxide improves the mechanical qualities of composites, such as their tensile strength and resistance to wear; its low density also helps create lightweight formulations, which is advantageous in different sectors (Agrawal & Satapathy, 2019; Rajesh et al., 2014). For this investigation, the material had been purchased from Addis Ababa, Ethiopia.

Table 3.3 Properties of aluminum oxide (Agrawal & Satapathy, 2019)

Properties	Density (g/cm)	Tensile strength (MPa)	Coefficient of thermal expansion ($10^{-6}/^{o}C$)	Compressive strength (MPa)
Properties of Al_2O_3	3.98	416	7.4	2600

Figure 3.3 (a) Aluminum oxide (b) Aluminum oxide measurement

3.2.4 Coffee husk

In this study, coffee husk was used as filler and it contains 29.7%, 24.5%, 23.7% and 22.5% of hemicellulose, cellulose, lignin, and other content, respectively. Coffee husks are used as fillers in composites to increase environmental sustainability and waste management. Coffee husks are hydrophilic and they do not readily absorb water due to their structure and composition. Coffee husk filler is more widely available and has a lower density than other natural fillers. In addition to having good electrical insulating qualities and a low moisture susceptibility (hydrophobic), coffee husk filler can also be utilized to boost mechanical strength (Huang et al., 2018).

Figure 3.4 (a) Untreated coffee husk (b) Treated coffee husk

The coffee husk utilized in this study was fresh and dry-processed, and it came from the Wollega zone, Oromiya, Ethiopia.

3.2.5 Hardener (catalyst)

Through a chemical process, the polyester resin is transformed from their liquid condition into a solid form. The liquid polyester resin employed in this study was cured with a hardener. The weight percentages of the two components were utilized to estimate the polyester resin to hardener ratio used in this investigation. The required percentage of polyester and hardener were combined in a weight ratio of 1.5 gram hardener per 100 gram of polyester to create the matrix for this experiment. The polyester and hardener are mixed together and stirred with deep stick material for a brief period of time after the proper quantity of coffee husk and aluminum oxide filler has been added.

Figure 3.5 Hardener

The hardener available is methyl ethyl ketone peroxide, it was purchased from World Fiber Glass (WFG) in Addis Ababa, Ethiopia.

3.2.6 Sodium Hydroxide (NaOH)

Sodium hydroxide also referred as caustic soda, is an alkali salt and highly caustic metallic base. It is a significant chemical utilized in the manufacturing and modification of composite materials. It is often used in fiber treatment, particularly natural fibers and agro waste, to improve their compatibility with polymer matrices. Sodium hydroxide treatment of the fibers alters the chemical composition of the fibers, which consequently affects their surface properties and bonding between the resin and fiber (Sanjay et al., 2019).

In this research Sodium hydroxide was used for treating coffee husks to remove unnecessary elements. This chemical was purchased from the local market of "Labcoom Trading PLC. Addis Ababa".

Figure 3.6 (a) Sodium hydroxide (b) Pellet form of sodium hydroxide

3.2.7 Mold release agent

The purpose of chemical release wax (mold release agent) is to stop the molding material from sticking to the mold. Mold release is essential during composite disassembly to avoid polyester resin from sticking to the mold. HONEY WAX 250 was mold release agent utilized for this investigation and it was purchased from purchased from World Fiber Glass (WFG), Addis Ababa, Ethiopia.

Figure 3.7 Mold release

3.3 Methodology

Design of the experiment, sample fabrication technique, testing and characterization of composite were provided in this portion.

3.3.1 Design of Experiment

The design of an experiment is the systematic strategy outlining how a research study will be carried out to test particular hypotheses using Taguchi technique. The Taguchi technique had been utilized in the experiment design because it is a problem solving tool that can improve the performance of the process, system, and product. This approach integrates analytical and experimental ideas to identify the greatest factor impacting the outcome's reaction the response of the outcome for a notable boost in overall performance. This method is an effective for a systematic process and for minimizing the number of experiments required to optimize parameters (S. Kumar & Balachander, 2020).

Taguchi L9 orthogonal array

Orthogonal array is one of the most straightforward techniques for changing all the parameter combinations at once, whose impact and performance relationships are examined concurrently. The primary goal of this approach is to reduce the total number of experiments needed to optimize the process variables that affect the process outcome (S. Kumar & Balachander, 2020). The L9 (3 x 3) orthogonal array was chosen for this investigation because it took into account three adjustable parameters and three levels for each parameter.

The fabrication of composites made from E-glass, aluminum oxide and coffee husk reinforced with polyester resin had been carried out by hand lay-up approach using three parameters with three levels. In this work, three parameters with three levels are experimented with using Minitab 18 software and the Taguchi method L9 orthogonal array.

Table 3.5 Process parameters for composite development

S/No.	Parameter	Parameter's Naming	L1	L2	L3
1	Wt.% of E-glass	A	15	20	25
2	Wt.% of Al_2O_3	B	0	2.5	5
3	Wt.% of coffee husk	C	10	15	20

Where L1, L2, L3 shows number of level for each parameter.

Table 3.6 The L9 orthogonal array (OA) and its level

No. of sample	Parameter A	Parameter B	Parameter C
1	1	1	1
2	1	2	2
3	1	3	3
4	2	1	2
5	2	2	3
6	2	3	1
7	3	1	3
8	3	2	1
9	3	3	2

This involved the fabrication of nine distinct composites at various levels and with varying characteristics. In the above table parameter A is Wt. % of E-glass, parameter B is Wt. % of Aluminum oxide (Al_2O_3) and parameter C is Wt. % of coffee husk.

3.3.2 The Weight Fraction of the Reinforcement and the Matrix Content of the Composite

Based on the literature paper from the previous work of researchers on different related material usages the compositions of reinforcements are selected as described in table below.

Table 3.7 Composition of matrix and reinforcements

S/No.	Reinforcement			Matrix
	E-glass (%)	Aluminum oxide (Al_2O_3%)	Coffee husk (%)	Polyester (%)
1	15	0	10	75
2	15	2.5	15	67.5
3	15	5	20	60
4	20	0	15	65
5	20	2.5	20	57.5
6	20	5	10	65
7	25	0	20	55
8	25	2.5	10	62.5
9	25	5	15	55

3.3.3 Weight fraction and volume fraction of composite content calculation

Volume of composite

The dimensions of the mold (length, width and thickness) which is ready to mold the composite material, determine composite volume. In this work, Composite volume is the sum of the volumes of E- glass, aluminum oxide, coffee husk and polyester.

$$\text{Composite volume} = l \times w \times t \tag{3.1}$$

Where,

l = length, w = width and t = thickness

l = 350mm, w = 250mm and t = 5mm

Composite volume = 350mm x 250x 5mm

= 437,500mm^3= 437.5cm^3

Table 3.8 Density of matrix and reinforcements

No.	Material list	Density(g/cm^3)
1	E glass	2.55
2	Aluminum oxide	3.98
3	Coffee husk	0.6
4	Polyester resin	1.2

Density of composite

$$\text{Density of composite} = \frac{\text{Mass of composite}}{\text{Volume of composite}} = \frac{\text{Mc}}{\text{Vc}} \quad (3.2)$$

$$\text{Vc} = \frac{\text{Mc}}{\mathcal{P}\text{c}} = \frac{\text{M } glass}{\mathcal{P}\text{ glass}} + \frac{\text{M } alumnium\ oxide}{\mathcal{P}\ alumnium\ oxide} + \frac{\text{M } coffee\ husk}{\mathcal{P}\text{ coffee husk}} + \frac{\text{M } polyester}{\mathcal{P}\text{ polyester}} \quad (3.3)$$

$$\frac{\text{Mc}}{\mathcal{P}\text{c}} = \frac{\text{M } g}{\mathcal{P}\text{ g}} + \frac{\text{M } Al2O3}{\mathcal{P}Al2O3} + \frac{\text{M } ch}{\mathcal{P}\text{ ch}} + \frac{\text{M } p}{\mathcal{P}\text{ p}} \quad (3.4)$$

Table 3.9 Weight fraction of sample 1

No.	Material list	Weight percentage (wt. %)
1	E glass	15
2	Aluminum oxide	0

3	Coffee husk	10
4	Polyester resin	75

The composite's density is determined by using the equation above

$$\frac{\mathrm{Mc}}{\mathcal{P}\mathrm{c}} = \frac{\mathrm{M}\,g}{\mathcal{P}\,\mathrm{g}} + \frac{\mathrm{M}\,Al2O3}{\mathcal{P}Al2O3} + \frac{\mathrm{M\,c}h}{\mathcal{P}\,\mathrm{ch}} + \frac{\mathrm{M}\,p}{\mathcal{P}\,\mathrm{p}} \tag{3.5}$$

$$\frac{\mathrm{Mc}}{\mathcal{P}\mathrm{c}} = \frac{0.15 \text{ x } \mathrm{M}c}{\mathcal{P}\,\mathrm{g}} + \frac{0 \text{ x } \mathrm{M}c}{\mathcal{P}\,Al2O3} + \frac{0.1 \text{ x } \mathrm{Mc}}{\mathcal{P}\,\mathrm{ch}} + \frac{0.75 \text{ x } \mathrm{Mc}}{\mathcal{P}\,\mathrm{p}}$$

$$\frac{1}{\mathcal{P}\mathrm{c}} = \frac{0.15 \text{ x } \mathrm{M}c}{\mathcal{P}\,\mathrm{g}} + \frac{0 \text{ x } \mathrm{M}c}{\mathcal{P}\,Al2O3} + \frac{0.1 \text{ x } \mathrm{Mc}}{\mathcal{P}\,\mathrm{ch}} + \frac{0.75 \text{ x } \mathrm{Mc}}{\mathcal{P}\,\mathrm{p}}$$

$$\frac{1}{\mathcal{P}\mathrm{c}} = \frac{0.15}{\mathcal{P}\,\mathrm{g}} + \frac{0}{\mathcal{P}\,Al2O3} + \frac{0.1}{\mathcal{P}\,\mathrm{ch}} + \frac{0.75}{\mathcal{P}\,\mathrm{p}}$$

$$\frac{1}{\mathcal{P}\mathrm{c}} = \frac{0.15}{2.55} + \frac{0}{3.98} + \frac{0.1}{0.6} + \frac{0.75}{1.2}$$

$$\frac{1}{\mathcal{P}\mathrm{c}} = 0.8505$$

$$\mathcal{P}\mathrm{c} = \frac{1}{0.8505} = 1.176 \ \frac{g}{cm^3}$$

Mass of Composite = Density of Composite x Volume of Composite (3.6)

$$\mathrm{Mc} = \mathcal{P}\mathrm{c} \text{ x } \mathrm{Vc} \tag{3.7}$$

$$\mathrm{Mc} = (1.176 \ \frac{g}{cm^3} \text{x } 437.5 \ cm^3)$$

Mc = 514.5g

For sample 1

- M glass = 0.15 x Mc = 0.15 x 514.5 = 77.175g
- M aluminum oxide = 0 x Mc = 0 x 514.5g = 0g
- M coffee husk = 0.1 x Mc = 0.1 x 514.5g = 51.45g
- M polyester = 0.75 x Mc = 0.75 x 514.5g = 385.875g
- Mass of hardener = 1.5% of total mass of the polyester

  = 0.015 x 385.875 = 5.79

Table 3.10 Weight fraction of sample 2

No.	Material list	Weight percentage (wt. %)
1	E glass	15
2	Aluminum oxide	2.5
3	Coffee husk	15
4	Polyester resin	67.5

Based on Eqn. 3.5,

$$\frac{\mathrm{Mc}}{\mathcal{P}\mathrm{c}} = \frac{0.15 \text{ x Mc}}{\mathcal{P}\text{ g}} + \frac{0.025 \text{ x Mc}}{\mathcal{P}\ Al2O3} + \frac{0.15 \text{ x Mc}}{\mathcal{P}\text{ ch}} + \frac{0.675 \text{ x Mc}}{\mathcal{P}\text{ p}}$$

$$\frac{1}{\mathcal{P}\mathrm{c}} = \frac{0.15 \text{ x Mc}}{\mathcal{P}\text{ g}} + \frac{0.025 \text{ x Mc}}{\mathcal{P}\ Al2O3} + \frac{0.15 \text{ x Mc}}{\mathcal{P}\text{ ch}} + \frac{0.675 \text{ x Mc}}{\mathcal{P}\text{ p}}$$

$$\frac{1}{\mathcal{P}\mathrm{c}} = \frac{0.15}{\mathcal{P}\text{ g}} + \frac{0.025}{\mathcal{P}\ Al2O3} + \frac{0.15}{\mathcal{P}\text{ ch}} + \frac{0.675}{\mathcal{P}\text{ p}}$$

$$\frac{1}{\mathcal{P}\mathrm{c}} = \frac{0.15}{2.55} + \frac{0.025}{3.98} + \frac{0.15}{0.6} + \frac{0.675}{1.2}$$

$$\frac{1}{\mathcal{P}\mathrm{c}} = 0.8776$$

$$\mathcal{P}\mathrm{c} = \frac{1}{0.8776} = 1.1395\,\frac{g}{cm^3}$$

Based on Eqn. 3.7,

$\mathrm{Mc} = \mathcal{P}\mathrm{c}$ x Vc

$$\mathrm{Mc} = (1.1395\,\frac{g}{cm^3} \text{x } 437.5\ cm^3)$$

Mc = 498.53g

- M glass = 0.15 x Mc = 0.15 x 498.53g = 74.78g
- M aluminum oxide = 0.025 x Mc = 0.05 x 498.53g = 12.46g
- M coffee husk = 0.15 x Mc = 0.15 x 498.53g = 74.78g
- M polyester = 0.675 x Mc = 0.675 x 498.53g = 336.508g
- Mass of hardener = 1.5% of total mass of the polyester

  = 0.015 x 336.508g = 5.047g

Table 3.11 Weight fraction of sample 3

No.	Material list	Weight percentage (wt. %)
1	E glass	15
2	Aluminum oxide	5
3	Coffee husk	20
4	Polyester resin	60

Based on Eqn. 3.5,

$$\frac{\mathrm{Mc}}{\mathcal{P}\mathrm{c}} = \frac{0.15 \text{ x } \mathrm{M}c}{\mathcal{P}\text{ g}} + \frac{0.05\text{x } \mathrm{M}c}{\mathcal{P}Al2O3} + \frac{0.2 \text{ x } \mathrm{Mc}}{\mathcal{P}\text{ ch}} + \frac{0.6 \text{ x } \mathrm{Mc}}{\mathcal{P}\text{ p}}$$

$$\frac{1}{\mathcal{P}\mathrm{c}} = \frac{0.15 \text{ x } \mathrm{M}c}{\mathcal{P}\text{ g}} + \frac{0.05\text{x } \mathrm{M}c}{\mathcal{P}Al2O3} + \frac{0.2 \text{ x } \mathrm{Mc}}{\mathcal{P}\text{ ch}} + \frac{0.6 \text{ x } \mathrm{Mc}}{\mathcal{P}\text{ p}}$$

$$\frac{1}{\mathcal{P}\mathrm{c}} = \frac{0.15}{\mathcal{P}\text{ g}} + \frac{0.05}{\mathcal{P}\ Al2O3} + \frac{0.2}{\mathcal{P}\text{ ch}} + \frac{0.6}{\mathcal{P}\text{ p}}$$

$$\frac{1}{\mathcal{P}\mathrm{c}} = \frac{0.15}{2.55} + \frac{0.05}{3.98} + \frac{0.2}{0.6} + \frac{0.6}{1.2}$$

$$\frac{1}{\mathcal{P}\mathrm{c}} = 0.905$$

$$\mathcal{P}\mathrm{c} = \frac{1}{0.905} = 1.105\ \frac{g}{cm^3}$$

Based on Eqn. 3.7,

Mass of Composite = Density of Composite x Volume of Composite

Mc = $\mathcal{P}$c x Vc

Mc = (1.105 $\frac{g}{cm^3}$ x 437.5 cm^3) = 483.57g

- M glass = 0.15 x Mc = 0.15 x 483.57g = 72.54g
- M aluminum oxide = 0.05 x Mc = 0.05 x 483.57g = 24.17g
- M coffee husk = 0.2 x Mc = 0.2 x 483.57g = 96.714 g
- M polyester = 0.6 x Mc = 0.6 x 483.57g = 290.14g

- Mass of hardener = 1.5% of total mass of the polyester
  0.015 x 290.14g = 4.35g

The left samples are calculated according to the above ways. The following table shows the mass of matrix and reinforcement for each sample.

Table 3.12 Mass of matrix and reinforcement for each sample

	Composition (%)				**Mass (g)**					
Sample	E glass	Al_2O_3	Coffee husk	Poly ester	E glass	Al_2O_3	Coffee husk	Polye ster	Hard ner	Total
S1	15	0	10	75	77.18	0	51.45	385.9	5.79	520.3
S2	15	2.5	15	67.5	74.78	12.46	74.78	336.5	5.05	503.6
S3	15	5	20	60	72.54	24.17	96.714	290.1	4.35	487.9
S4	20	0	15	65	100.5	0	75.403	326.8	4.9	500.8
S5	20	2.5	20	57.5	97.93	12.24	97.93	281.5	4.22	493.8
S6	20	5	10	65	109.5	27.34	54.73	355.8	5.34	552.7
S7	25	0	20	55	122.9	0	98.32	270.4	4.06	495.7
S8	25	2.5	10	62.5	138.1	27.63	55.25	345.3	5.18	571.5
S9	25	5	15	55	133.6	26.71	80.13	293.8	4.41	538.65
Total					943	240.4	696.3	2815	42.3	

3.3.4 Grey relational analysis based on Taguchi

The combination of GRA with the Taguchi method enables practitioners to identify best parameters for achieving target levels of quality. In manufacturing processes, the combination can help to determine the optimum settings for various parameters to lower defects and enhance product performance. The following basic steps were used to perform the gray relational analysis:

1. Signal to noise ratio was computed using Minitab software program

   For larger the better $\frac{S}{N} ratio = -10(log\frac{1}{n}) + (\frac{1}{Y^2 ij})$ (3.8)

   For smaller the better $\frac{S}{N} ratio = -10(log\frac{1}{n}) + (Y^2 ij)$ (3.9)

   In this, the response values are displayed by $Y^2 ij$ and the number of replications for every test is indicated by n.

2. Signal to noise ratio normalization

   According to the principle of larger the better $X_{ij} = \frac{Y_{ij} - minY_{ij}}{maxY_{ij} - minY_{ij}}$ (3.10)

   According to the principle of smaller the better $X_{ij} = \frac{maxY_{ij} - Y_{ij}}{maxY_{ij} - minY_{ij}}$ (3.10)

   In this, Y_{ij} displays the S/N ratio derived from Taguchi analysis, X_{ij} displays the normalized S/N ratio.

3. The deviation sequence and quality loss are calculated.

   $\Delta = 1 - Xij$ (3.12)

   In this, Δ indicates quality loss and 1 indicates the maximum degree of quality loss.

4. Calculation of the grey relation coefficient

   $$GC_{ij} \frac{\Delta_{min} + \varphi\Delta_{max}}{\Delta_{ij} + \varphi\Delta_{max}} \quad (3.13)$$

   In this, Δmin and Δmax indicate the least and largest absolute differences, respectively, that deviate from the goal value, GC_{ij} represents the gray relational coefficient. The distinguishing coefficient is displayed by φ which is between 0 and

5. Grey relational grade (GRG) calculation

   $GRG = \frac{1}{m}\sum_{i=1}^{m} GC_{ij}$ (3.14)

   Where m shows the number of process responses

3.3.5 The required load to compact a sample without affecting the sample and mold

To achieve uniform thickness in polyester resin composite samples reinforced with E-glass, aluminum oxide, and coffee husk, it's crucial to apply appropriate molding pressure during the curing process. Based on the dimensions of the sample and the presence of a welded rectangular bar to prevent movement of the liquid mixture, the required load is calculated in this form:-

Sample dimensions and mold area

Length (L): 350 mm

Width (W): 250 mm

Thickness (T): 5 mm

The area of the mold is calculated as:

$$\text{Area} = L \times W \qquad (3.15)$$

$A = 350\ \text{mm} \times 250\ \text{mm} = 87{,}500\ \text{mm}^2 = 0.0875\ \text{m}^2$

Recommended molding pressure

For polyester resin composites, a typical molding pressure range is between 2×10^4Pa to 7×10^4Pa. Valente et al., (2023) found that a molding pressure of 3×10^4Pa was optimal for jute fabric reinforced poly lactic acid (JF-PLA) composites in terms of molding time, microstructural compaction, and mechanical strength. Kazano et al., (2023) reported that a molding pressure of 4×10^4Pa was optimal for carbon fiber fabric reinforced polyimide (CFF-PI) composites, as it resulted in 100% resin impregnation and reduced void content.

Based on Eqn. 3.15,

$\text{Area} = L \times W = 350\ \text{mm} \times 250\ \text{mm} = 87{,}500\ \text{mm}^2 = 0.0875\ \text{m}^2$

$$\text{Required load} = \text{Molding pressure} \times \text{Area of the mold} \qquad (3.16)$$

Where molding pressure is 3×10^4Pa based on the above literature review and area of the mold is 0.0875m^2.

Required load = $3 \times 10^4\text{Pa} \times 0.0875 = 0.002625\text{MN} = 2625\text{N}$

For liquid mixture, factor of safety is between 2 to 3.

Appropriate load = (26250)/ (2.5) = 1050N

The maximum load the welded rectangular bar can withstand

A rectangular bar is fabricated from steel through welding to prevent the movement of the liquid mixture of reinforcement and matrix from the specified dimensions. The load-bearing capacity of the welded rectangular bar depends on its material properties and dimensions. The bar is made of steel, which has a tensile strength of 250 MPa, the maximum load can be calculated using the below formula:-

$$P_{max} = \sigma_{TS} \times Ac \qquad (3.17)$$

Where, P_{max} is the maximum load, σ_{TS} is the maximum tensile strength of the material, and Ac is the cross sectional area of the welded bar.

The cross sectional area is

$$Ac = W \times T \qquad (3.18)$$

Where, Ac is cross sectional area, W is width of the mold, and T is thickness of the mold

$A = W \times T = 5mm \times 250mm = 0.005m \times 0.25m = 0.00125m^2$

$P_{max} = \sigma_{TS} \times A = 250 \times 10^6 \times 0.00125m^2 = 31250N$

The welded rectangular bar can with stand a maximum load of 31250N before failure.

Therefore, the appropriate load mentioned above, used for compacting the sample during fabrication, does not affect the welded rectangular bar, as it is less than the maximum load that the welded rectangular bar can withstand. For this reason, the calculated appropriate load is highly suitable for use during the fabrication of the composite sample.

3.3.6 Sample preparation method

Materials used for sample preparation were E glass, aluminum oxide, Coffee Husk, Polyester Resin, Hardener, Honey Wax, Protective Gear (glove, musk), Mold and String Rod.

Figure 3.8 Materials used for composite fabrication

Preparation of coffee husk

The coffee husk utilized in this study was acquired from kellem wollega zone; it was fresh and dry processed. Coffee husks are the primary solid waste product that remains after coffee is processed; they are currently unmarketable and pose a significant environmental danger if not disposed of properly. Coffee husk is usually prepared in a number of stages to guarantee that it is suitable for a range of uses. The husk is first gathered from the coffee processing facilities. After that, it is cleaned to get rid of any dirt, twigs, or stones that might be present. Then, the cleaned husk undergoes alkaline treatment. Alkaline treatment is a common method employed to modify the properties of coffee husk, primarily to enhance its digestibility or to extract valuable compounds.

Coffee husk is frequently treated with alkali to change its characteristics, usually to improve its usability. The coffee husk for this investigation is soaked in an alkaline solution using 5% of sodium hydroxide, for 24 hrs. Cellulose and hemicellulose, two complex carbohydrate molecules, are broken down by the alkaline solution, increasing the husk's accessibility for mixture.

Figure 3.9 Coffee husk treatment: (a) Raw CH (b) Manual cleaning of CH (c) Mixture of distilled water with NaOH (d) CH treated with NaOH (e) Dried CH after treatment

Preparation of materials

The hardener (catalyst), E glass, aluminum oxide and polyester resin were purchased from Addis Ababa. The mold was prepared from metal. In order to eliminate superfluous resin and air bubbles, a straightforward hand lay-up composite production method was employed, followed by 24 hours of compression molding and 24 hours of curing. The specimen's cutter or grinder machine was used to cut the samples into specimens that met the standard dimensions for every test. Every test was conducted at ambient temperature.

3.3.7 Specimens Preparation and Procedures

A. First, the raw materials need to be prepared for mix. The E-glass fibers were cut to the required length which was mixed uniformly in the resin. To increase aluminum oxide surface area, aluminum oxide of fine powder is selected to provide more surface area for bonding with the resin. To enhance the polyester resin compatibility, the coffee husk was dried and ground down to particles of smaller sizes.

Figure 3.10 Prepared raw materials for mix

B. In a clean container, polyester resin, aluminum oxide and coffee husk were mixed together according to the manufacturer instructions. Then, hardener was gradually added according to their weight percentage ratio and mixing (continuous stirring) was applied to ensure that all components were well dispersed within the matrix to promote uniformity.

Figure 3.11 Mixture of raw materials (E-glass, Al_2O_3, and Coffee Husk)

C. The homogeneous mixture of E glass, aluminum oxide, coffee husk, polyester resin and hardener were poured to the prepared mold.

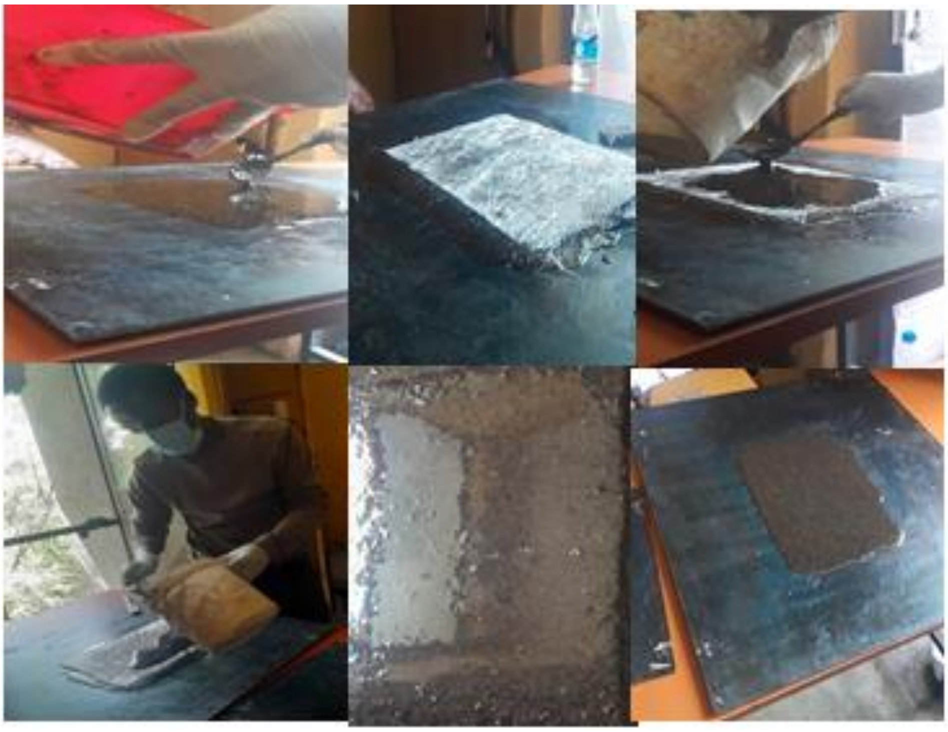


Figure 3.12 Mixture pouring process

D. Put load which is uniformly distributed on the sample, then the prepared samples in the mold had been allowed to cure at ambient temperature. After the samples had been cured, they were carefully removed from the molds to avoid damage.

Figure 3.13 Curing process with uniform distribution of load

E. Collecting the prepared samples in a single location and labeling each samples according to its weight percentage composition.

Figure 3.14 Labeling the prepared samples

F. After the samples were prepared the specimen's cutter or grinder machine was used to cut the samples into specimens that met the standard dimensions for every test. Every test was conducted at ambient temperature.

Figure 3.15 Specimen preparations from the sample

Figure 3.16 Prepared specimens

Generally, the basic procedures used for sample preparation were shown in figure below

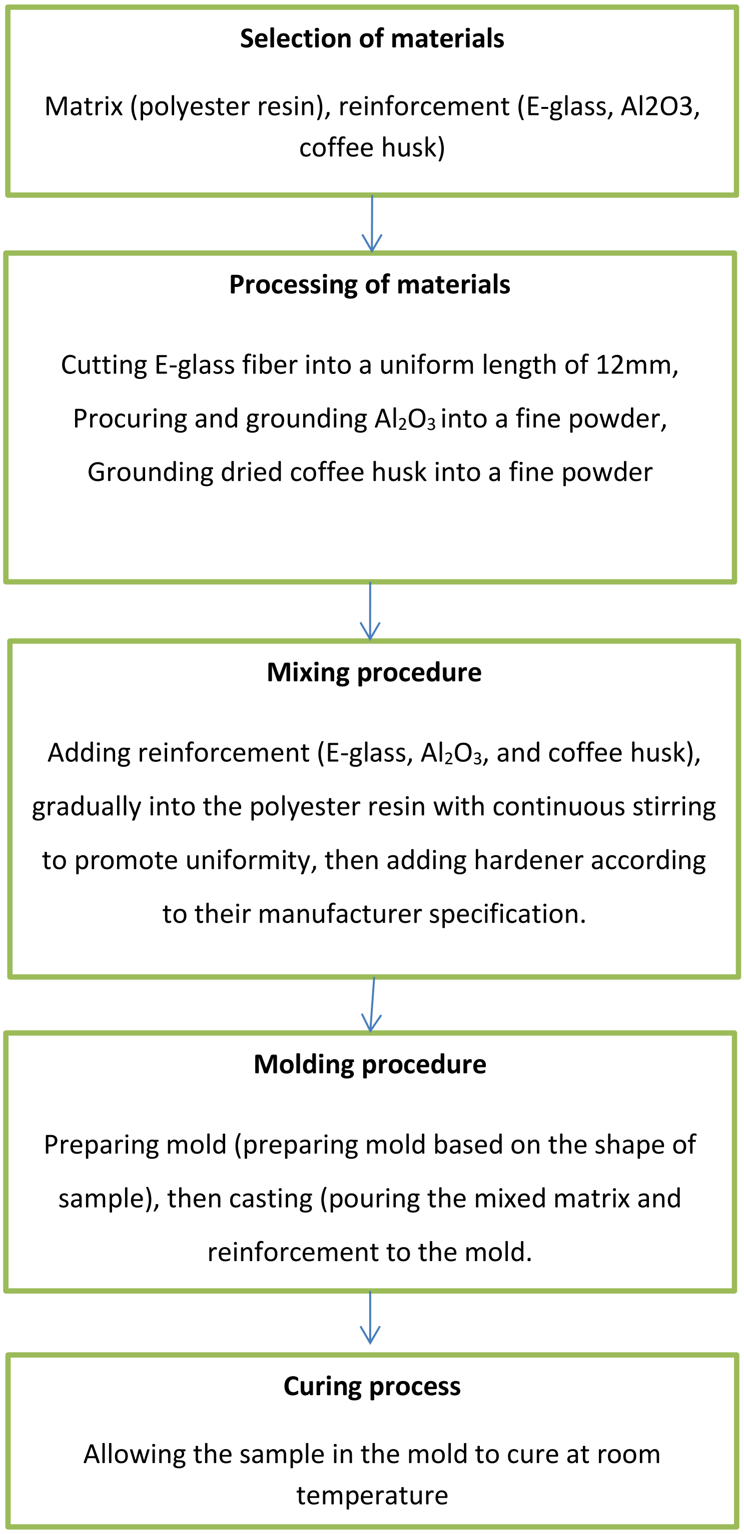


Figure 3.17 Specimen preparation and procedure

3.4 Testing and Characterization

The manufactured specimens undergo both mechanical and physical testing to identify their performance. Flexural, impact, Tensile, compressive strength, and Vickers hardness tests are included under mechanical characterizations. Water absorption testing, SEM analysis, porosity and density testing are classified under physical characterization. The ASTM standard was followed for each test, and these characterizations had been conducted at room temperature.

3.4.1 Tensile strength testing

Tensile strength testing is the method employed to assess a material's mechanical qualities. Particularly by measuring the highest tensile stress (pulling stress) that a material can withstand before failing. The primary goal of this testing is to determine material behavior under tension; this will provides information about material’s strength, durability, ductility and overall performance when subjected to tension forces. The flat type specimen is utilized in the tensile test (Khan et al., 2018). During the testing, a unidirectional load is applied to both ends of the sample. The samples were placed in the testing apparatus's grips vertically. After that, the grips were securely and uniformly tightened to stop any slipping. A load cell detects the specimen's increased resistance as it elongates as the tensile test begins. Until the specimen ruptured, this load value (F) was noted. Tensile properties for elongation at break and yield point had been calculated using the instrument software that comes with the apparatus. Tensile strength at yield is calculated as the cross-section area divided by the maximum recorded load.

Tensile strength testing was performed as per ASTM D3039. According to ASTM D3039 standard, the dimensions of the tensile strength test specimen were 25mm width, 250mm length, and 5mm thickness. The test was carried out utilizing a universal testing machine (UTM), the INSTRO 5985 UTM, located at Defense University in Bishoftu, Ethiopia, with a 50KN capacity.

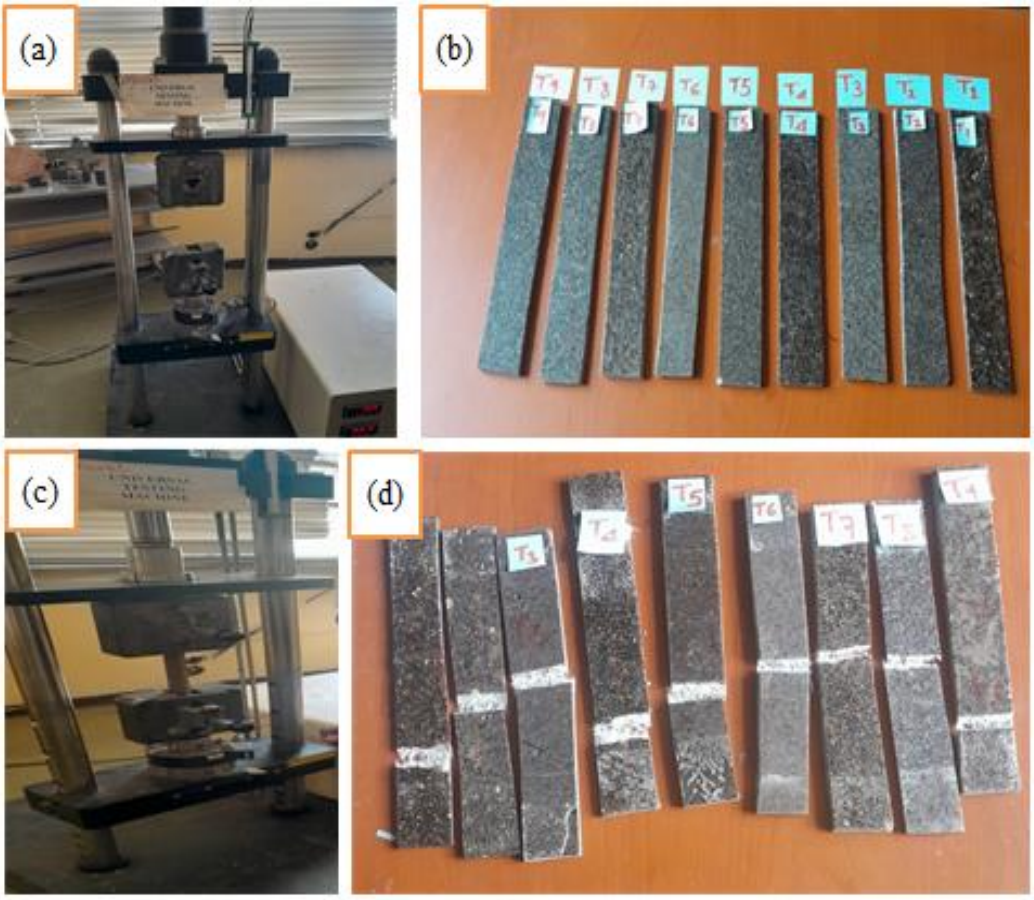


Figure 3.18 Tensile strength testing: (a) Universal testing machine (b) Specimen before test (c) Adjusted specimen (d) Specimen after test

3.4.2 Flexural Strength Testing

Flexural strength testing is a technique for determining a material's resistance to deformation under bending force or the material's resistance to bending force applied counter to its longitudinal axis. The most important intent of this test is to determine how well a material can resist bending stress; this will provides crucial information about the material’s stiffness, ductility and overall structural integrity when subjected to bending force.

Flexural strength test was performed using universal testing machine (UTM) with a 50KN capacity. The specimen dimension for this test was prepared based on the ASTM D790, according to this standard the specimen dimensions were 150 mm × 25 mm × 4 mm. This test was conducted in the Engineering College of Defense University in Bishoftu, Ethiopia.

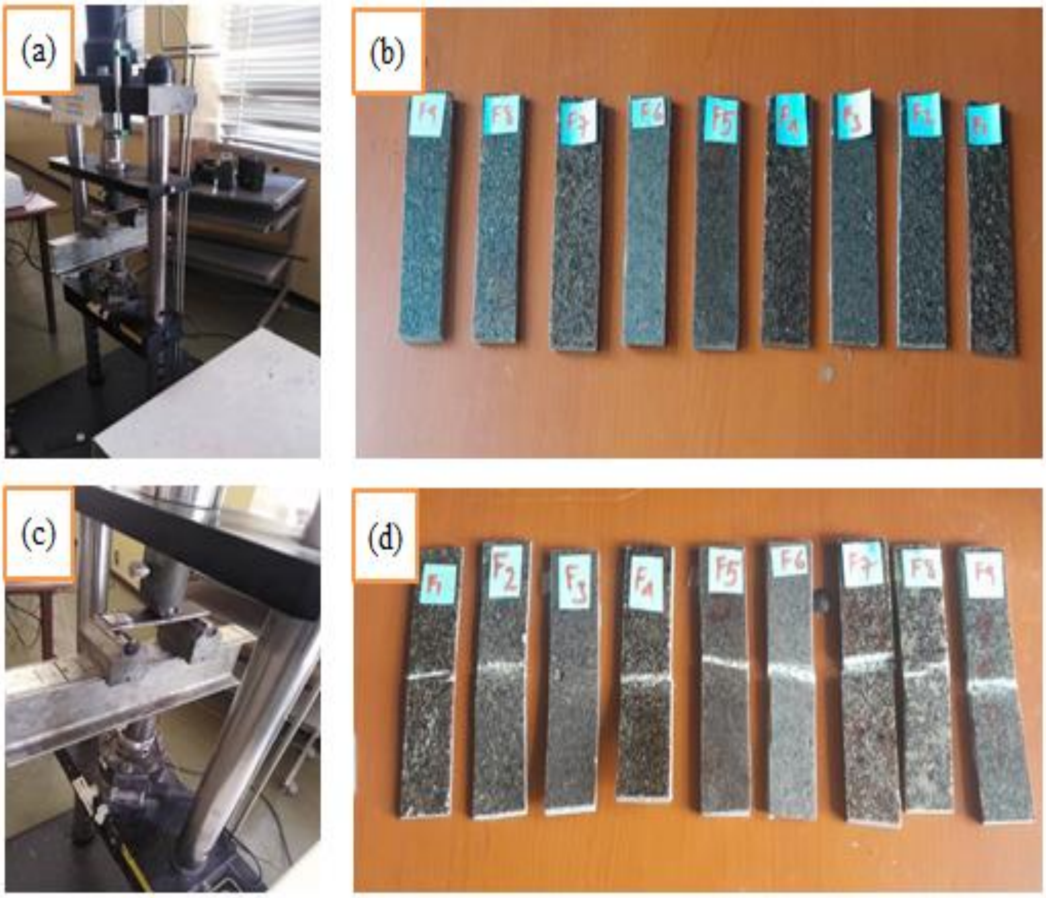


Figure 3.19 Flexural strength testing: (a) Universal testing machine (b) Specimen before test (c) Adjusted specimen (d) Specimen after testing

3.4.3 Impact strength testing

The main goal of an impact test is to determine whether a material can resist deformation when subjected to a sudden force or shock load. This type of test assesses how materials behave under rapid loading conditions. One commonly used method is the Charpy impact test, which evaluates the amount of energy a material absorbs during fracture. In this test, a notched specimen is struck on the side by a swinging pendulum hammer. The energy absorbed during the break is an indicator of the material's toughness.

Charpy impact testing was conducted following ASTM D 6110 standards on specimens sized 55 × 12.7 × 3.5 mm and featured a 45° notch with 2.5 mm depth on the specimen's surface; tests were carried out at Engineering College of Defense University, located in Bishoftu, Ethiopia.

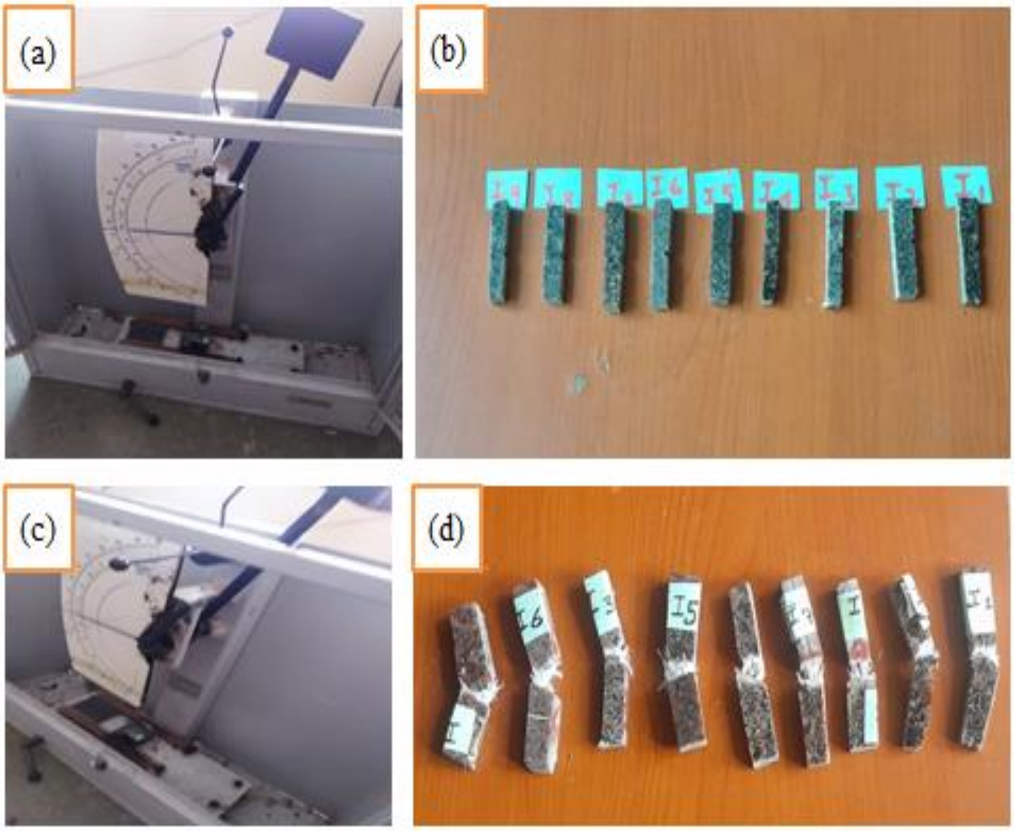


Figure 3.20 Impact testing (a) Impact testing machine (b) Specimen before test (c) adjusted specimen (d) Specimen after test

3.4.4 Vickers hardness testing

Vickers hardness testing is a method of material hardness testing, which uses a diamond pyramid indenter. The indenter, during the test, is applied to the material's surface under a particular load for a certain time. The diagonals of the indentation that remains on the surface after the load has been removed are measured to get the hardness value. Hardness testing by Vickers basically tests resistance to deformation and wear, and materials are normally tested for numerous industrial applications. The hardness determined by the above method can help the engineer and manufacturer assess whether or not a material will serve in an application, anticipate performance under stress, and guarantee quality in production.

Specimens for hardness using a Vickers hardness tester (HVS-50) were prepared as per ASTM E-384 standards with dimensions of 20 × 20 × 5 mm and tested under a 10 kg load with 10-second dwell time.

Figure 3.21 Hardness testing: (a) Specimens for hardness testing (b) Vickers hardness machine (c) Adjusted specimen

3.4.5 SEM analysis

Using SEM equipment, the morphology of the composite was examined. Based on the performance of their mechanical properties, four samples were chosen for morphological study. The test was carried out at Haramaya University, College of Engineering, located in Haramaya, Ethiopia.

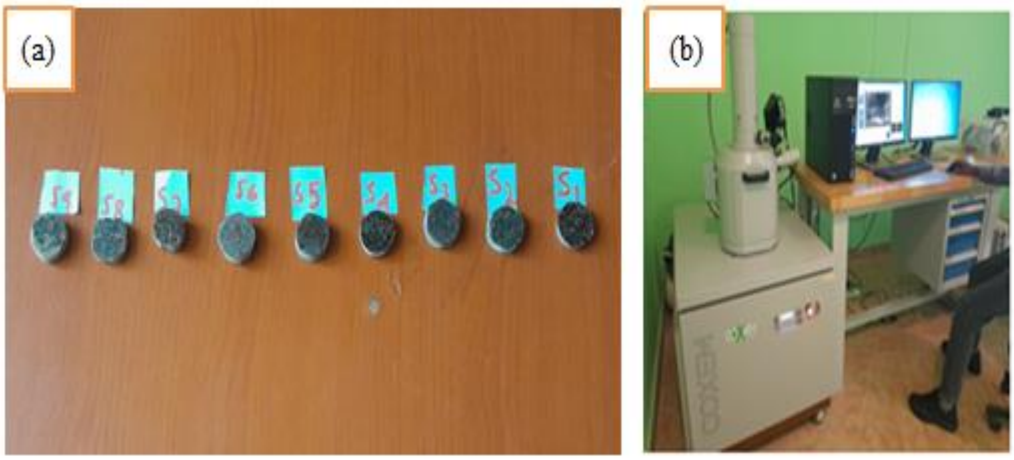


Figure 3.22 SEM analysis: (a) Specimen for SEM analysis (b) Adjusted specimen under SEM

3.4.7 Physical Characterization

3.4.7.1 Water absorption testing

Water absorption testing is the practice of evaluating a composite material's ability to absorb water under particular circumstances. This test helps to evaluate the durability and performance of the composite in humid or wet environments.

Water absorption tests on polyester resin reinforced with E-glass, aluminum oxide, and coffee husk were conducted as per ASTM D570, using 30 × 28 × 4 mm specimen dimensions and it is immersed in distilled water at room temperature and weighed at 24 hour intervals up to 168 hours (for seven days) to measure absorption by mass difference. Using the following formula, the specimens' percentage weight gain is calculated at various time points.

$$\text{Water absorption (\%)} = \frac{W2-W1}{W1}\ x\ 100 \tag{3.19}$$

Where, W1 and W2 represent the dry and wet specimens' respective weights.

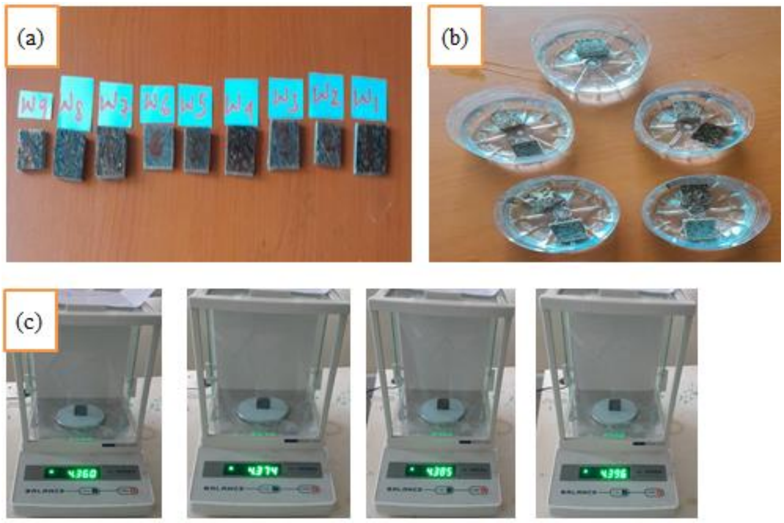


Figure 3.23 Water absorption test (a) Specimens (b) Specimen in water (c) measured specimens within 24hrs difference

3.4.7.2 Density and porosity

Porosity and density are basic characteristics that have a significant impact on the functionality and use of composite materials. Density is extremely crucial in determining the mechanical strength, weight, and stiffness of the composite. Materials with high density are likely to possess higher strength and toughness, hence being most appropriate for applications demanding high performance in automotive, and construction industries. Conversely, low-density composites are used for light applications where weight savings are essential. The density of composite materials can be determined using the density gradient technique, sink-float method, or Archimedes method; in this study, the Archimedes method was applied to measure actual density (ρa) based on ASTM D792-13, using specimens with dimensions of 30 × 25 × 4 mm. This principle (Archimedes principle) states that the apparent weight loss of an item submerged in a liquid is equal to the up push and the weight of the liquid ejected (Cavazzini, 2019). The actual and theoretical density of the fabricated composite material can be calculated as below formula (Venkatesh et al., 2023).

$$\rho a = \frac{\rho w \, Wa}{Wa - Ww} \tag{3.20}$$

Where, ρa = actual density or experimental density, ρw = density of water, Wa = composite weight in air and Ww = composite weight in water

$$\rho t = \frac{1}{\frac{Wr}{\rho r} + \frac{Wm}{\rho m} + \frac{Wf}{\rho f}} \tag{3.21}$$

Where, ρt = theoretical density, Wr = weight fraction of reinforcement, Wm = weight fraction of matrix and Wf = Weight fraction of filler.

Porosity refers to the presence of voids or pores in material. It is one of the considerations that determine mechanical qualities of composites. High porosity would induce weak mechanical strength as well as be prone to environment degradation, while low porosity is associated in general with desirable performance qualities. Porosity level may be controlled by the production process, such as the reinforcement and matrix type, as well as curing conditions. Control and understanding of porosity is crucial to optimizing the performance of composite materials. Using the following formula, the volume fraction of porosity (Vp) in the composites is determined (Venkatesh et al., 2023) .

$$Vp = \frac{\rho t - \rho a}{\rho t} \tag{3.22}$$

Where, ρt represents the composite's theoretical density and ρa its experimental density.

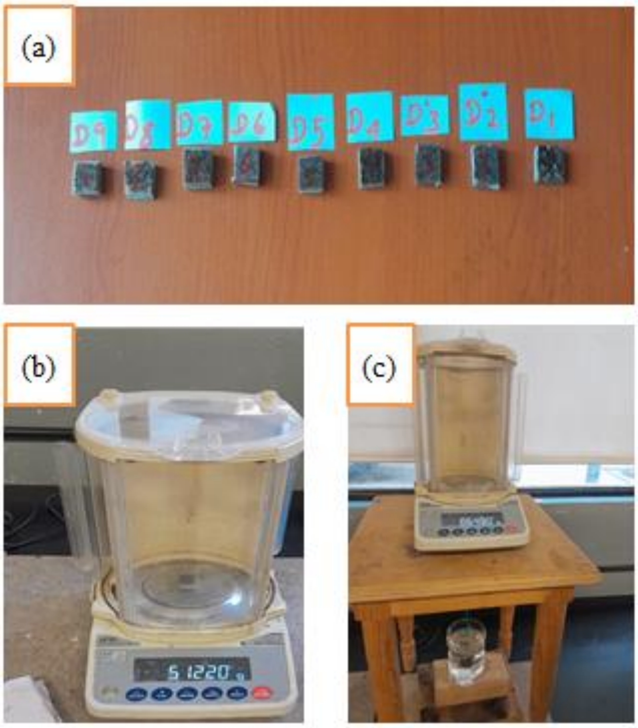


Figure 3.24 Density and porosity test: (a) Specimens for density and porosity test (b) Measured specimen in air (c) Measured specimen in water

3.5 Research methodology

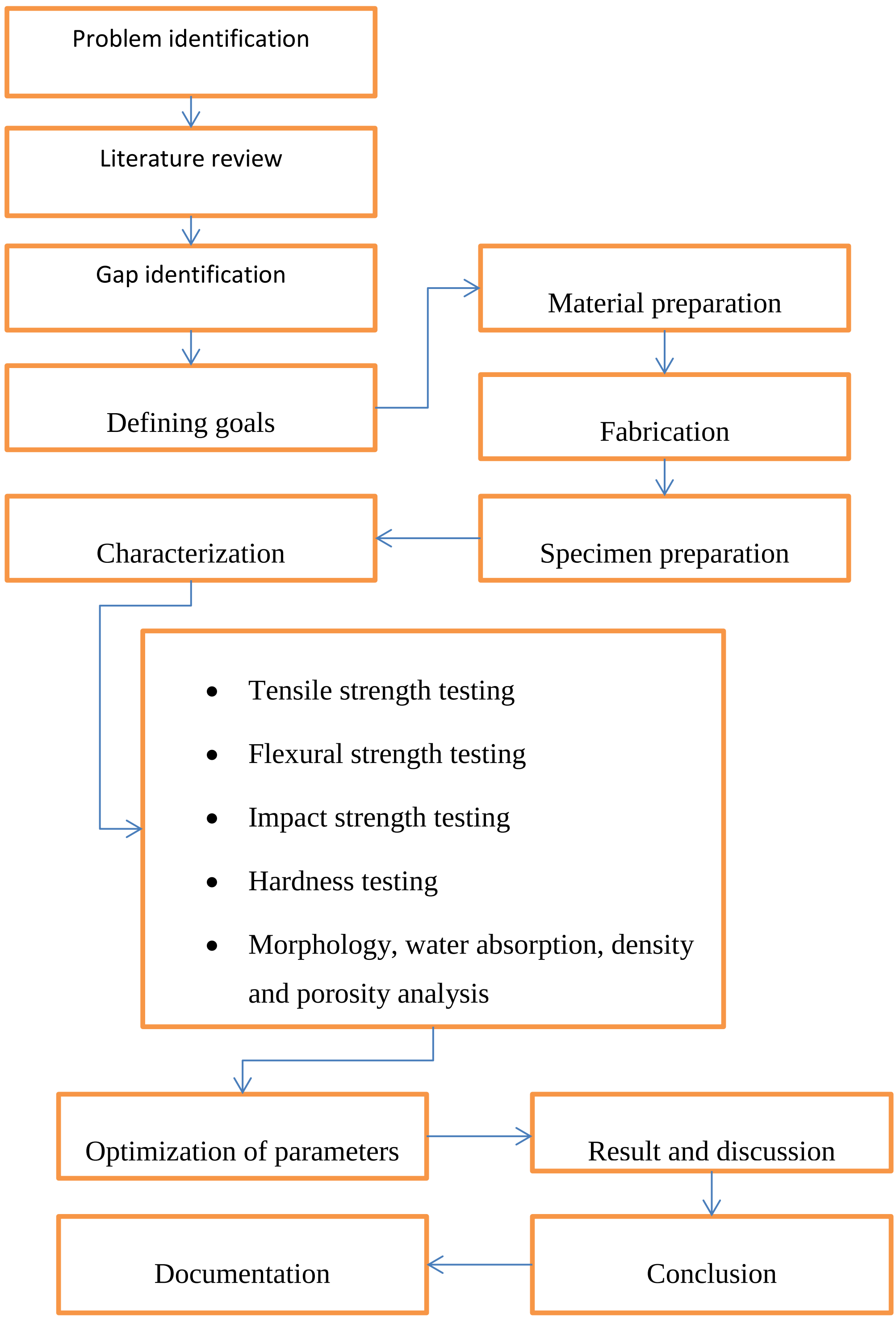


Figure 3.25 Research methodology

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Introduction

All test results from the experimental work have been thoroughly examined in this chapter. Tensile, impact, Vickers hardness, flexural, absorption of water, density, porosity, and morphological (SEM) analysis on polyester resin reinforced with E-glass, aluminum oxide, and coffee husk are the tests conducted in this chapter. Polyester resin matrix reinforced with E-glass, aluminum oxide, and coffee husk, was analyzed using the Taguchi method. Lastly, the importance of the data was assessed by comparing the results to the relevant literature.

4.2 Results of the Tested Composite

4.2.1 Analysis of tensile strength

The experimentally determined tensile strength of polyester resin reinforced with E-glass, aluminum oxide, and coffee husk was found to be as follows.

Table 4.1 Results of experiments on composite tensile strength testing

Samples	E-glass (wt. %)	Aluminum oxide (wt. %)	Coffee husk (wt. %)	Tensile strength (MPa)
S.1	15	0	10	52.14
S.2	15	2.5	15	53.06
S.3	15	5	20	69.24
S.4	20	0	15	52.9
S.5	20	2.5	20	101.1
S.6	20	5	10	75.01
S.7	25	0	20	67.3
S.8	25	2.5	10	89.84
S.9	25	5	15	82.8

Table 4.1 above shows the experimental data for the tensile strength of nine samples. In this table the fifth sample exhibited the maximum tensile strength, 101.1Mpa. This was fabricated by combining 20 weights percent of E-glass, 2.5 weight percent of aluminum oxide and 20 weight percent of coffee husk. Because the weight percentage of the components utilized varied, the composite samples' strengths varied as well. Minimum strength was achieved for sample one (52.14MPa) since there was no aluminum oxide added to the polyester resin and amount of E-glass fiber was minimum. This sample was fabricated using 15 wt. % of E-glass, 0wt. % of aluminum oxide and 10 wt. % of coffee husk.

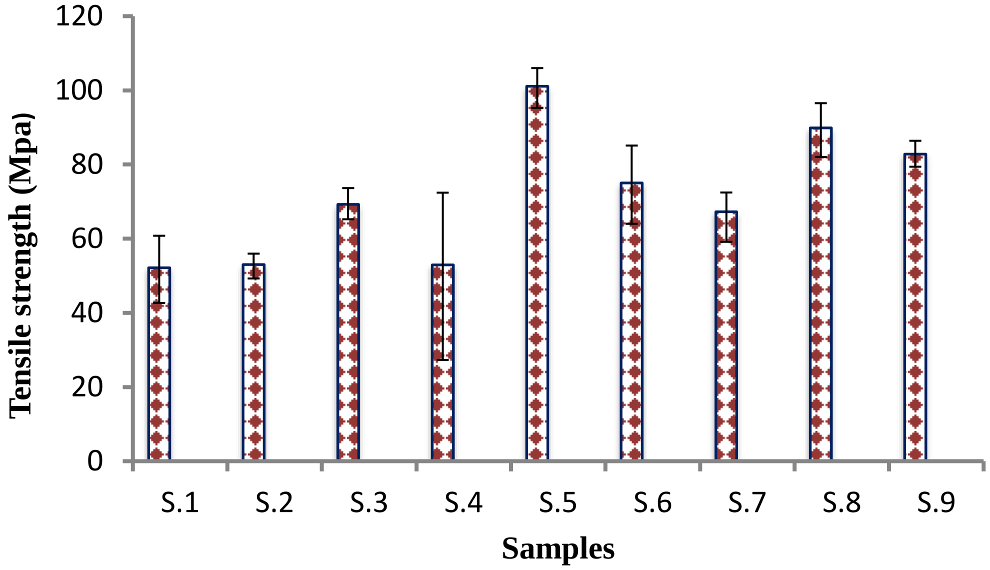


Figure 4.1 Experimental outcomes on tensile strength

Referring to the above Figure 4.1, the experimental outcomes on tensile strength show significant variations among the nine samples of E-glass, aluminum oxide, and coffee husk-reinforced polyester resin. The results show that adding E-glass tends to increase the tensile strength, resulting in a strong composite material. Praveena, Santhosh, Archana, et al., (2022) investigated that E-glass increases the tensile strength of composite based on polymer matrix. The tensile strength was found to be improved by using aluminum oxide up to 2.5% and coffee husk up to 20% in addition to E-glass fiber, indicating that the aforementioned filler component is essential for strengthening the polyester matrix.

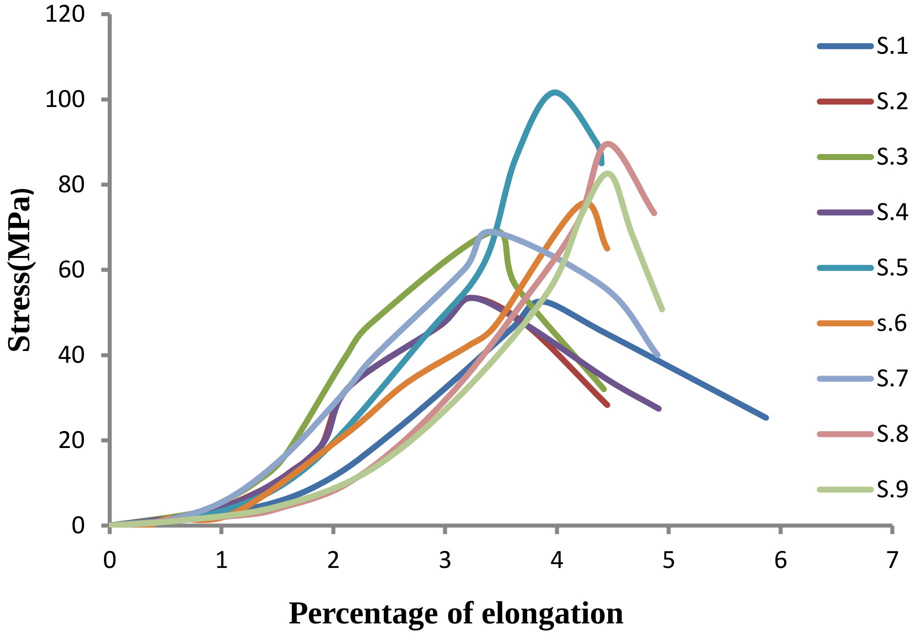


Figure 4.2 Stress – elongation diagram outcomes on tensile strength

Figure 4.2 illustrates the stress- elongation behavior of the nine samples made of polyester resin composites reinforced with E-glass, aluminum oxide, and coffee husk. The graph reflects how each of the reinforcement components affects the tensile strength and ductility of the composite materials. The findings through the stress- elongation tests display appreciable fluctuations in tensile strength and ductility among varied samples. The sample with the highest tensile strength exhibits the least amount of elongation in comparison to the others. The measured elongation of sample 1 and 5 was the highest and lowest, respectively.

Taguchi analysis for tensile strength using S/N ratios

Table 4.2 Tensile strength response data based on S/N ratios

Level	E-glass	Aluminum oxide	Coffee husk
1	35.22	35.12	36.97
2	37.36	37.89	35.78
3	38.00	37.56	37.82
Delta	2.78	2.76	2.05

Rank	1	2	3

According to the above mentioned data, with a delta number of 2.78, the glass fiber weight percentage is the primary contributor to the composite's higher tensile strength. Aluminum oxide weight percentage, with a delta value of 2.76, ranks second, while Coffee husk weight percentage, with a delta number of 2.05, ranks third as a contributing factor to the composites' higher tensile strength.

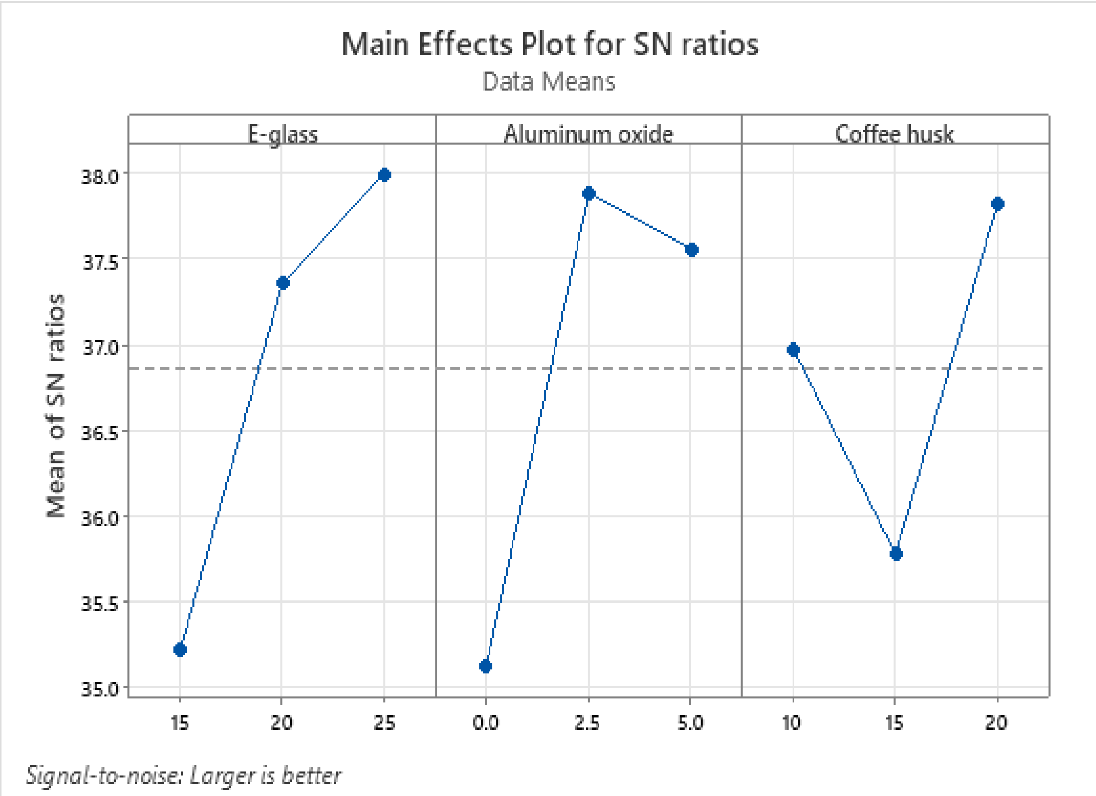


Figure 4.3 Main effects graph of S/N ratio for tensile strength

Main effects graph of S/N ratio for tensile strength above illustrate how different reinforcement materials influence tensile properties of composites made of polyester resin. The plot indicates each factor level's average S/N ratio, enabling us to find out which combination of reinforcement level offers the optimum tensile properties. Notably, tensile strength is maximum at level 3 of E-glass, level 2 of aluminum oxide and level 3 of coffee husk. The composite fabricated from polyester matrix material, glass fiber, and coffee husk can have its tensile strength increased by adjusting the parameters to A3B2C3.

Analysis of variance for the fabricated composite's tensile strength

Table 4.3 analysis of variance output for tensile strength

Source	DF	Adj SS	Adj MS	F-Value	P-Value	
E-glass	2	820.8	410.4	29.44	0.026	41.93
Aluminum oxide	2	735.1	367.55	26.37	0.029	37.55
Coffee husk	2	401.4	200.7	14.4	0.032	20.5
Error	2	27.88	13.94			
Total	8	1985.18				
S = 2.384, R-Sq = 93.43%, R-Sq(adj) = 81.86%						

From the above table 4.3, E-glass fibers contribute 41.93 percent of the total, indicating that its impact on the composite's tensile strength was greater. Aluminum oxide and coffee husk contributes 37.55% and 20.5 of the total, respectively.

4.2.2 Analysis of flexural strength test

Experimental studies revealed the following flexural strength values for polyester resin matrix reinforced with E-glass, aluminum oxide, and coffee husk.

Table 4.4 Results of experiments on the flexural strength testing of composite

Samples	E-glass (wt. %)	Aluminum oxide (wt. %)	Coffee husk (wt. %)	Flexural strength (MPa)
S.1	15	0	10	149.72
S.2	15	2.5	15	208.01
S.3	15	5	20	234.85
S.4	20	0	15	208.655
S.5	20	2.5	20	480.27
S.6	20	5	10	393.07
S.7	25	0	20	282.085
S.8	25	2.5	10	444.24
S.9	25	5	15	453.21

According to the experimental outcomes presented in Table 4.3 above, it can be seen that the presence of E-glass, aluminum oxide, and coffee husk greatly contributes to the flexural strength of the composite made of polyester resin. Out of the nine samples analyzed, Sample 5, which contains 20 weight percent of E-glass, 2.5 weight percent of aluminum oxide, and 20 weight percent of coffee husk, showed a maximum flexural strength of 480.27 MPa. This indicates that sample with high E-glass fiber and aluminum oxide, when blended with 20% of coffee husk in polyester resin, has the ability to synergistically enhance the flexural strength of the composite. The high strength in this specimen can have resulted due to improved load transfer from matrix to reinforcement, good particle dispersion, and also perhaps ideal interfacial bonding.

Sample with no aluminum oxide, low weight percentage of E-glass and coffee husk showed significantly reduced flexural strength. So, sample 1 which had 15% of E-glass, 10% of coffee husk and no aluminum oxide, revealed the lowest flexural strength which was 149.72MPa.

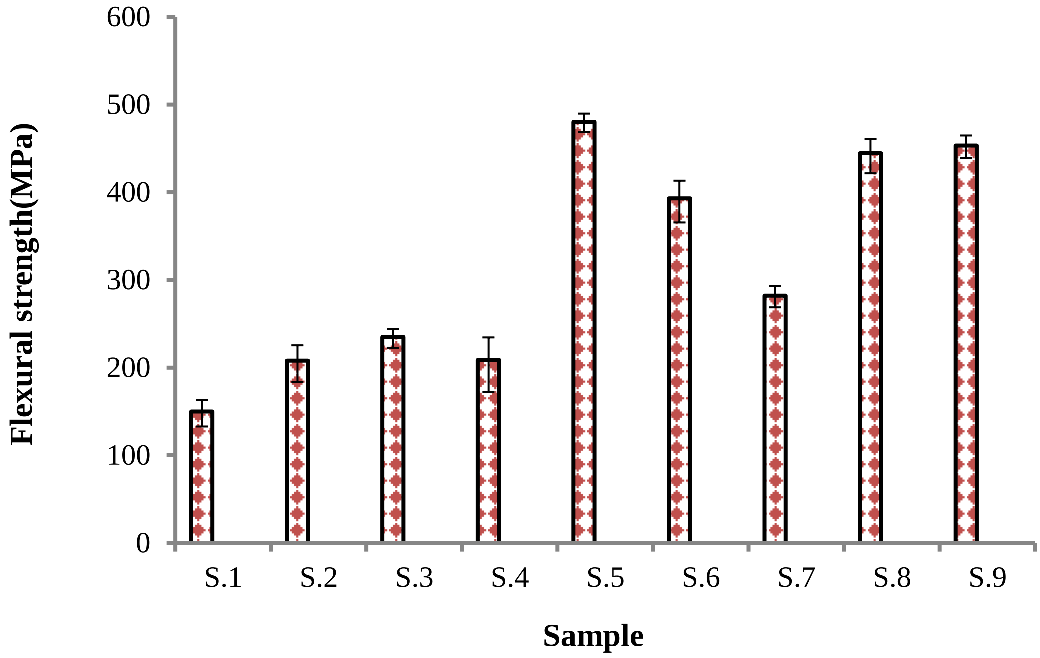


Figure 4.4 Experimental outcomes on flexural strength

From the above Figure 4.4, flexural strength test demonstrates varying performance in nine samples of polyester resin matrix reinforced with E-glass, aluminum oxide, and coffee husk. The result indicates that reinforcement of E-glass, aluminum oxide and coffee husk greatly enhances flexural strength. The samples with high E-glass content had better flexural strength, which indicates that, the structural property of the fiber play significant role in its ability to bear loads. As reported by Hatti et al., (2022); Morampudi et al., (2021), adding E-glass leads to an improvement in flexural strength. The results also indicate the impact of coffee husk and aluminum oxide on flexural strength of the composite material. An overall improvement was observed in the reinforcement by aluminum oxide and coffee husk. Farhan & Hussein, 2020; R. Kumar et al., (2023) revealed that, adding aluminum oxide filler improves composite's flexural strength.

Taguchi analysis for flexural strength using S/N ratios

Table 4.5 Flexural strength response data based on S/N ratios

Level	E-glass	Aluminum oxide	Coffee husk
1	45.76	46.30	49.45
2	50.64	50.98	48.20
3	51.27	50.39	50.02
Delta	5.51	4.68	1.82
Rank	1	2	3

Based on the data provided above, with a delta number of 5.51, E-glass fiber's contributes high impact to the composite's increased flexural strength. Aluminum oxide (with a delta value of 4.68) and coffee husk (with a delta number of 1.82) rank second and third, respectively, in terms of factors that contribute to the composites' increased flexural strength.

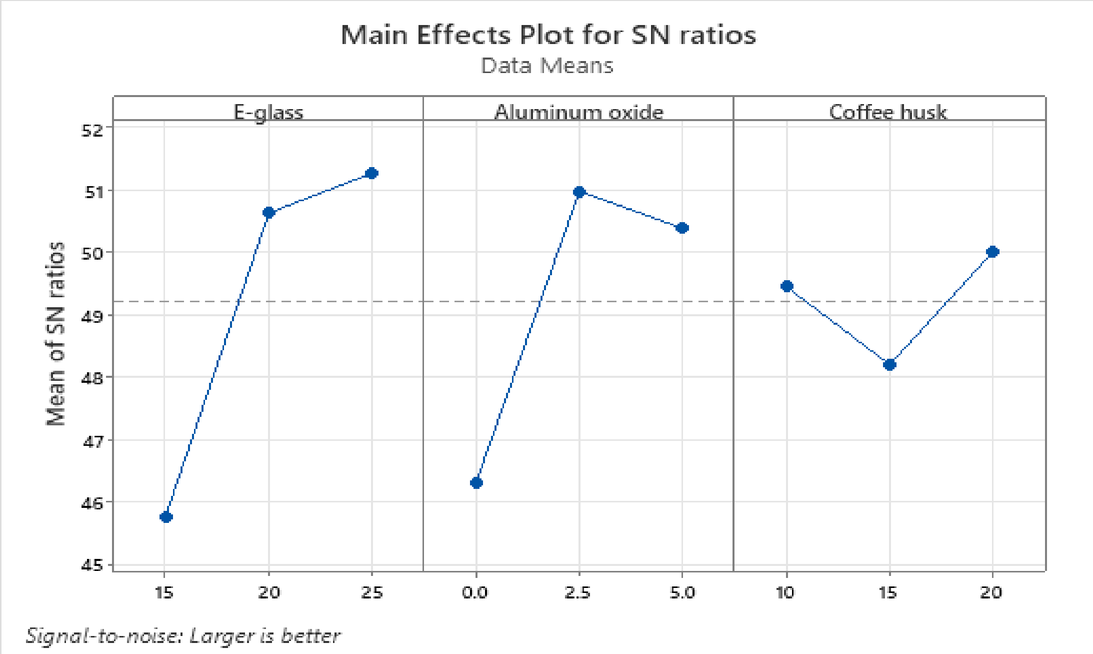


Figure 4.5 Main effects graph of S/N ratio for flexural strength

The above Figure 4.5 illustrates the level at which different reinforcement materials coffee husk, E glass, and aluminum oxide affects the composites' flexural strength. Every line on the graph illustrates how one type of reinforcement affects the S/N ratio, displaying the variations of composition on flexural strength performance. The trends displayed reveal the extent to which specific reinforcements greatly increase flexural strength over others. So, the flexural strength of hybrid composite made from samples of E-glass fiber, coffee husk, and polyester matrix material can be raised by adjusting the parameters to A3B2C3.

Analysis of variance for the fabricated composite's flexural strength

Table 4.6 analysis of variance output for flexural strength

Source	**DF**	**Adj SS**	**Adj MS**	**F-Value**	**P-Value**	**Contribution (%)**
E-glass	2	6595.1	3297.55	75.8	0.013	53.6
Aluminum oxide	2	4877.3	2438.65	56.01	0.016	39.64
Coffee husk	2	833.8	416.9	9.6	0.037	6.77

Error	2	86.93	43.465
Total	8	12393.13	
S = 4.384, R-Sq = 97.43%, R-Sq(adj) = 91.86%			

From the above table 4.6, E-glass fibers contribute 53.6 percent of the total, indicating that its impact on the composite's tensile strength was greater. Aluminum oxide and coffee husk contributes 39.64% and 6.77% of the total, respectively.

4.2.3 Analysis of impact test

Experimental studies revealed that a polyester resin reinforced with coffee husk, aluminum oxide, and E-glass has the following Impact strength result.

Table 4.7 Results of experiments on impact strength testing composites

Samples	E-glass (wt. %)	Aluminum oxide (wt. %)	Coffee husk (wt. %)	Impact strength (J)
S.1	15	0	10	25.4
S.2	15	2.5	15	31.385
S.3	15	5	20	30.885
S.4	20	0	15	28.01
S.5	20	2.5	20	33.9
S.6	20	5	10	32.4
S.7	25	0	20	29.3
S.8	25	2.5	10	34.13
S.9	25	5	15	32.8

The above Table 4.7 displays the impact strength results for nine samples. The eighth sample in the table above showed the maximum impact strength, 34.13J. This was fabricated by combining 25 weights percent of E-glass fiber, 2.5 weight percent of aluminum oxide and 10 weight percent of coffee husk. The impact strengths of the fabricated samples varied because of the weight proportion of the components used was varying. Due to the absence of aluminum oxide in the polyester resin and the little amount of E-glass fiber, sample one had the lowest impact strength (25.4J)

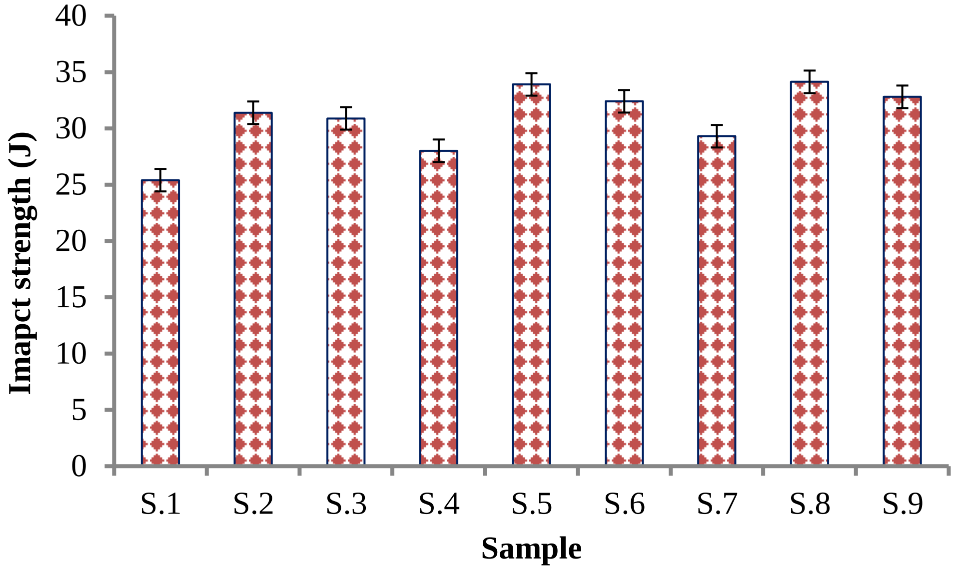


Figure 4.6 Experimental outcomes on impact strength

From the above Figure 4.6, there is a notable variation in impact strength between the various compositions; the data indicates that specific combinations of reinforcing materials considerably improve the polyester matrix's ability to withstand impacts. This reveals that the kind and percentage of reinforcements play a significant role in the composite materials' mechanical performance. The maximum weight percentage of E glass and medium weight percentage of aluminum oxide reinforced sample exhibited the optimum impact strength, which implies that this material possesses superior toughness and energy absorption behavior compared to the other reinforcements employed.

Taguchi analysis for impact strength using S/N ratios

Table 4.8 Impact strength response data based on S/N ratios

Level	E-glass	Aluminum oxide	Coffee husk
1	29.28	28.79	29.66
2	29.92	30.40	29.73
3	30.11	30.11	29.91
Delta	0.833	1.61	0.26
Rank	2	1	3

Aluminum oxide contributes the most to the composite's increased impact strength, with a delta number of 1.61, according to the data above. E-glass and coffee husk, with a delta value of 0.833 and 0.26 are the second and third ranking factors, respectively, that support the composites' enhanced impact strength.

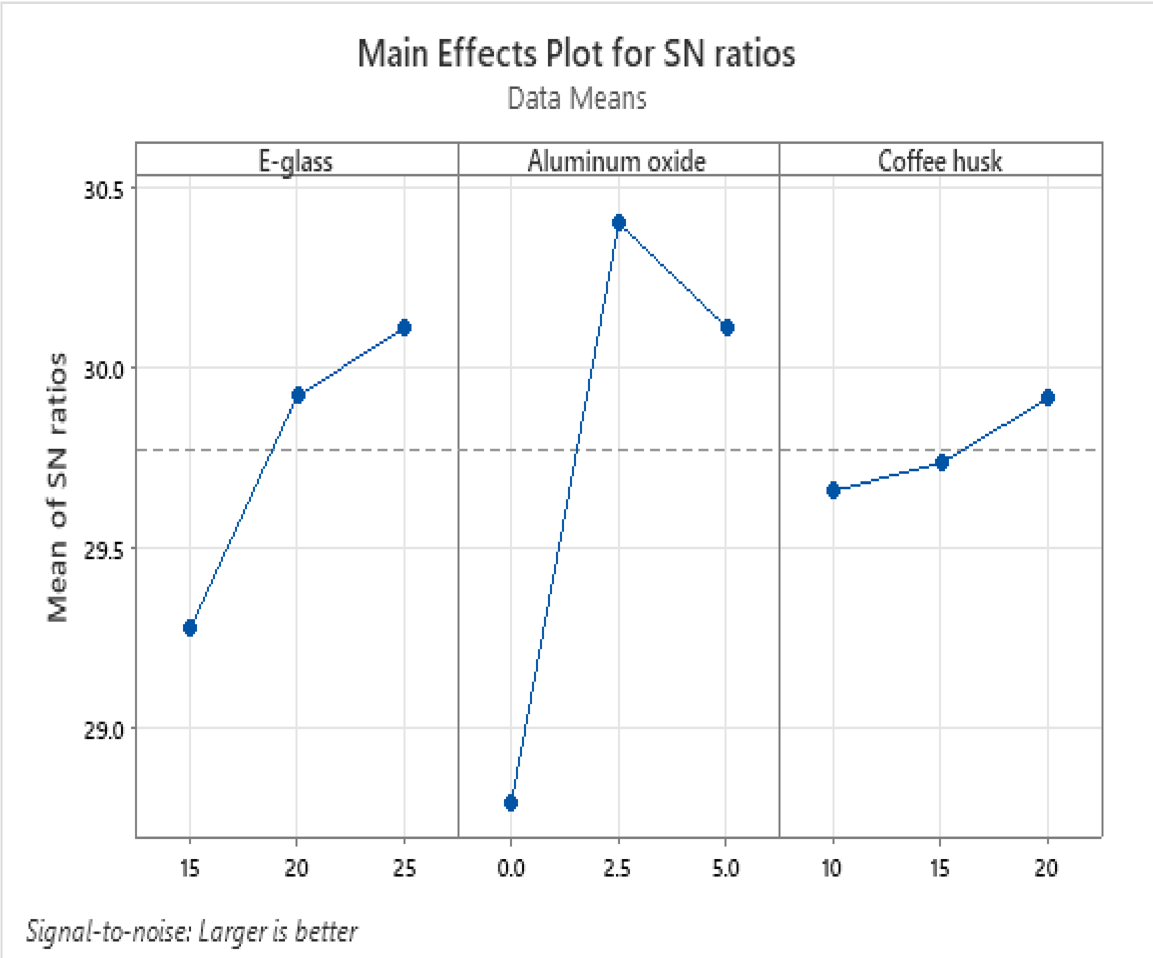


Figure 4.7 Main effects graph of S/N ratio for impact strength

The above graph (Figure 4.6) demonstrates the level of influence for the E glass, aluminum oxide, and coffee husk reinforced polyester resin matrix. Every graph line represents the effect of individual reinforcement on the impact strength, and the performance can be easily observed through a visual comparison. From the graph, one can observe that the type and proportion of reinforcement significantly affect the impact strength. So, according to the graph impact strength can be raised by adjusting the parameters to A3B2C3.

Analysis of variance for the fabricated composite's Impact strength

Table 4.9 Analysis of variance output for Impact strength

Source	**DF**	**Adj SS**	**Adj MS**	**F-Value**	**P-Value**	**Contribution (%)**
E-glass	2	13.45	6.725	66.17	0.015	38.41
Aluminum oxide	2	17.54	8.77	86.31	0.011	50.1
Coffee husk	2	4.027	2.014	19.82	0.031	11.5
Error	2	0.2033	0.1016			
Total	8	12393.13				
S = 0.3188, R-Sq = 98.7%, R-Sq(adj) = 96.78%						

Aluminum oxide contributes the most to the composite's increased impact strength, with 50.1% of contribution, according to the data above. E-glass and coffee husk, 38.41% and 11.5% of contribution are the second and third ranking factors, respectively.

4.2.4 Vickers hardness test

Experimental studies of Vickers hardness test revealed that a polyester resin reinforced with coffee husk, aluminum oxide, and E-glass has the following hardness result.

Table 4.10 Results of experiments on Vickers hardness testing composites

Samples	E-glass (wt. %)	Aluminum oxide (wt. %)	Coffee husk (wt. %)	Vickers hardness (HV)
S.1	15	0	10	66.2
S.2	15	2.5	15	74.85
S.3	15	5	20	77
S.4	20	0	15	70.25
S.5	20	2.5	20	144.5
S.6	20	5	10	81.55
S.7	25	0	20	73.6
S.8	25	2.5	10	81.1

S.9	25	5	15	91.65

The above table shows the results of Vickers hardness testing; it confirms that incorporating aluminum oxide and coffee husk in to polyester resin significantly improves the composites hardness. Samples contains higher percentage of E-glass, aluminium oxide and coffee husk such as sample 5 (20% of E-glass, 2.5% of aluminum oxide, and 20% of coffee husk) and sample 9 (25% of E-glass, 5% of aluminum oxide and 15% of coffee husk) yielded extremely high values of hardness: 144.5HV and 91.65HV, respectively.

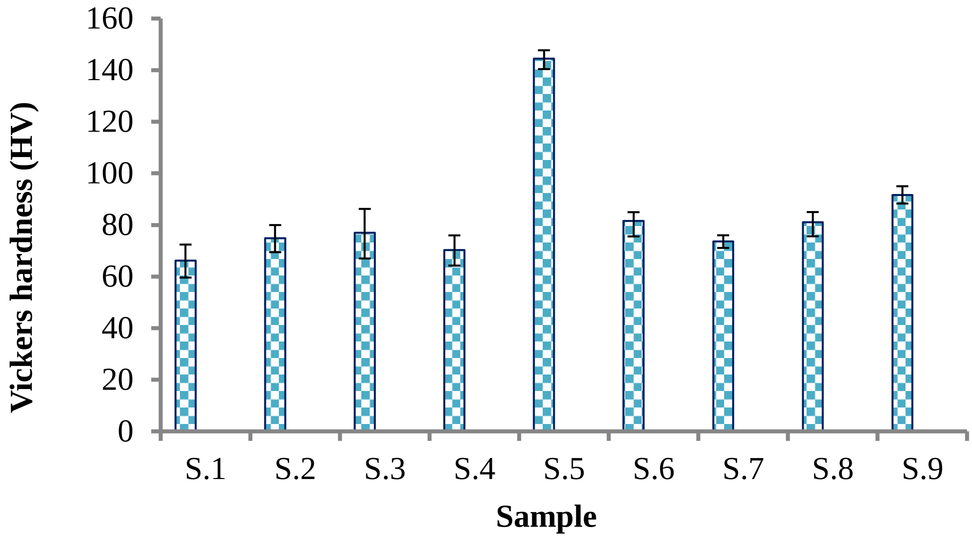


Figure 4.8 Experimental outcomes on Vickers hardness

The above outcomes indicate that there is high variation between the nine samples prepared by using polyester resin reinforced with E-glass, aluminum oxide, and coffee husk. This variation was occurred due to different weight percentage of reinforcements were mixed in each samples. Among all samples, samples that consists high amount of coffee husk and better aluminum oxide had revealed greatest hardness value. Sample 5 has the highest hardness value (144.5HB) of any sample. This sample was made with 20 weight percent of E-glass, 2.5 weight percent of aluminum oxide and 20 weight percent of coffee husk. Sample one, which was made from 15 weight percent of E-glass, 10 weight percent of coffee husk, and no aluminum oxide had the lowest strength (58.3 HV) this was due to minimum weight percent of coffee husk and no aluminum oxide in polyester matrix. The addition of aluminum oxide to a polyester resin based composite results in increased hardness and better Vickers hardness values. The same results were reported by (Farhan & Hussein, 2020; Rawat et al., 2019).

Taguchi analysis for Vickers hardness test using S/N ratios

Table 4.11 Vickers hardness response data based on S/N ratios

Level	E-glass	Aluminum oxide	Coffee husk
1	37.46	36.78	37.83
2	38.21	38.38	37.74
3	38.24	38.75	38.34
Delta	0.78	1.98	0.6
Rank	2	1	3

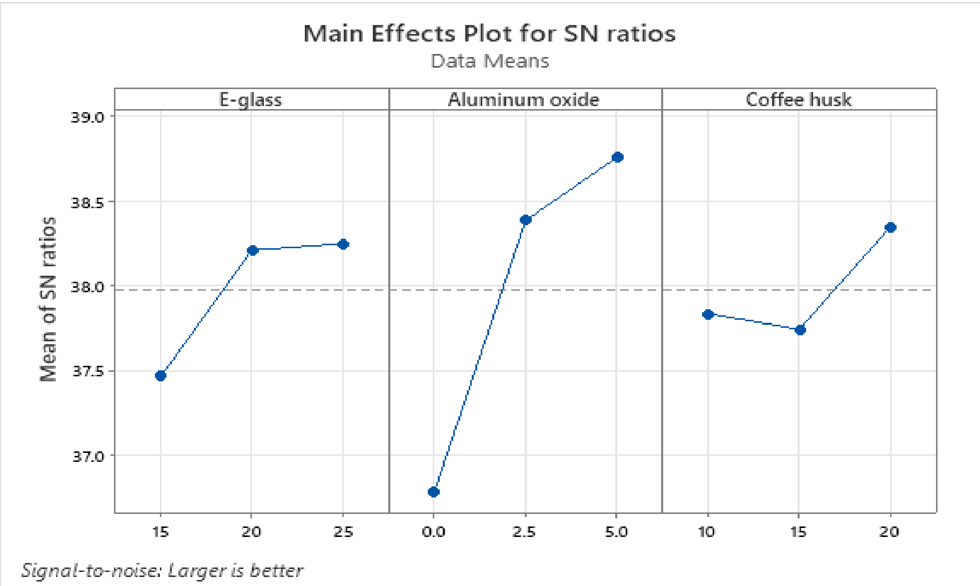


Figure 4.9 Main effects graph of S/N ratio for Vickers hardness

The above outcome provides the influence of each reinforcing material on the performance and hardness of the fabricated composite. Based on the above plot it was found that the aluminum oxide content, which ranks first at level 3 (5wt. %), E-glass content, which ranks second at level 3 (25wt. %), and coffee husk content, which ranks third at level 3 (20wt. %), are the most effective process factors for hardness. Based on the above figure, hardness value can be raised by adjusting the parameters to A3B3C3 with the combination of process parameters A3B3C3.

Analysis of variance for the fabricated composite's flexural strength

Table 4.12 Analysis of variance output for flexural strength

Source	DF	Adj SS	Adj MS	F-Value	P-Value	Contribution (%)
E-glass	2	446.8	223.4	41.14	0.022	42.5
Aluminum oxide	2	486.43	243.215	44.79	0.021	46.27
Coffee husk	2	118	59	10.86	0.034	11.22
Error	2	10.86	5.43			
Total	8	1062.09				
S = 1.84, R-Sq = 96.28%, R-Sq(adj) = 94.36%						

From the above table 4.6**,** aluminum oxide contributes 46.27 percent of the total, indicating that its impact on the composite's tensile strength was greater. E-glass fiber and coffee husk contributes 42.5% and 11.22% of the total, respectively.

4.2.5 Water absorption test

One of the major testing techniques for establishing the hydrophilic character of composite materials is the water absorption test. The test establishes the strength and performance of the samples under high moisture content conditions by quantifying the water absorbed by the samples over a specified duration of time. Water absorption can result in weakening of the matrix, loss of mechanical properties, micro cracking at the fiber-matrix interface zone and ultimate degradation of material. The samples prepared were subjected to water absorption for seven days. The daily variations of each sample were noted so that a thorough study of water absorption for seven days is carried out. The results of all such tests are provided in the table below. Performance and durability of the different samples are represented in these numbers, which show the difference in their water absorption rates.

Table 4.13 Results of water absorption test

Sample	Mass	Water absorption time and the outcomes within a specified time frame							
		24hrs	48hrs	72hrs	96hrs	120hrs	144hrs	168hrs	Average
S1	4.36	4.374	4.385	4.396	4.407	4.417	4.427	4.439	
WA (%)		0.321	0.251	0.25	0.252	0.227	0.226	0.271	0.257
S2	4.589	4.607	4.615	4.622	4.634	4.644	4.653	4.663	
WA (%)		0.392	0.174	0.152	0.26	0.216	0.194	0.215	0.229
S3	5.423	5.436	5.447	5.459	5.47	5.482	5.493	5.505	
WA (%)		0.239	0.202	0.22	0.201	0.219	0.206	0.218	0.215
S4	3.53	3.54	3.548	3.555	3.564	3.574	3.582	3.589	
WA (%)		0.283	0.226	0.197	0.253	0.28	0.223	0.195	0.237
S5	3.754	3.762	3.77	3.776	3.783	3.791	3.798	3.805	
WA (%)		0.213	0.212	0.159	0.185	0.211	0.184	0.21	0.17
S6	4.838	4.847	4.855	4.865	4.874	4.882	4.891	4.899	
WA (%)		0.186	0.165	0.206	0.185	0.164	0.184	0.163	0.179
S7	4.582	4.596	4.604	4.611	4.618	4.6305	4.642	4.653	
WA (%)		0.305	0.174	0.152	0.15	0.27	0.248	0.237	0.219
S8	4.667	4.678	4.689	4.696	4.703	4.712	4.722	4.7315	
WA (%)		0.236	0.235	0.15	0.149	0.191	0.212	0.201	0.196
S9	4.745	4.754	4.765	4.772	4.78	4.788	4.795	4.805	
WA (%)		0.19	0.231	0.147	0.168	0.167	0.146	0.208	0.18

The above table indicates the water absorption percentage for each sample at different time points, ranging from 24 hours to 168 hours (for seven days). Each sample has a different average water absorption percentage. This variation implies that the amount of reinforcement used for mixture is significantly influences the hydrophilic properties of the composites.

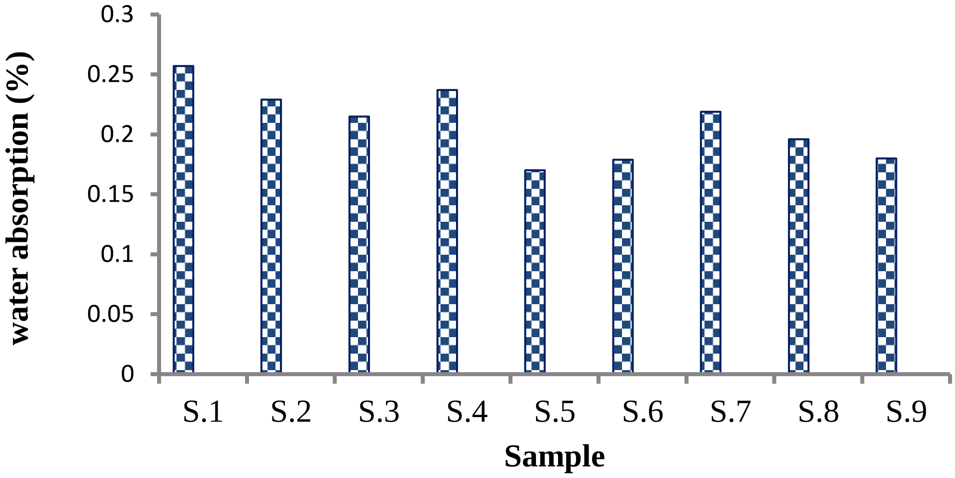


Figure 4.10 Experimental outcomes on water absorption

The above figure shows the results of water absorptions tests conducted on nine samples of polyester resin matrix reinforced with E-glass, aluminum oxide and coffee husks. Based on these finding, sample 5 and 6 has minimum amount of water absorption. This indicates that the reinforcement and matrix had the finest possible bond; this is due to consist best combination of reinforcements. The material used to fabricate sample 5 was 20% of E-glass fiber, 2.5% of aluminum oxide and 20% of coffee husk, for sample 6, 20% of E-glass, 5% aluminum oxide, and 10% of coffee husk. Among all samples, sample 1 has large amount of water absorption. This indicates that the reinforcement and matrix had the weakest possible bond; this is due to consist small amount of E-glass, coffee husk, and no aluminum oxide. This sample was fabricated by combining 15% of E-glass, 0% of aluminum oxide and 10% percent of coffee husk.

4.2.6 Analysis of density and porosity

Measuring density is crucial for describing the composites' material characteristics. To calculate the nine samples actual densities, the Archimedes method was utilized. The samples' theoretical density was determined using the densities of each component and the corresponding weight fraction. Actual density was calculated by using Archimedes principle based on the below shown figures.

Porosity is also an important parameter for the assessment of composite material performance. Porosity of each sample was assumed through a comparison between actual and theoretical densities. Increased difference between the two densities indicated higher porosity, which can potentially reducing the strength and longevity of the composite. The test provided critical information concerning the effect of incorporating E-glass, aluminum oxide, and coffee husk on the structural strength and potential applications of the polyester resin composites.

Sample-1 **Sample-2** **Sample-3** **Sample-4** **Sample-5**

Figure 4.11 Mass of samples in air

Sample-1 **Sample 2** **Sample 3**

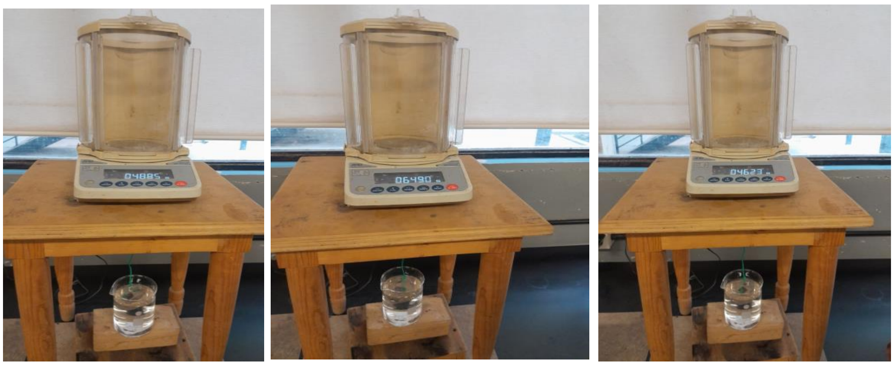


Figure 4.12 Mass of samples in water

Sample-1

Theoretical density

Based on Eqn. 3.21,

$$\text{Pt} = \frac{1}{\frac{Wr}{\rho r}+\frac{Wm}{\rho m}+\frac{Wf}{\rho f}} = \frac{1}{\frac{W\,g}{\rho g}+\frac{W Al2O3}{\rho Al2O3}+\frac{wch}{\rho ch}+\frac{Wp}{\rho g}}$$

$$= \frac{1}{\frac{0.15}{2.55}+\frac{0}{3.98}+\frac{0.1}{0.6}+\frac{0.75}{1.2}} = 1.176\,\frac{g}{\mathrm{cm3}}$$

Based on Eqn. 3.20,

Actual density

$$\rho a = \frac{\rho w\ Wa}{Wa-Ww} = \rho a = \frac{\rho w\ Ws1a}{Ws1a-Ws1w}$$

$$= \frac{1\frac{g}{\mathrm{cm3}}\ \mathrm{x}\ 4.412\mathrm{g}}{4.412\mathrm{g}-0.4885} = 1.1245\frac{g}{\mathrm{cm3}}$$

Based on Eqn. 3.22,

Weight percentage of Porosity

$$\mathrm{Vw} = \frac{\rho t - \rho a}{\rho t} =$$

$$= \frac{1.176 - 1.1245}{1.176} = 4.38\%$$

Sample 2

Theoretical density

$$\rho t = \frac{1}{\frac{Wr}{\rho r}+\frac{Wm}{\rho m}+\frac{Wf}{\rho f}} = \frac{1}{\frac{W\,g}{\rho g}+\frac{WAl2O3}{\rho Al2O3}+\frac{wch}{\rho ch}+\frac{Wp}{\rho g}}$$

$$= \frac{1}{\frac{0.15}{2.55}+\frac{0.025}{3.98}+\frac{0.15}{0.6}+\frac{0.65}{1.2}} = 1.1395\,\frac{g}{\mathrm{cm3}}$$

Actual density

$$\rho a = \frac{\rho w\ Wa}{Wa-Ww} = \rho a = \frac{\rho w\ Ws1a}{Ws1a-Ws1w}$$

$$= \frac{1\frac{g}{\mathrm{cm3}}\ \mathrm{x}\ 5.122\mathrm{g}}{5.122\mathrm{g}-0.5591\mathrm{g}} = 1.1205\,\frac{g}{\mathrm{cm3}}$$

Weight percentage of Porosity

$$Vw = \frac{\rho t - \rho a}{\rho t} x\ 100$$

$$= \frac{1.1395 - 1.1205}{1.1395} x\ 100 = 1.49\%$$

Sample 3

Theoretical density

$$\rho t = \frac{1}{\frac{Wr}{\rho r}+\frac{Wm}{\rho m}+\frac{Wf}{\rho f}} = \frac{1}{\frac{W\,g}{\rho g}+\frac{WAl2O3}{\rho Al2O3}+\frac{wch}{\rho ch}+\frac{Wp}{\rho g}}$$

$$= \frac{1}{\frac{0.15}{2.55}+\frac{0.05}{3.98}+\frac{0.2}{0.6}+\frac{0.6}{1.2}} = 1.105\frac{g}{cm3}$$

Actual density

$$\rho a = \frac{\rho w\ Wa}{Wa - Ww} = \rho a = \frac{\rho w\ Ws1a}{Ws1a - Ws1w}$$

$$= \frac{1\frac{g}{cm3}\ x\ 5.4676g}{5.467g - 0.4623g} = 1.0924\frac{g}{cm3}$$

Weight percentage of Porosity

$$Vw = \frac{\rho t - \rho a}{\rho t} x\ 100$$

$$= \frac{1.105 - 1.0924}{1.105} x\ 100 = 1.4\%$$

Sample 4

Theoretical density

$$\rho t = \frac{1}{\frac{Wr}{\rho r}+\frac{Wm}{\rho m}+\frac{Wf}{\rho f}} = \frac{1}{\frac{W\,g}{\rho g}+\frac{WAl2O3}{\rho Al2O3}+\frac{wch}{\rho ch}+\frac{Wp}{\rho g}}$$

$$= \frac{1}{\frac{0.2}{2.55}+\frac{0}{3.98}+\frac{0.15}{0.6}+\frac{0.65}{1.2}} = 1.149 \ \frac{g}{cm3}$$

Actual density

$$\rho a = \frac{\rho w \ Wa}{Wa - Ww} = \rho a = \frac{\rho w \ Ws1a}{Ws1a - Ws1w}$$

$$= \frac{1\frac{g}{cm3} \ x \ 5.0245g}{5.0245g - 0.5002g} = 1.1106\frac{g}{cm3}$$

Weight percentage of Porosity

$$Vw = \frac{\rho t - \rho a}{\rho t} x \ 100$$

$$= \frac{1.149 - 1.1106}{1.149} x \ 100 = 3.34\%$$

Sample 5

Theoretical density

$$\rho t = \frac{1}{\frac{Wr}{\rho r}+\frac{Wm}{\rho m}+\frac{Wf}{\rho f}} = \frac{1}{\frac{W\,g}{\rho g}+\frac{WAl2O3}{\rho Al2O3}+\frac{wch}{\rho ch}+\frac{Wp}{\rho g}}$$

$$= \frac{1}{\frac{0.2}{2.55}+\frac{0.025}{3.98}+\frac{0.2}{0.6}+\frac{0.575}{1.2}} = 1.12\frac{g}{cm3}$$

Actual density

$$\rho a = \frac{\rho w \ Wa}{Wa - Ww} = \rho a = \frac{\rho w \ Ws1a}{Ws1a - Ws1w}$$

$$= \frac{1\frac{g}{cm3} \ x \ 5.5234g}{5.5234g - 0.5759g} = 1.1164\frac{g}{cm3}$$

Weight percentage of Porosity

Vw = $\frac{\rho t - \rho a}{\rho t} x\ 100$

$= \frac{1.12 - 1.1164}{1.12} x\ 100 = 0.32\%$

Sample 6

Theoretical density

$$\rho t = \frac{1}{\frac{Wr}{\rho r}+\frac{Wm}{\rho m}+\frac{Wf}{\rho f}} = \frac{1}{\frac{W\,g}{\rho g}+\frac{WAl2O3}{\rho Al2O3}+\frac{wch}{\rho ch}+\frac{Wp}{\rho g}}$$

$$= \frac{1}{\frac{0.2}{2.55}+\frac{0.05}{3.98}+\frac{0.1}{0.6}+\frac{0.65}{1.2}} = 1.25\,\frac{g}{cm^3}$$

Actual density

$$\rho a = \frac{\rho w\ Wa}{Wa - Ww} = \rho a = \frac{\rho w\ Ws1a}{Ws1a - Ws1w}$$

$$= \frac{1\frac{g}{cm3}\ x\ 5.1606g}{5.1606g - 0.9937g} = 1.245\frac{g}{cm3}$$

Weight percentage of Porosity

Vw = $\frac{\rho t - \rho a}{\rho t} x\ 100$

$= \frac{1.251 - 1.245}{1.251} x\ 100 = 0.48\%$

Sample 7

Theoretical density

$$\rho t = \frac{1}{\frac{Wr}{\rho r}+\frac{Wm}{\rho m}+\frac{Wf}{\rho f}} = \frac{1}{\frac{W\,g}{\rho g}+\frac{WAl2O3}{\rho Al2O3}+\frac{wch}{\rho ch}+\frac{Wp}{\rho g}}$$

$$= \frac{1}{\frac{0.25}{2.55}+\frac{0}{3.98}+\frac{0.2}{0.6}+\frac{0.55}{1.2}} = 1.123\,\frac{g}{cm^3}$$

Actual density

$$\rho a = \frac{\rho w\ Wa}{Wa-Ww} = \rho a = \frac{\rho w\ Ws1a}{Ws1a-Ws1w}$$

$$= \frac{1\frac{g}{cm3}\ x\ 6.1355g}{6.1355g-0.5501g} = 1.0985\frac{g}{cm3}$$

Weight percentage of Porosity

$$Vw = \frac{\rho t - \rho a}{\rho t} x\ 100$$

$$= \frac{1.1234 - 1.0985}{1.1234} x\ 100 = 2.22\%$$

Sample 8

Theoretical density

$$\rho t = \frac{1}{\frac{Wr}{\rho r}+\frac{Wm}{\rho m}+\frac{Wf}{\rho f}} = \frac{1}{\frac{W\,g}{\rho g}+\frac{WAl2O3}{\rho Al2O3}+\frac{wch}{\rho ch}+\frac{Wp}{\rho g}}$$

$$= \frac{1}{\frac{0.25}{2.55}+\frac{0.025}{3.98}+\frac{01}{0.6}+\frac{0.625}{1.2}} = 1.163\,\frac{g}{cm^3}$$

Actual density

$$\rho a = \frac{\rho w\ Wa}{Wa-Ww} = \rho a = \frac{\rho w\ Ws1a}{Ws1a-Ws1w}$$

$$= \frac{1\frac{g}{cm3}\ x\ 5.449g}{5.449g-0.725g} = 1.153\frac{g}{cm3}$$

Weight percentage of Porosity

$$Vw = \frac{\rho t - \rho a}{\rho t} x\ 100$$

$$= \frac{1.163 - 1.153}{1.163} x\ 100 = 0.86\%$$

Sample 9

Theoretical density

$$\rho t = \frac{1}{\frac{Wr}{\rho r}+\frac{Wm}{\rho m}+\frac{Wf}{\rho f}} = \frac{1}{\frac{W\,g}{\rho g}+\frac{W Al2O3}{\rho Al2O3}+\frac{wch}{\rho ch}+\frac{Wp}{\rho g}}$$

$$= \frac{1}{\frac{0.25}{2.55}+\frac{0.15}{3.98}+\frac{0.1}{0.6}+\frac{0.55}{1.2}} = 1.12 \frac{g}{cm^3}$$

Actual density

$$\rho a = \frac{\rho w\ Wa}{Wa - Ww} = \rho a = \frac{\rho w\ Ws1a}{Ws1a - Ws1w}$$

$$= \frac{1\frac{g}{cm3} x\ 5.5093g}{5.5093g - 0.5591g} = 1.113\frac{g}{cm3}$$

Weight percentage of Porosity

$$Vw = \frac{\rho t - \rho a}{\rho t} x\ 100$$

$$= \frac{1.12 - 1.113}{1.12} x\ 100 = 0.625\%$$

Table 4.14 Weight percentage of porosity for each sample with their composition

Samples	Composition			Experimental results
	E-glass (Wt. %)	Al_2O_3 (Wt. %)	Coffee husk (Wt. %)	Porosity (%)
S1	15	0	10	4.38
S2	15	2.5	15	1.49
S3	15	5	20	1.4

S4	20	0	15	3.34
S5	20	2.5	20	0.32
S6	20	5	10	0.48
S7	25	0	20	2.22
S8	25	2.5	10	0.86
S9	25	5	15	0.625

The above table shows analysis of the porosity of polyester resin matrix reinforced with E-glass, aluminum oxide, and coffee husk involved the fabrication of nine varied samples that varied in composition. It can be observed from the data that the porosity levels differ significantly across the samples, this variance suggests that the weight proportion of reinforcement components has a significant impact on the porosity of the composites.

4.2.7 Structure and morphology analysis using SEM and OM

A SEM testing was performed to determine the microstructure properties of selected polyester resin matrix composites reinforced with E-glass, aluminum oxide, and coffee husk. The distribution and orientation of the reinforcing material in the matrix were investigated to study their interaction and bonding at the microscopic scale, which is required for enhancing mechanical qualities of the composite.

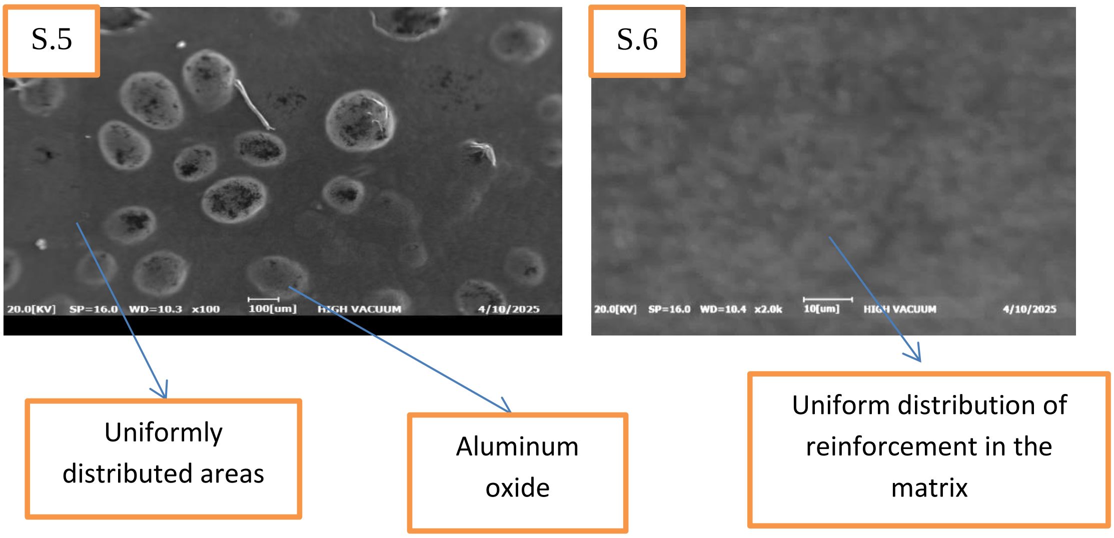
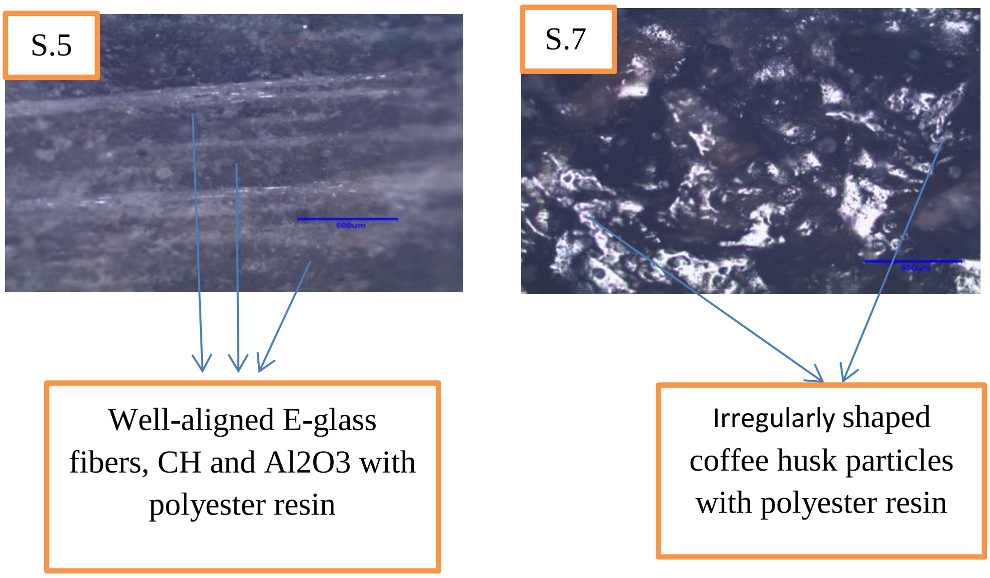


Figure 4.11 SEM image

The SEM images above highlighted the impact of aluminum oxide and coffee husk as the reinforcement. Aluminum oxide possessed spherical morphology, which had better stress distribution over the matrix with lower incidence of stress concentration more prevalent with unreinforced resins. The coffee husk fibers also possessed rough surface topography, which provided higher interfacial bonding with polyester matrix. The greater the bonding is, the greater its impact upon the efficiency of load transfers between the reinforcing and matrix, leading to an overall improvement in the composite's mechanical qualities.



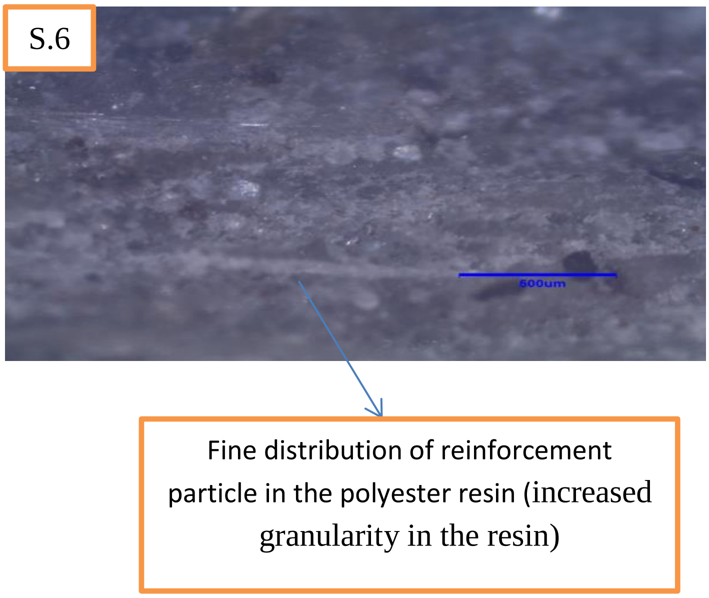


Figure 4.12 Image obtained from Optical Microscope (OP)

The optical microscopic analysis of polyester resin reinforced with E-glass, aluminum oxide, and coffee husk reveals critical structural features essential for understanding the material's mechanical properties. Figure 4.12 (a) shows well-aligned E-glass fibers, crucial for effective load transfer and overall strength, although the presence of voids indicates potential weaknesses where the resin may not bond fully with the fibers. Figure 4.12 (b) highlights irregularly shaped coffee husk particles, demonstrating a heterogeneous distribution that varies in size and shape, potentially creating stress concentration points affecting toughness and durability. Figure 4.12 (c) further illustrates increased granularity in the resin, likely due to interactions between aluminum oxide, E-glass fibers, and coffee husk.

4.3 Grey Relational Analysis of the Outcomes of Mechanical and Physical Tests

Grey relational analysis (GRA) is a powerful decision-making tool used to ascertain the relationship between different experimental conclusions. In this investigation, the mechanical and physical characteristics of nine samples made for this study were carefully analyzed. This is started by computing the signal to noise ratio of each response, which allowed normalizing the data and computing the deviation sequence. Normalization is critical because it transforms the different measurement scales into one common scale, allowing for better comparison of the samples.

Following normalization, the grey relational coefficients that indicate the degree to which the reference and experiment are related was computed. The last step was ranking these coefficients to identify the optimized values for each property. This systematic process not only highlights the best performing samples for all mechanical tests but also indicates how different properties are related to one another. The final outcome of the GRA offers a sound foundation for understanding the material's mechanical performance, with the implications indicating future optimization and development in material science.

Table 4.15 Experimental responses to physical and mechanical testing

Exp. No.	Tensile (MPa)	Flexural (MPa)	Impact (J)	Hardness (HB)	Water absorption	Void content
1	52.14	149.72	25.4	66.2	0.257	4.38
2	53.06	208.01	31.385	74.85	0.229	1.49
3	69.24	234.85	30.885	77	0.215	1.4
4	52.9	208.655	28.01	70.25	0.237	3.34
5	101.1	480.27	33.9	144.5	0.17	0.32
6	75.01	393.07	32.4	81.55	0.179	0.48
7	67.3	282.085	29.3	73.6	0.219	2.22
8	89.84	444.24	34.13	81.1	0.196	0.86
9	82.8	391.48	32.8	91.65	0.18	0.625

Table 4.16 Values of the S/N ratio for each experimental response

Exp. No.	Tensile (MPa)	Flexural (MPa)	Impact (J)	Hardness (HB)	Water absorption	Void content
1	34.3434	43.5056	28.0967	36.4172	11.8013	-12.8295
2	34.4953	46.3617	29.9344	37.4838	12.8033	-3.46373
3	36.8071	47.4158	29.7950	37.7298	13.3512	-2.92256
4	34.4691	46.3886	28.9432	36.9329	12.5050	-10.4749

5	40.0950	53.6297	30.6040	43.1974	15.3910	9.89700
6	37.5024	51.8894	30.2109	38.2285	14.9429	6.37518
7	36.5603	49.0076	29.3374	37.3376	13.1911	-6.92706
8	39.0694	52.9524	30.6627	38.1804	14.1549	1.31003
9	38.3606	51.8542	30.3228	39.2426	14.8945	4.08240

Table 4.17 S/N ratio normalization (Adjusting the S/N ratio to normal)

Exp. No.	Tensile (MPa)	Flexural (MPa)	Impact (J)	Hardness (HB)	Water absorption	Void content
1	0	0	0	0	1	1
2	0.0264	0.2821	0.7162	0.1573	0.7209	0.5879
3	0.4284	0.3862	0.6618	0.1936	0.5682	0.5641
4	0.0219	0.2848	0.3299	0.0761	0.8040	0.8964
5	1	1	0.9771	1	0	0
6	0.5492	0.8281	0.8239	0.2671	0.1248	0.1550
7	0.3854	0.5435	0.4835	0.1357	0.6128	0.7403
8	0.8217	0.9331	1	0.2601	0.3443	0.3778
9	0.6984	0.8246	0.8675	0.4167	0.1383	0.2559

Table 4.18 Deviation sequence analysis

Exp. No.	Tensile (MPa)	Flexural (MPa)	Impact (J)	Hardness (HB)	Water absorption	Void content
1	1	1	1	1	0	0
2	0.9736	0.7179	0.2838	0.8427	0.2791	0.4121
3	0.5716	0.6138	0.3382	0.8064	0.4318	0.4359
4	0.9781	0.7152	0.6701	0.9239	0.1960	0.1036
5	0	0	0.0229	0	1	1
6	0.4508	0.1719	0.1761	0.7329	0.8752	0.8450
7	0.6146	0.4565	0.5165	0.8643	0.3872	0.2597
8	0.1783	0.0669	0	0.7399	0.6557	0.6222
9	0.3016	0.1754	0.1325	0.5833	0.8617	0.7441

Table 4.19 Grey relational coefficient analysis

Exp. No.	Tensile (MPa)	Flexural (MPa)	Impact (J)	Hardness (HB)	Water absorption	Void content
1	0.3333	0.3333	0.3333	0.3333	1.0000	1.0000
2	0.3393	0.4105	0.6379	0.3724	0.6417	0.5482
3	0.4666	0.4489	0.5965	0.3827	0.5366	0.5342
4	0.3383	0.4114	0.4273	0.3511	0.7184	0.8284
5	1.0000	1.0000	0.9562	1.0000	0.3333	0.3333
6	0.5259	0.7442	0.7396	0.4056	0.3636	0.3717
7	0.4486	0.5227	0.4919	0.3665	0.5636	0.6581
8	0.7371	0.8820	1.0000	0.4032	0.4327	0.4456
9	0.6238	0.7403	0.7906	0.4616	0.3672	0.4019

Table 4.20 Gray relational grade analysis

Exp. No.	Tensile (MP)	Flexural (MPa)	Impact (J)	Hardnes s (HB)	Water absorption	Porosity	Grade
1	0.3333	0.3333	0.3333	0.3333	1.0000	1.0000	0.4555
2	0.3393	0.4105	0.6379	0.3724	0.6417	0.5482	0.4917
3	0.4666	0.4489	0.5965	0.3827	0.5366	0.5342	0.4943
4	0.3383	0.4114	0.4273	0.3511	0.7184	0.8284	0.5125
5	1.0000	1.0000	0.9562	1.0000	0.3333	0.3333	0.7705
6	0.5259	0.7442	0.7396	0.4056	0.3636	0.3717	0.5251
7	0.4486	0.5227	0.4919	0.3665	0.5636	0.6581	0.5086
8	0.7371	0.8820	1.0000	0.4032	0.4327	0.4456	0.6501
9	0.6238	0.7403	0.7906	0.4616	0.3672	0.4019	0.5642

The above table shows the grade and ranking analysis that is achieved through grey relational analysis of the nine experimental samples. Based on the computed grey relational grades, all of the samples are ranked in reference to a number of mechanical and physical characteristics.

The best-performing sample among the evaluated samples was Sample 5, which obtained the highest grade of 0.7705, demonstrating a stronger balance of tensile strength, flexural strength, and other mechanical parameters. This sample was made from 20% of E-glass, 2.5% of aluminum oxide, and 20% of coffee husk.

4.3.1 Taguchi analysis of gray relational grade

This method is systematically finding the optimum levels of factors that affect the grey relational grades of the physical and mechanical tests.

Table 4.21 Gray relational grade response data based on S/N ratios

Level	E-glass	Aluminum oxide	Coffee husk
1	-6.372	-6.170	-5.389
2	-4.555	-4.057	-5.648
3	-4.861	-5.562	-4.752
Delta	1.817	2.113	0.895
Rank	2	1	3

The above table shows significant information on the performance of materials (E-glass, aluminum oxide, and coffee husk). The result indicates that aluminum oxide possesses the first rank with a 2.113 delta number to positively affect the physical and mechanical qualities. E-glass and coffee husk possess the second and third ranks with 1.817 and 0.895 of delta number, respectively.

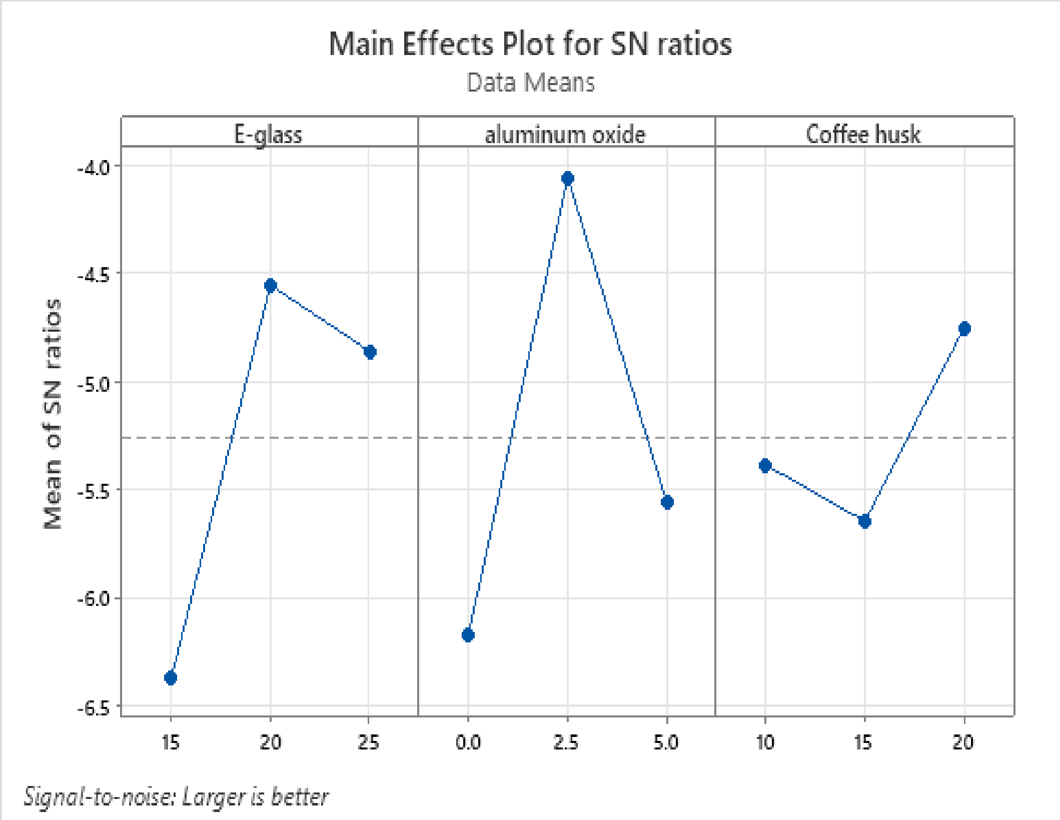


Figure 4.13 Main effects graph of S/N ratio for gray relational grade

The figure shown above illustrates the performance of E-glass, aluminum oxide, and coffee husk at different levels. E-glass and aluminum oxide have high performance at level 2; coffee husk has high performance at level 3. Therefore, it has been proven that A2B2C3 is the optimal prediction condition for multi response above properties.

4.3.2 Confirmation of the obtained result

There would be no need for a confirmation test if the set of optimal process parameters was identical to any trial in the orthogonal array. The fifth sample in this investigation had the best set of process parameters for the composite's mechanical and physical properties. This similarity suggests that the outcomes of the experiment and the predictions are consistent with the data from this sample. As a result, no confirmatory test would be necessary.

4.4 Applications of the Fabricated Composite

The innovative development of the polyester resin composite with E-glass, aluminum oxide, and coffee husk reinforcement offers excellent benefits to automotive parts, especially in automotive door panels. Through the incorporation E-glass, the composite achieves high tensile and flexural strength (for example, sample 5 achieves 101.1 and 480.27 MPa tensile and flexural strength, respectively), enabling toughness in withstanding the mechanical stresses of everyday driving. The addition of aluminum oxide improves hardness and impact strength (for example, sample 5 achieves high impact strength), offering scratch and minor collision protection. Utilizing coffee husk enhances fuel effectiveness because of it is lightweight and also contributes to sustainability by decreasing waste. Therefore, the fabricated composite from polyester resin matrix reinforced with E-glass, aluminum oxide, and coffee husk can be used for the applications of automotive door panels.

Additionally, due to the fabricated composite revealed good properties in terms of strength, weight, durability and sustainability, it can be used in the manufacturing of bed frame, which requires high load bearing capacity. Also it can be utilized for the manufacturing of false ceilings, which requires light weight and strength, windows (Frames or structures that hold glass panels) and furniture. The use of these sustainable composites fits well with the growing need for eco-friendly and recyclable materials, making them a great choice for modern applications that prioritize sustainability.

4.5 Validation of the Obtained Results with Previous Research (Publications) based on Mechanical Properties

Table 4.22 Comparison of mechanical properties

Matrix	Reinforcement	Fabrication method	Mechanical properties obtained				
			TS (MPa)	FS (MPa)	IS (J)	H (HV)	Reference
Unsaturated polyester resin	E-glass and Jute fiber with nano clay filler	Hand layup method	69.7	90.22	17.86	-	(Praveena et al., 2022)
Epoxy Resin	E-glass Fiber and pine tree leaves as natural filler	Hand layup method	76	220	-	79	(Balaji Ayyanar et al., 2024)

Unsaturated polyester resin	E-glass fiber	Hand layup method	72	81	21.56	-	(keya et al., 2019)
	Jute fiber		42	36	21	-	
Unsaturated polyester resin	E-glass fiber	Hand layup method	72	80	22	-	(M. N. Islam et al., 2019)
Unsaturated polyester resin	E glass fiber, aluminum oxide and coffee husk	Hand layup method	101.1	480.27	33.9	144.5	**Present work (current work)**

Table 4.23 Comparison of mechanical properties based on its application

Matrix	Reinforcement	Application	Mechanical properties				Reference
			TS(MPa)	FS(MPa)	IS (J)	H(HV)	
Polyvinyl Alcohol	Ceiba pentandra bark fiber	Automotive door panel	85.92	98.49	32.01	-	(Subhakanta et al., 2022)
Epoxy	Flax, hemp and kenaf fiber mats	Automotive door panel	28	62.7	9	45.1	(Prasad et al., 2021)
Polyester resin	Kenaf fiber	Interior car door panel	87.4	137.2	-	-	
Unsaturated polyester resin	E glass fiber, aluminum oxide and coffee husk	Automotive door panel, Bed frame,	101.1	480.27	33.9	144.5	**Present work (current work)**

CHAPTER FIVE

CONCLUSION AND RECCOMENDETION

5.1 Conclusion

The study of polyester resin reinforced with E-glass, aluminum oxide, and coffee husk has provided enhanced properties about the composite's mechanical and physical characteristics, proving its versatility in a variety of applications. Their fabrication was effectively accomplished with the use of the hand layup technique. A total of nine samples were made using this technique, which was led by the Taguchi method and incorporated three levels of weight percentages of reinforcement. The investigation's findings led to the following conclusion:

- The composites' remarkable tensile strength was shown by sample 5 (20% of E-glass, 2.5% of aluminum oxide and 20% of coffee husk) which reached a maximum of 101.1 MPa. The primary reason for this improvement is the right pairing of aluminum oxide, coffee husk and E-glass fibers, which efficiently absorb stress and disperse load.
- The flexural strength test revealed that sample 5 (20% of E-glass, 2.5% of aluminum oxide, and 20% of coffee husk) reached a maximum flexural strength of 480.27MPa. In this the increments of E-glass fiber and aluminum oxide up to optimum with 20% of coffee husk, significantly providing the fabricated composite to resist bending force without failure.
- The impact test indicated that sample 8 (25% of E-glass, 2.5% of aluminum oxide, and 10% of coffee husk) reached a maximum impact strength of 34.13KJ. This reveals the combination of high weight percentage of E-glass (level 3) and medium weight percentage of aluminum oxide (level 2) highly improved toughness and energy absorption properties of the composite.
- The Vickers hardness revealed the increments of aluminum oxide and coffee husk up to optimum value increases the ability of composite to resist indentation. Sample 5 (20% of E-glass, 2.5% of aluminum oxide, and 20% of coffee husk) reached a maximum Vickers hardness of 144.5.

- The water absorption test revealed that sample 5 and 6 showed reduced water absorption rate. This suggests the matrix and reinforcements have stronger bonding relationship. The main cause for this improvement is aluminum oxide and coffee husk, because of coffee husk contains lingo-cellulosic materials and aluminum oxide act as barrier to moisture, highly crucial in water absorption properties improvement.
- Sample 5 and 6 exhibited low porosity due to high interfacial bonding between reinforcement and matrix. This shows as the percentage of reinforcement (E-glass, aluminum oxide, and coffee husk) increases, especially at 20% of E-glass, 2.5% of aluminum oxide and 20% of coffee husk, porosity level was reduced.
- SEM analysis showed that sample 5 and 6 had well-defined features with good orientation and distribution of reinforcing materials in the matrix. The existence of aluminum oxide in a spherical morphology assisted with stress distribution, and the surface topography of coffee husk with roughness assisted in bonding improvement with the polyester matrix.

5.2 Recommendation

Based on the development and investigation of polyester resin polymer matrix reinforced with E-glass, aluminum oxide, and coffee husk, the following recommendations were taken into account.

- Incorporate agricultural waste in composite fabrication to encourage sustainability and biodegradability.
- Utilize the fabricated composite for long lasting and lightweight components including automotive door panel, dashboard and body panel. Also utilize for construction materials and household items where strength and light weight are highly crucial.
- Look into mixture of agricultural waste and synthetic fiber to achieve a balance between light weight and performance.

5.3 Future work

This research has provided valuable information, but there are still some new areas that may be explored to improve our understanding and use of the findings. Future work should seek to overcome the limitations of this research and create new opportunities for innovation. The following subjects are proposed for future studies:

- Compare and analyze the effect of coffee husk that has been chemically treated and that has not, on the mechanical qualities of composite
- Develop hybrid composites that combine various agricultural waste and synthetic fiber to highly improve sustainability and performance.
- Examine how various processing techniques affect the mechanical characteristics to further maximize performance.
- Examine other mechanical properties, such as machining, compressive, and fatigue analysis, for further research.
- Compare and contrast mechanical characteristics of the composite using other polymer matrix.

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APPENDICES

Appendix A: Experimental results of the fabricated composite

Experimental results of tensile strength testing

Samples	Trials	S.1	S.2	S.3	S.4	S.5	S.6	S.7	S.8	S.9
Tensile strength (MPa)	Trial-1	52.57	53.43	68.91	53.4	101.6	82.59	68.9	90.31	82.5
	Trial-2	47.2	51.12	72.3	63.2	99.87	67.3	62.23	83.34	80.1
	Trial-3	56.65	54.63	66.51	42.1	101.3	75.14	70.77	95.87	85.8
Average of tensile strength (MPa)		52.14	53.06	69.24	52.9	101.1	75.01	67.3	89.84	82.8
Standard deviation		3.87	1.46	1.78	4.31	1.775	2.21	2.75	5.12	2.33

Experimental results of flexural strength testing

Samples	Trials	S.1	S.2	S.3	S.4	S.5	S.6	S.7	S.8	S.9
Flexural strength (MPa)	Trial-1	149.14	208.29	234	208.2	480.27	393.43	282.86	444.86	448.87
	Trial-2	153.45	204.3	238	203.7	479.68	388.73	279.4	440.62	457.53
	Trial-3	146.57	211.44	232.55	214.06	480.86	397.05	283.995	447.12	453.23
Average of flexural strength (MPa)		149.72	208.01	234.85	208.655	480.27	393.07	282.085	444.24	453.21
Standard deviation		2.83	2.92	1.74	4.12	1.87	3.2	2.12	2.56	3.54

Experimental results of impact strength testing

Samples	Trials	S.1	S.2	S.3	S.4	S.5	S.6	S.7	S.8	S.9
Impact strength (MPa)	Trial-1	24	31.9	31.5	27.4	33.5	33.87	30.2	34.5	30.3
	Trial-2	21	33.2	32.7	25.6	32.2	30.93	33.4	31.76	33.3
	Trial-3	31.2	29.05	28.5	31	36	32.4	24.3	36.13	34.8
Average of impact strength (MPa)		25.4	31.385	30.885	28	33.9	32.4	29.3	34.13	32.82
Standard deviation		4.28	1.733	1.77	2.24	1.58	2.21	2.47	1.8	1.87

Experimental results of hardness testing

Samples	Trials	S.1	S.2	S.3	S.4	S.5	S.6	S.7	S.8	S.9
Hardness test (HB)	Trial-1	70.3	71	76.9	66.2	138.8	86	71.8	84.3	88.6
	Trial-2	62.1	74.85	70	70.3	149.2	75.1	75.4	76.9	94.7
	Trial-3	66.2	78.7	84.1	74.25	145.5	83.55	73.6	82.1	91.5
Average of hardness results (HV)		66.2	74.85	77	70.25	144.5	81.55	73.6	81.1	91.6
Standard deviation		3.35	3.14	5.75	3.28	4.26	4.67	1.68		2.49

Experimental results of water absorption testing

Samples	S.1	S.2	S.3	S.4	S.5	S.6	S.7	S.8	S.9
Average of Water absorption test (%)	0.257	0.23	0.215	0.237	0.17	0.179	0.219	0.196	0.18

Experimental results of porosity testing

Samples	S.1	S.2	S.3	S.4	S.5	S.6	S.7	S.8	S.9
Average of Porosity results (%)	2.38	1.5	1.4	1.66	0.32	0.48	1.45	0.86	0.63

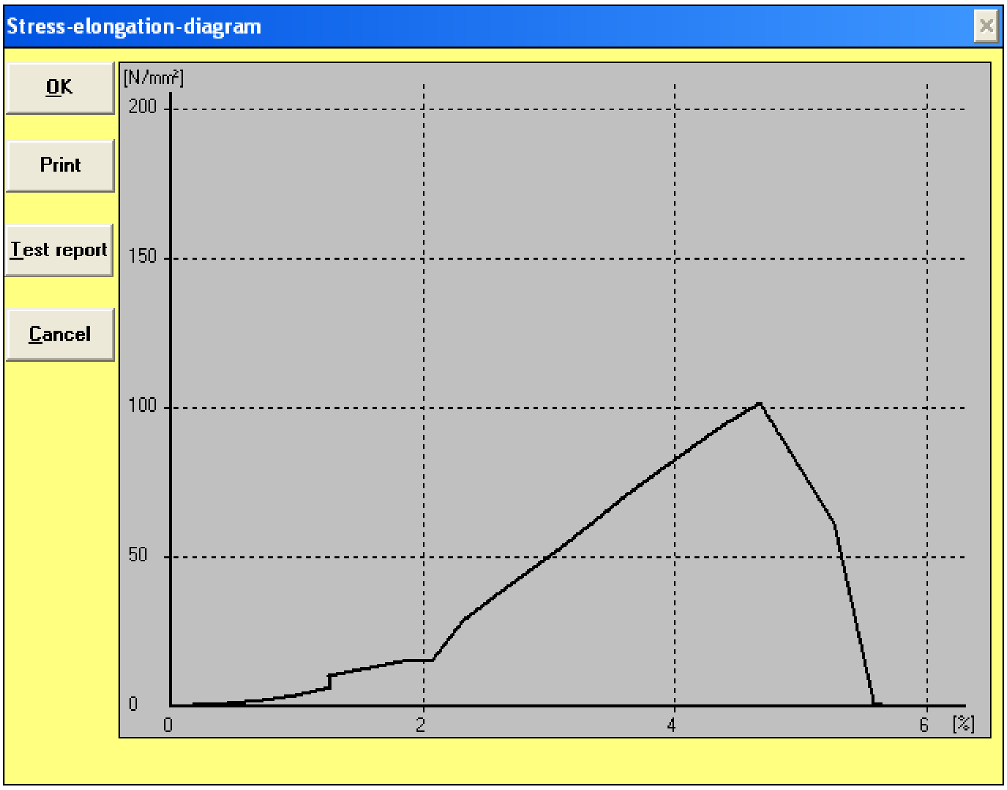
Appendix B: Results from tensile strength test

Sample-5: Trial-1

Test report

Kind of test:	Tensile test DIN 50106
Material of specimen:	comp.
Dimensions of specimen:	Tension specimen B35 x 250 DIN 50125
Temperature:	20°C
Upper/lower tensile yield strength ReU/ ReL:	___
Yield stress Rp:	___
Tensile Strength Rm:	101.60 N/mm²
Elongation at fracture A:	___
Contraction at fracture Z:	___
Date:	11.03.2025

Stress-elongation diagram

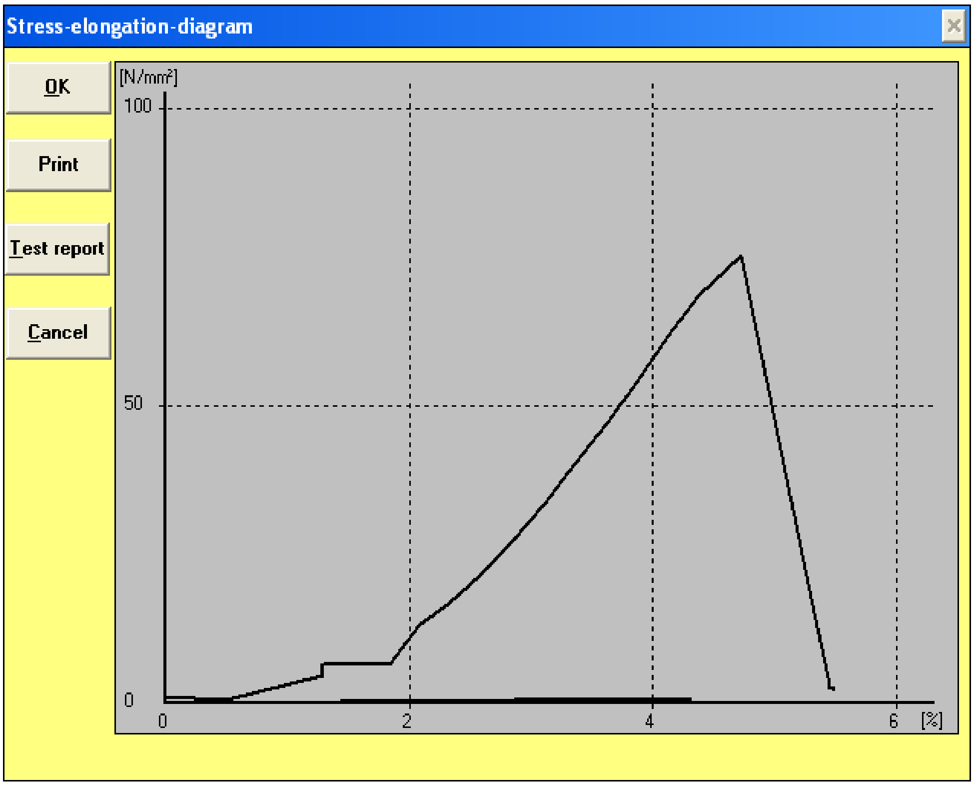


Sample-6: Trial-3

Test report

Kind of test:	Tensile test DIN 50106
Material of specimen:	comp.
Dimensions of specimen:	Tension specimen B35 x 250 DIN 50125
Temperature:	20°C
Upper/lower tensile yield strength ReU/ ReL:	________________
Yield stress Rp:	________________
Tensile Strength Rm:	75.14 N/mm²
Elongation at fracture A:	________________
Contraction at fracture Z:	________________
Date:	07.03.2025

Stress-elongation diagram

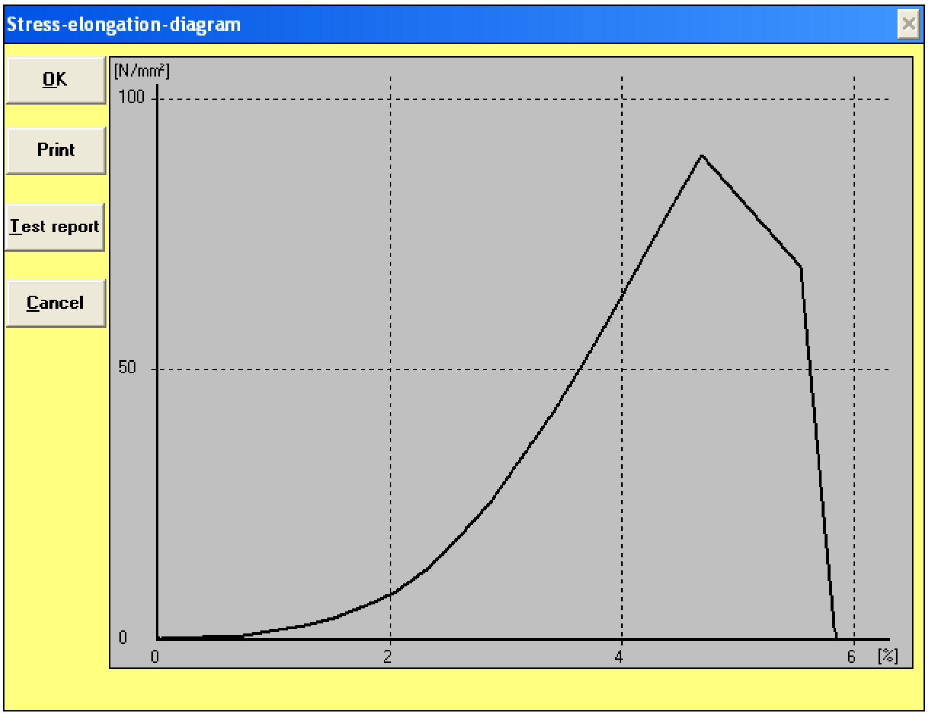


Sample-8: Trial-2

Test report

Kind of test:	Tensile test DIN 50106
Material of specimen:	comp.
Dimensions of specimen:	Tension specimen B35 x 250 DIN 50125
Temperature:	20°C
Upper/lower tensile yield strength ReU/ ReL:	______________________
Yield stress Rp:	______________________
Tensile Strength Rm:	89.54 N/mm²
Elongation at fracture A:	______________________
Contraction at fracture Z:	______________________
Date:	11.03.2025

Stress-elongation diagram

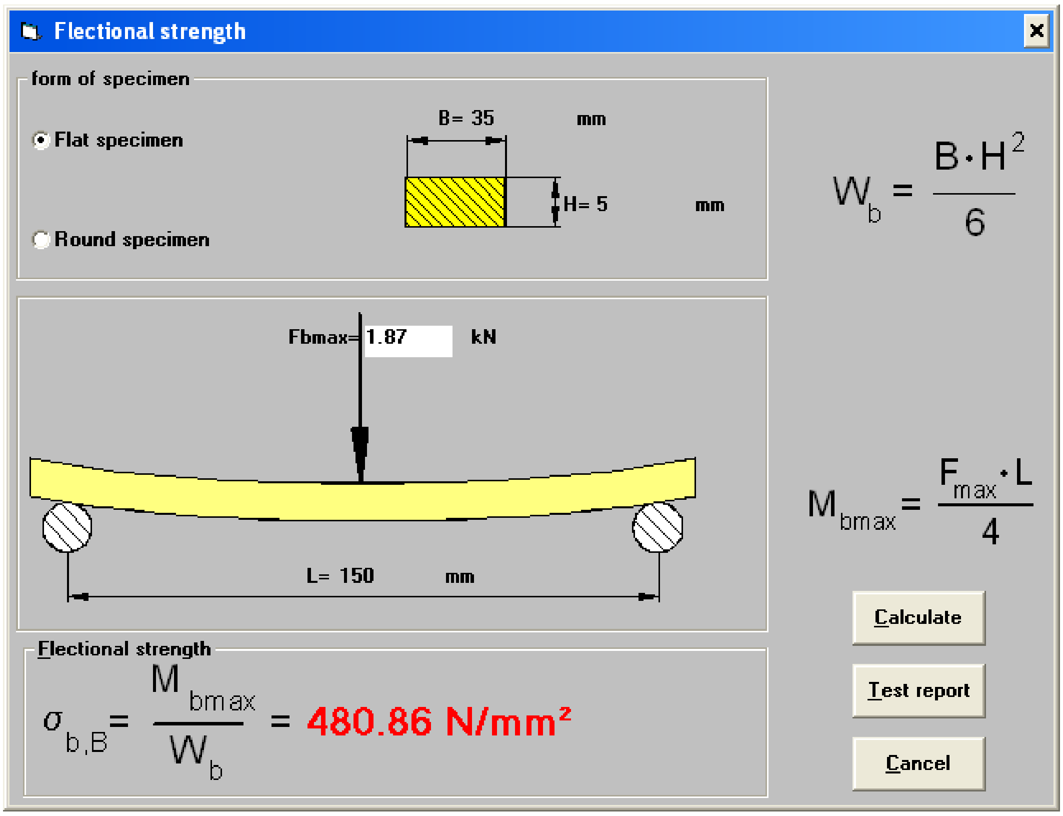


Appendix C: Results from Flexural strength test

Sample-5: Trial-3

Test report

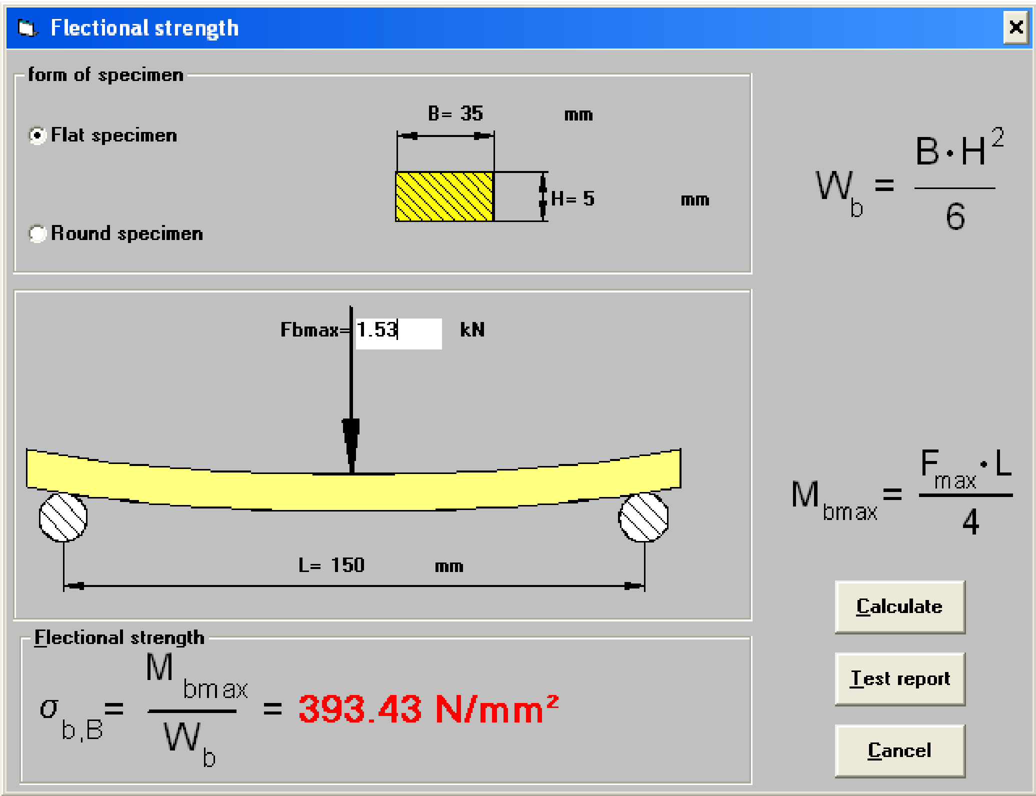
Kind of test:	Bending test DIN 50110
Material of specimen:	______________________
Kind of specimen	Bending specimen 35 DIN 50110
Temperature:	20°C
max.test force:	1870.0 N
flectional strength	480.86 N/mm²
Ductile yield	______________________
Description of the fracture area:	______________________
Distance between supports:	150 mm
Date:	11.03.2025



Sample-6: Trial-1

Test report

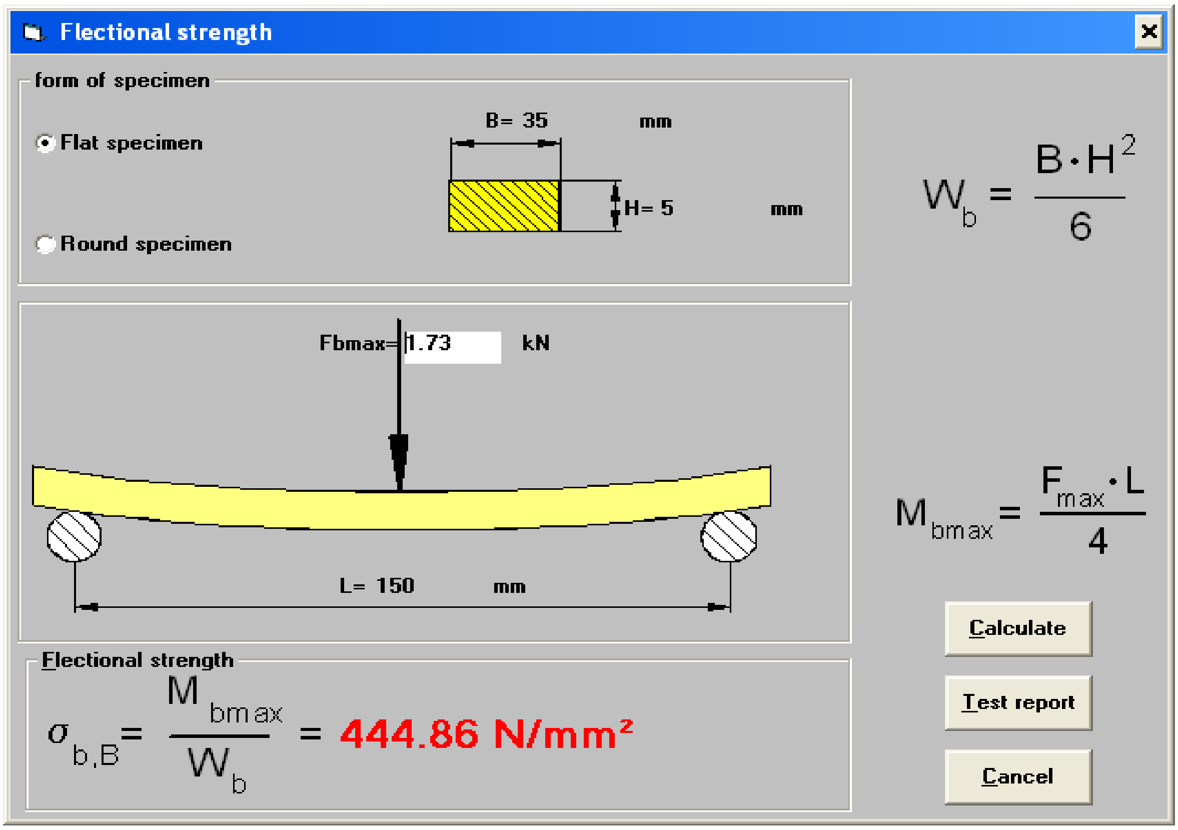
Kind of test:	Bending test DIN 50110
Material of specimen:	______________________
Kind of specimen	Bending specimen 35 DIN 50110
Temperature:	20°C
max.test force:	1530.0 N
flectional strength	393.43 N/mm²
Ductile yield	______________________
Description of the fracture area:	______________________
Distance between supports:	150 mm
Date:	11.03.2025



Sample-8: Trial-1

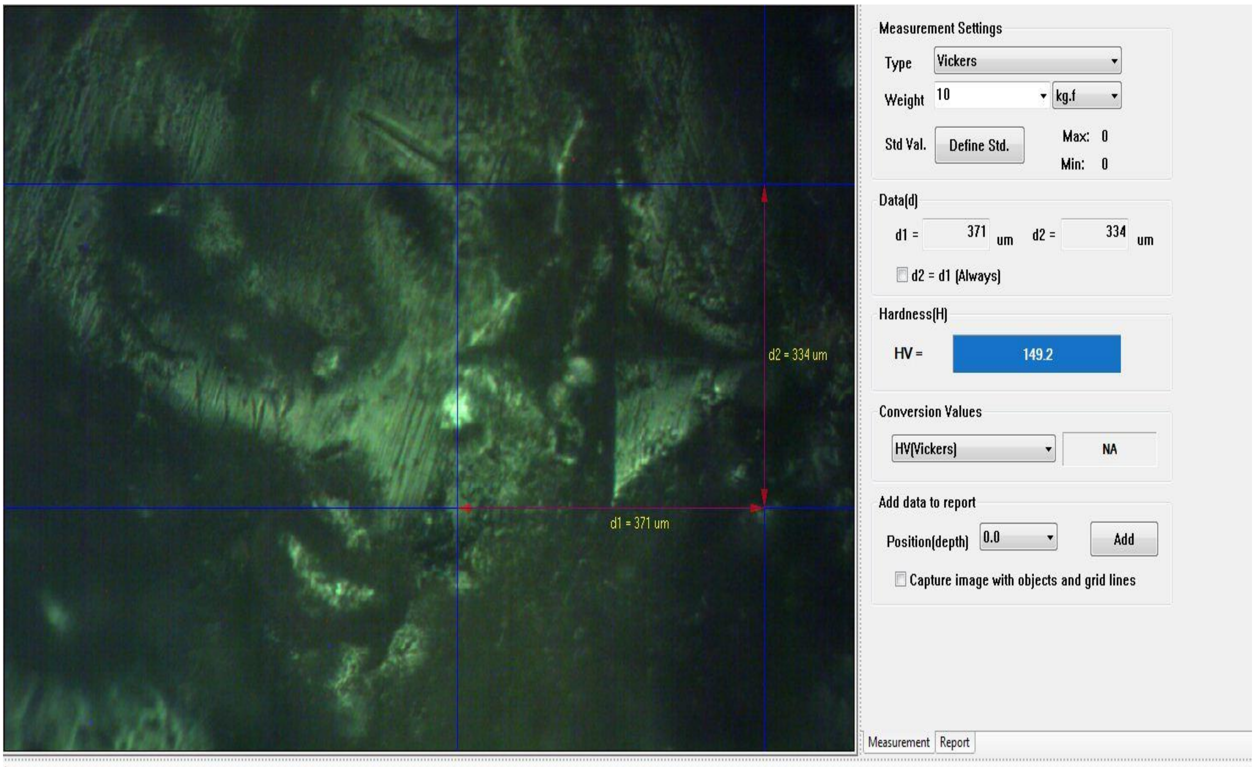
Test report

Kind of test:	Bending test DIN 50110
Material of specimen:	___
Kind of specimen	Bending specimen 35 DIN 50110
Temperature:	20°C
max.test force:	1730.0 N
flectional strength	444.86 N/mm²
Ductile yield	___
Description of the fracture area:	___
Distance between supports:	150 mm
Date:	11.03.2025

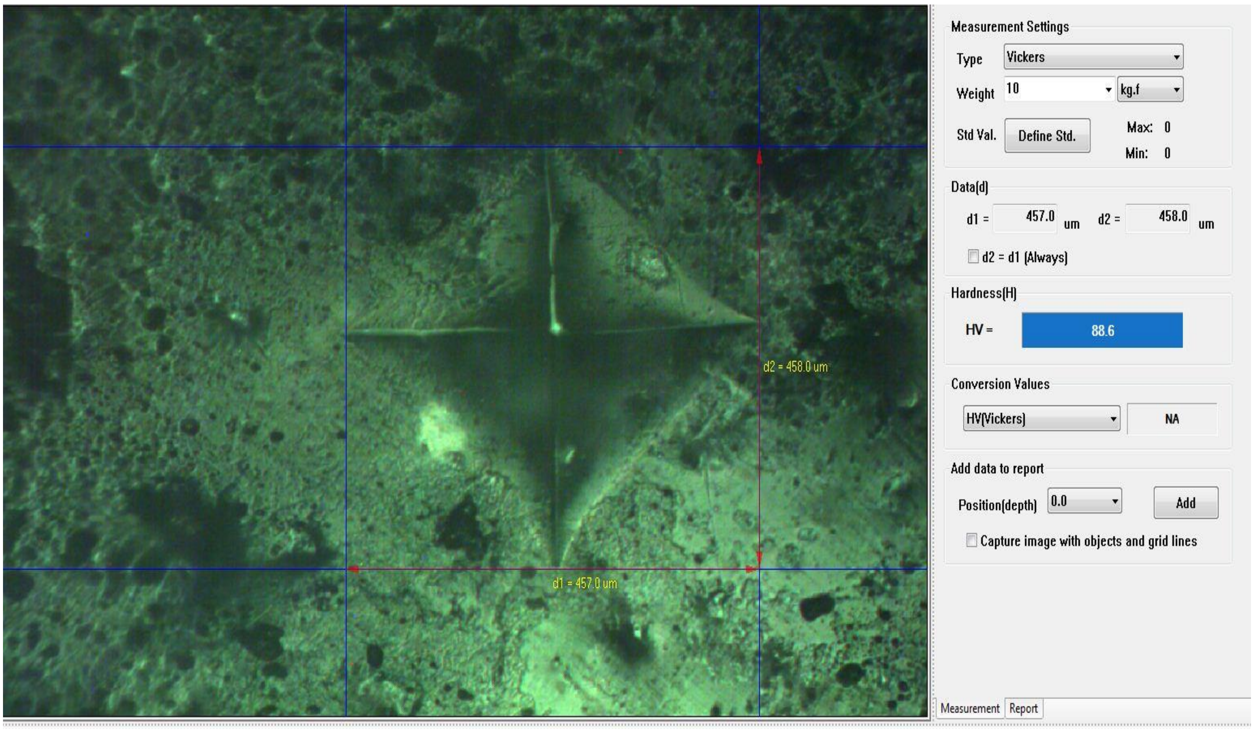


Appendix D: Results from Vickers hardness test

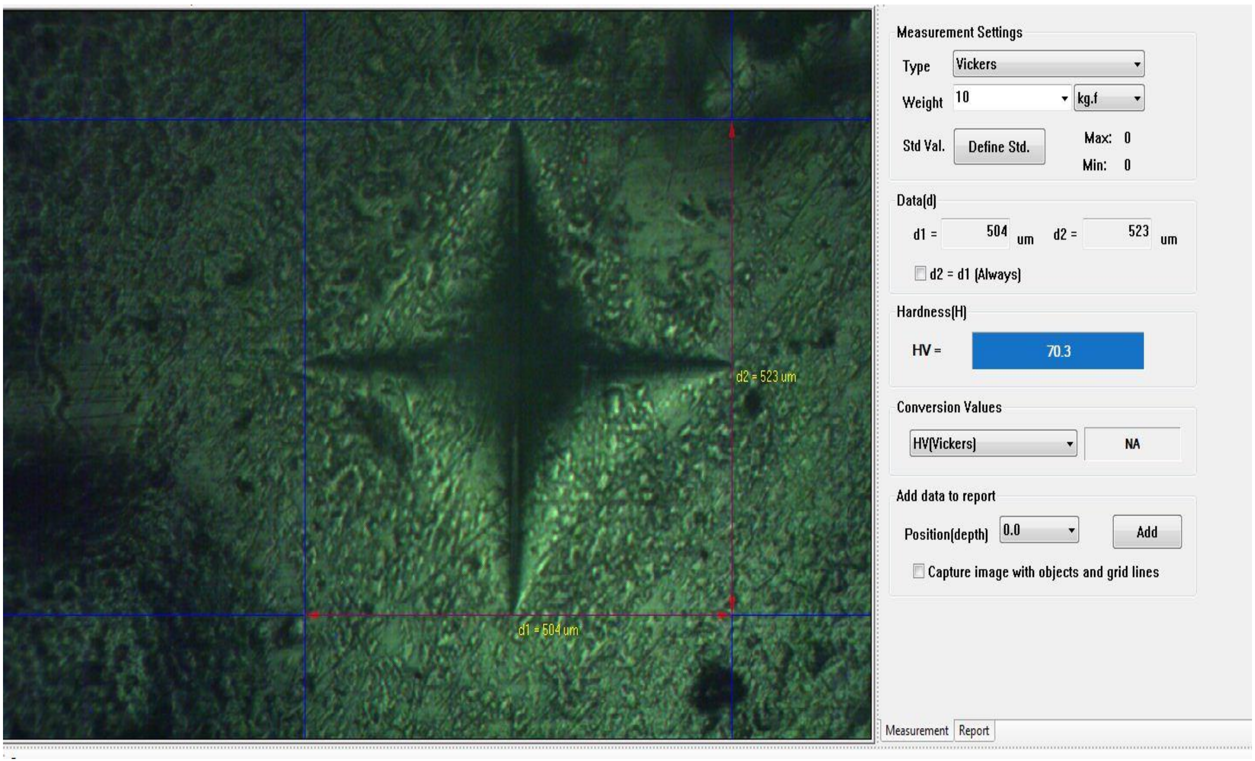
Sample-5: Trial-2



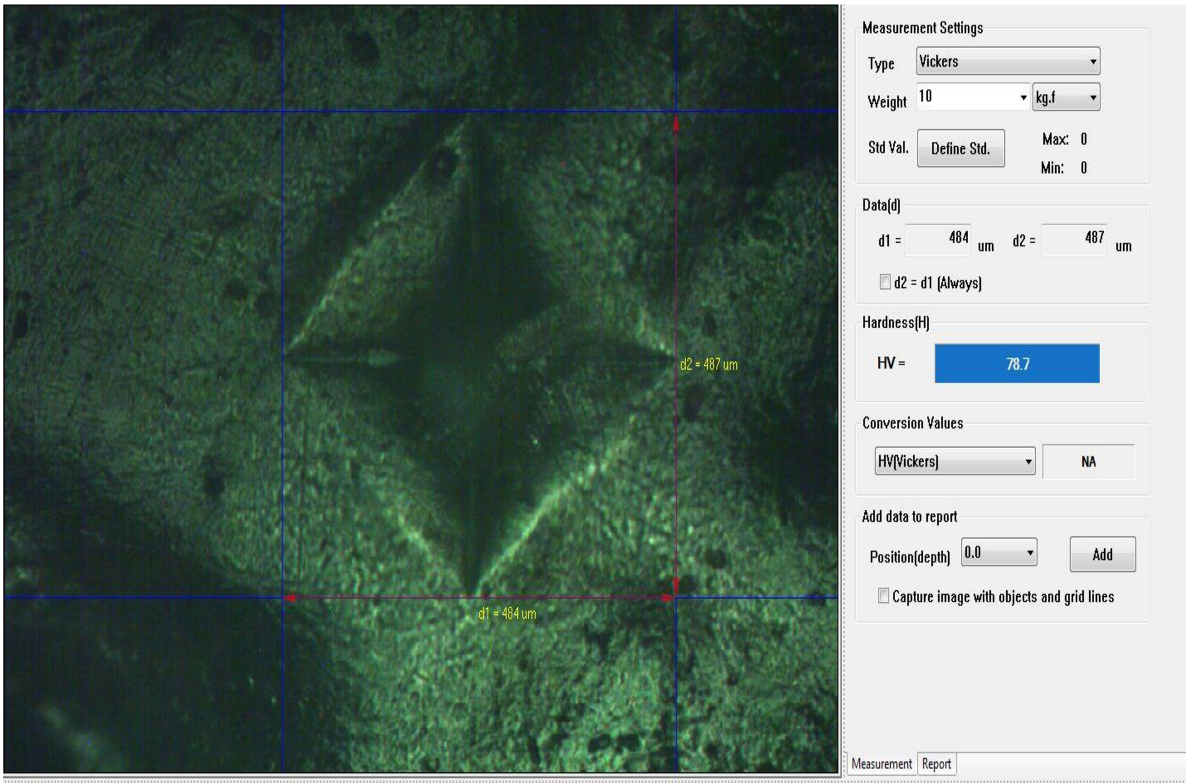
Sample-9: Trial-1



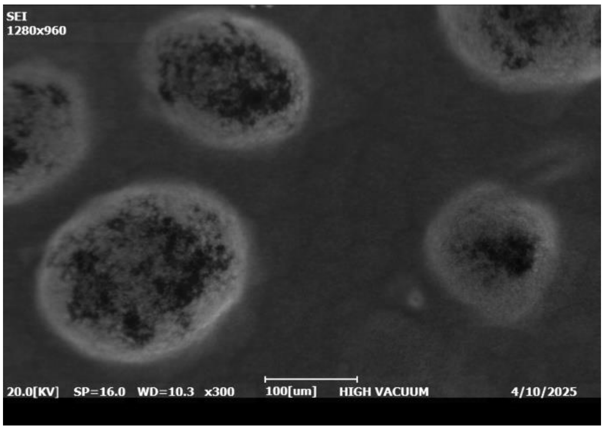
Sample-1: Trial-1



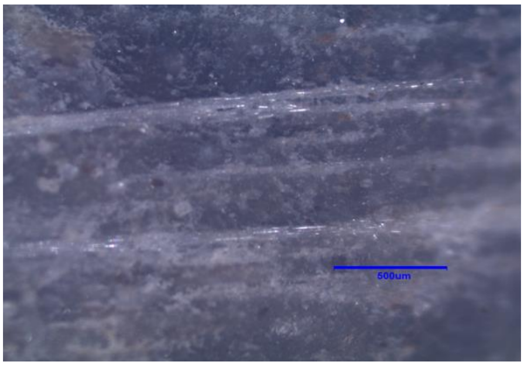
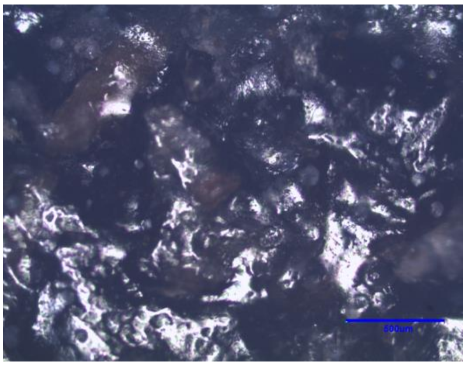
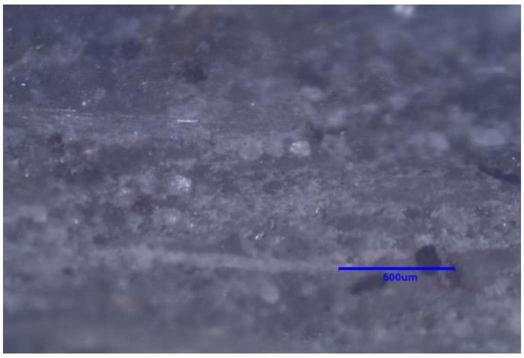
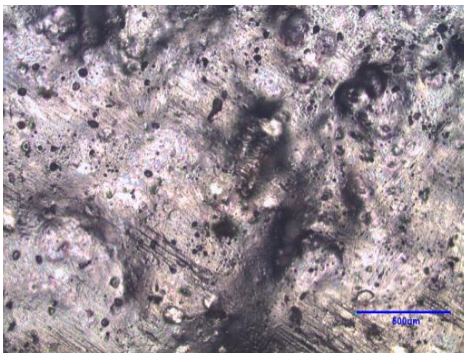
Sample-2: Trial-3



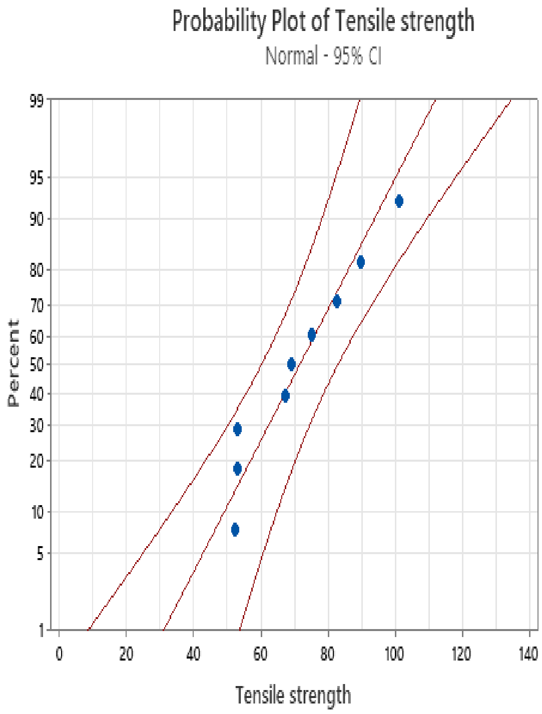
Appendix E: Image from SEM

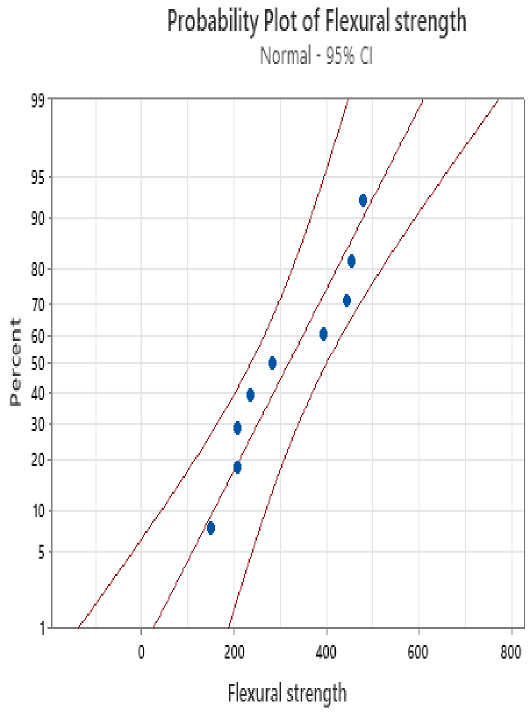
Sample-5	Sample-7
	

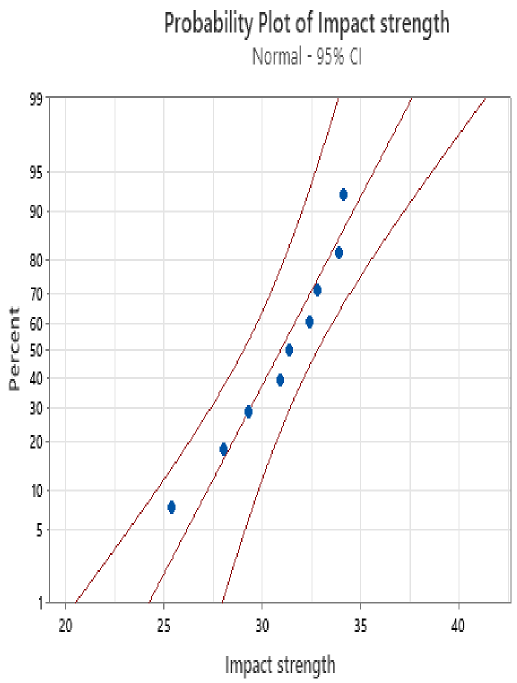
Appendix E: Image from OP

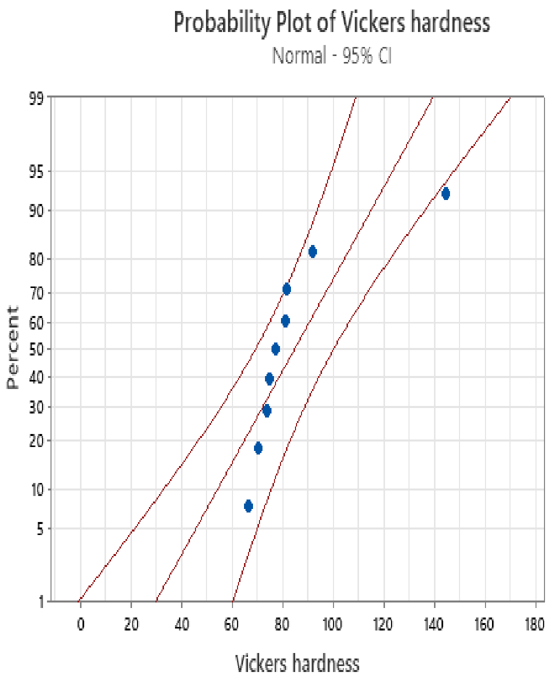
Sample-5	Sample 7
	
Sample-6	**Sample 7**
	

Appendix F: Data from Minitab









Appendix F: Mass of samples measured in air and water for theoretical and actual density

Mass of samples in air

Sample-1 **Sample-2** **Sample-3** **Sample-4** **Sample-5**



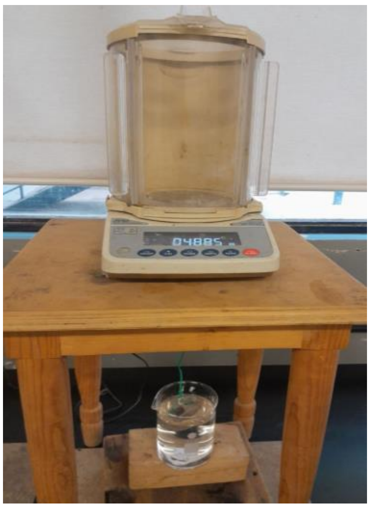


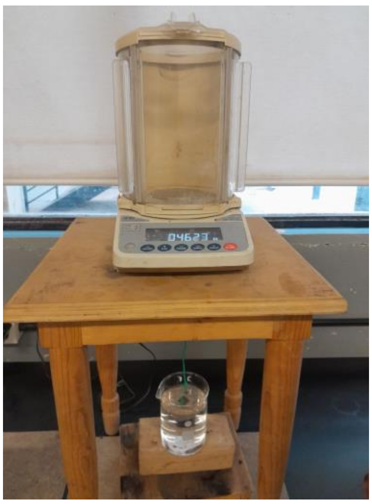
Sample-6 **Sample-7** **Sample-8** **Sample-9**



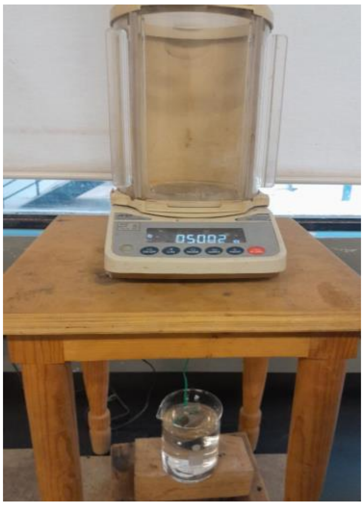

Mass of samples in water

Sample-1 **Sample-2** **Sample-3**

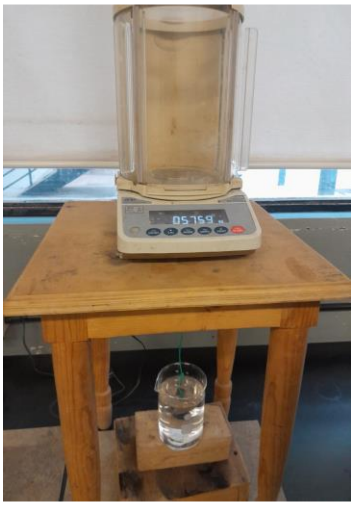




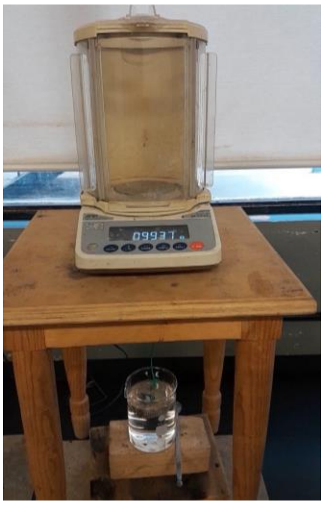
Sample-4



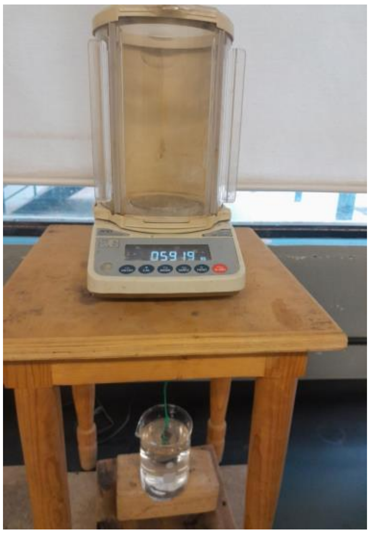
Sample-5



Sample-6

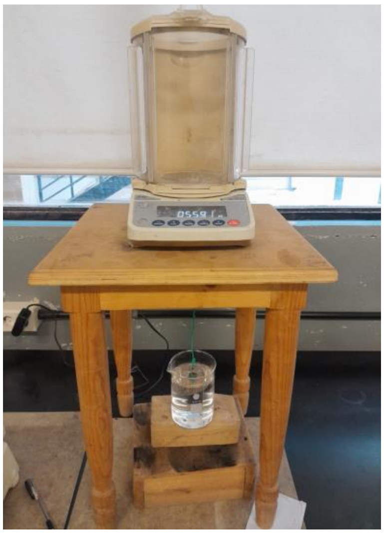


Sample-7



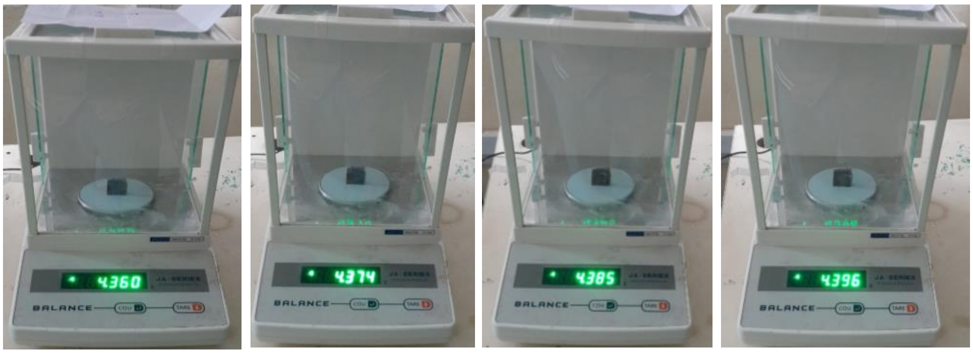
Sample-8

Sample-9

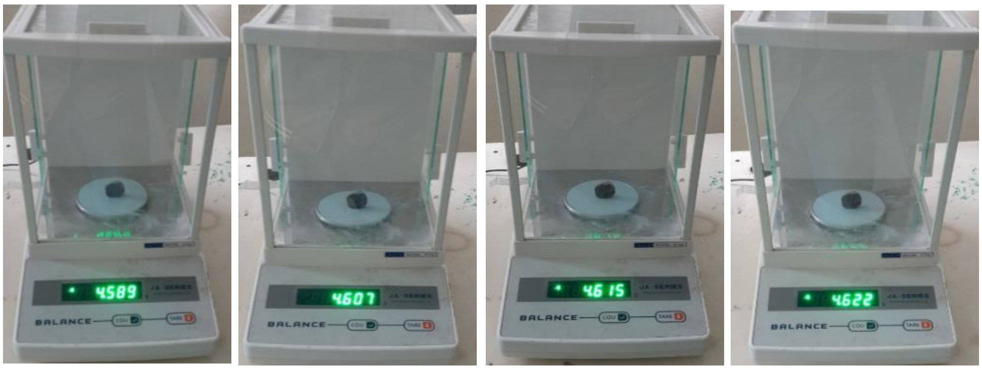


Appendix G: Water absorption test

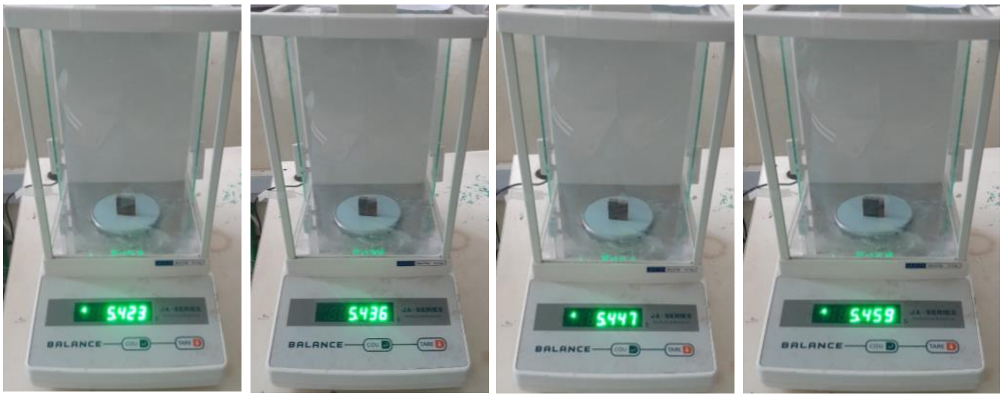
Sample-1



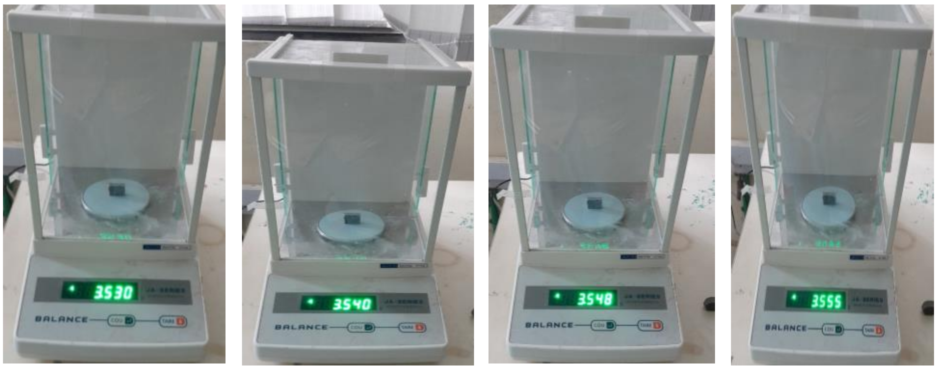
Sample-2



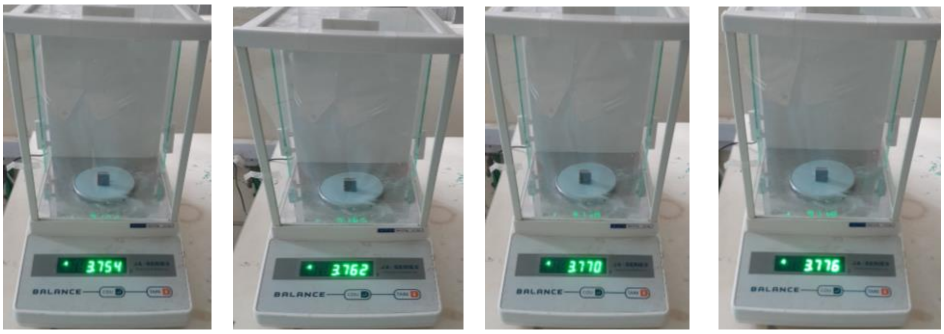
Sample-3



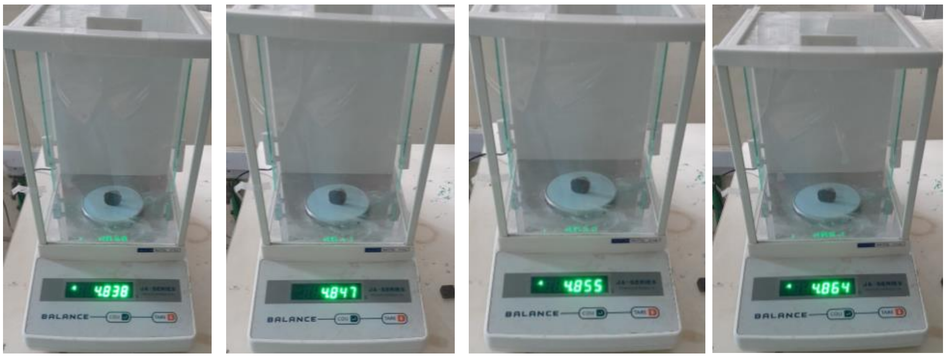
Sample-4



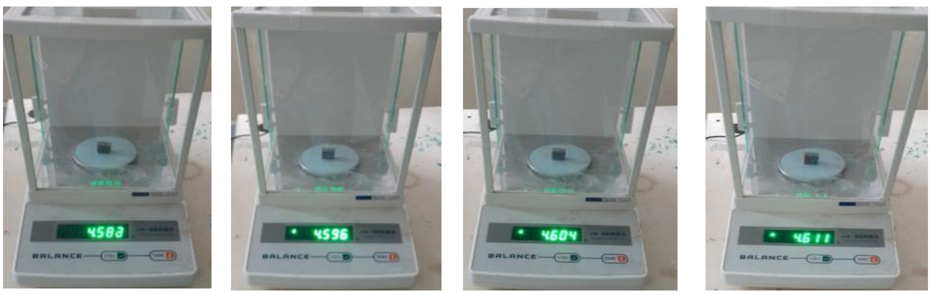
Sample-5



Sample-6

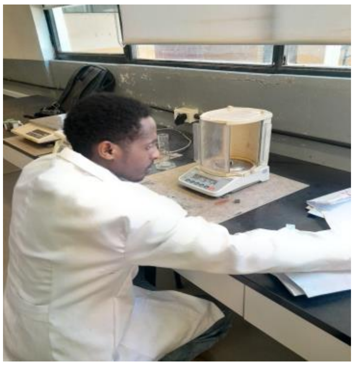


Sample-7



Appendix H: Sample and specimen preparation



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