MECHANICAL PROPERTIES OF ALUMINIUM REINFORCED WITH CRUSHED GRAVEL AND COCONUT SHELL ASH FOR VARIOUS APPLICATIONS

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A DISSERTATION SUBMITTED TO THE DIRECTORATE OF RESEARCH AND GRADUATE TRAINING IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE AWARD OF THE DEGREE OF MASTER OF SCIENCE IN ADVANCED MANUFACTURING SYSTEMS ENGINEERING OF KYAMBOGO UNIVERSITY

OCTOBER, 2024

DECLARATION

I, Gyagenda Remegio Lubowa, declare that this dissertation is my original work and it has never been presented to any higher institution of learning for an academic award.

Sign…………………………………………………….. Date……………………………………...

APPROVAL

This Dissertation titled "Mechanical Properties of Aluminium Reinforced with Crushed Gravel and Coconut Shell Ash for Various Applications", prepared and submitted by Gyagenda Remegio Lubowa in partial fulfilment of the requirements for the Masters of Science in Advanced Manufacturing Systems Engineering of Kyambogo University, has been under our supervision and is ready for examination.

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DEDICATION

I dedicate the hard work in this dissertation to God and my family.

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LIST OF ABBREVIATIONS AND ACRONYMS

AMCs:	Aluminium Matrix Composites
ASTM:	American Society for Testing and Materials
BLA:	Bamboo Leaf Ash
CGP:	Crushed gravel powder
CEDAT:	College of Engineering Design and Arts Technology
CSAp:	Coconut Shell Ash particulate
EDX/EDS:	Energy Dispersive X-ray spectroscope.
GSAp:	Groundnut Shell Ash
ISO:	International Organization of Standardization
MMCs:	Metal matrix composites
PSA:	Peanut Shell Ash
SDGs:	Sustainable Development Goals
SEM:	Scanning Electron Microscopy
UIRI:	Uganda Industrial Research Institute
UNBS:	Uganda National Bureau of Standards
UTM:	Universal Testing Machine
UTS:	Ultimate Tensile Strength

ABSTRACT

This work investigated the mechanical characteristics of Aluminium reinforced with coconut shell-ash and crushed gravel powder because pure Aluminium presents limitations due to its low tensile strength of less than 90 N/mm^2 under annealed conditions. To fabricate the composite, the present work utilized weight percentages of 4, 5, 7.5 and 10% for coconut shell ash powder (CSAp) and 5, 6, 7, and 7.5% for crashed gravel (CGp). The chemical analysis of the reinforcement materials was carried out using the scanning electron microscope coupled with the Energy dispersive x-ray analysis (EDX). The aluminium matrix composite was produced by a stir casting process at a firing temperature of 650 0C. These composite samples were prepared and subjected to microstructural and mechanical properties tests using the scanning electron microscopy (SEM) and the universal testing machine (UTM). Microstructural analysis revealed the presence of significant voids that were identified with dark patches within all the samples and the presence of striations that resulted from the irregular and non-uniform distribution between the matrix and the reinforcement materials. The mechanical property test results revealed that the composite sample S5 only reinforced with 5 wt% of crushed gravel exhibited the highest tensile strength of 157.5 MPa but with the smallest compressive strength of 111.13 MPa. Sample S2 which was reinforced with equal 7.5 wt% of crushed gravel and coconut shell ash produced the highest Rockwell's hardness of 117 HRB with the least value of 66 HRB produced by sample S1. Sample S4 that was reinforced with 5 wt% of coconut shell ash only, produced the highest compressive strength of 355.83 MPa. Additionally, sample S3 exhibited the maximum elongation among the tested samples, with a value of 9.59%. With the exception of AMC sample 4, all other fabricated AMCs exhibited tensile strengths above that of pure Aluminium (90 MPa), hence the fabricated AMC can be used for various structural applications in the building and construction industries.

CHAPTER ONE: INTRODUCTION

1.1 Background of the Study

Globally, engineers are continuously engaged in the pursuit of designing engineering materials capable of meeting the different demands of various structural applications in industries such as building and construction, energy, aerospace, and automotive (Wan et al., 2022). These materials must demonstrate exceptional durability and resilience to succeed in the harsh working environments to which they are exposed. Qiu and Wang (2023) highlighted the value of Aluminium alloys and how they may be applied to a wide range of applications due to their lightweight design and high strength-to-weight ratio. Pure Aluminium, however, presents inherent limitations due to its relatively low mechanical properties. With a tensile strength of less than 90 N/mm^2 under annealed conditions, pure Aluminium finds limited application in fields necessitating high tensile strengths (Younes, 2010). It is within this context that Aluminium alloys have gained prominence across diverse engineering domains.

In response to the limitations of pure Aluminium, researchers in the engineering field have recently focused on innovative techniques to enhance their utility and application. Grain reinforcement through extreme plastic deformation is one of the methods that is used in the creation of Aluminium matrix composites (AMCs). Hynes et al. (2022) noted the potential of metal matrix composite (MMC) materials to perform effectively in high-temperature environments, indicating a promising direction for material enhancement. Additionally, Zhang et al. (2023) demonstrated the preparation of graphene-aluminium composites through the friction stir alloying (FSA) method, yielding materials with superior strength at uniform stirring of 700 rpm compared to the original aluminium sheet.

Meanwhile, Wan et al. (2022) conducted research on micro-layered aluminium composites, exploring the effects of varying ceramic fractions on interfacial, mechanical, and microstructure properties. Their findings revealed that high ceramic fractions, ranging from 60% to 85%, resulted in interface flaws, negatively impacting the composites' mechanical characteristics and performance. However, all these reinforcing materials are expensive and the methods that are being employed to make the AMCs are complex.

This research study therefore centers on evaluating the microstructure characteristics and the mechanical properties of an aluminium matrix composite developed using locally sourced low-cost reinforcing materials such as crushed gravel powder and coconut shell ash. Coconut shell ash contains silica in a fine-grained form that makes it a valuable binder when producing composites (Shanmuga Priya & Padmanaban, 2024). Coconut shell ash imparts strength to the composite as crushed gravel brings in the element of hardness. The stir-casting method used to fabricate the AMCs in this work is user-friendly and cheap. In terms of mechanical properties, the fabricated AMC was compared with other alloys and pure aluminium.

1.2 Problem Statement

Aluminium matrix composites have attracted significant attention across various engineering applications, particularly in the structural industry (Abdulrazaq et al., 2023). Although significant research has been conducted on aluminium alloys, pure aluminium still exhibits limited mechanical qualities, notably a tensile strength of 90 MPa which restricts its application in various fields such as the automotive and aerospace industries. But also, the methods used to make the AMCs are complex and the cost of the current reinforcing materials is high. Therefore, to meet the changing needs of users and reduce the environmental impact, it is essential to explore new aluminium matrix composites (AMCs) that offer improved properties while utilizing low cost reinforcement materials and easy methods of fabricating the AMCs.

1.3 Research Objectives

1.3.1 Main Objective

To investigate the mechanical properties of aluminium reinforced with crushed gravel and coconut shell ash for various applications.

1.3.2 Specific Objectives

The specific objectives of the study are to;

i) Determine the chemical composition of coconut shell ash and crushed gravel powder.

ii) Analyze and examine the microstructure of the aluminium matrix composite formed.

iii) Assess the tensile strength, compressive strength, Hardness and the elongation of the aluminium matrix composite formed.

iv) Determine the performance of the fabricated AMC's with the existing aluminium alloys and pure aluminium.

1.4 Research Questions

i) What is the chemical composition of coconut shell ash and the crushed gravel?

ii) What is the microstructure of the AMC after reinforcement with crushed gravel and coconut shell ash?

iii) What is the tensile strength, yield strength, compressive strength, hardness and the elongation of the composite?

iv) How will the AMC perform in comparison with other existing aluminium alloys and pure aluminium?

1.5 Significance of the Study

This section effectively highlights the alignment between the research on Aluminium Matrix Composites (AMCs) reinforced with crushed gravel powder and coconut shell ash and several Sustainable Development Goals (SDGs):

By exploring innovative materials like AMCs, this research contributes to SDG 12, which focuses on sustainable consumption and production patterns. Utilizing locally sourced reinforcement materials such as coconut shells and gravel promotes resource efficiency and reduces reliance on non-renewable resources, thus supporting sustainable material practices. The development of AMCs aims to reduce the environmental impact of engineering materials, aligning with SDG 13's objective of climate action. By enhancing the mechanical properties of aluminium through sustainable practices, such as utilizing natural reinforcements, this research contributes to mitigating greenhouse gas emissions. Improving the mechanical properties of AMCs supports SDG 9, which emphasizes industry, innovation, and infrastructure. By developing materials that offer enhanced performance, this research facilitates the advancement of innovative solutions in engineering, contributing to building resilient infrastructure and promoting sustainable industrialization.

Overall, this research initiative not only addresses specific engineering challenges but also aligns with broader sustainable development objectives, demonstrating the potential for collaboration to drive positive social, economic, and environmental outcomes.

1.6 Scope of the Study

Although many aluminium matrix composites have been exclusively utilized as structural design materials particularly in Uganda, the most commonly used are those reinforced with ceramics. Reinforcement materials such as biomass and crushed gravel powder have not been currently utilized in the fabrication of aluminium composites. Therefore, the scope of the study was specifically limited to locally available materials in Uganda including aluminium, coconut shells, and gravel. These materials, aluminium, gravel and coconut shells were purchased from Jinja, Mukono and Nakasero market respectively. The materials were used in right proportions with the weight percentages ranging from 0-10 % for coconut shell ash and 0-7.5 % for crushed gravel powder. The fabricated AMCs were then subjected to mechanical tests of tensile strength, compressive strength, hardness and elongation to evaluate their performance with existing Aluminium alloys.

1.7 Conceptual Framework

This research aimed at carrying out an investigation on the mechanical properties of aluminium reinforced with crushed gravel powder and coconut shell ash powder for various applications. The conceptual framework of the study is presented in Figure 1.1. The independent variables include the firing temperature of coconut shell powder, the percentage weight and chemical composition of aluminium, coconut shell ash, and crushed gravel powder, which do influence the tensile strength, compressive strength, Hardness and Elongation as the dependent variables of the composite.

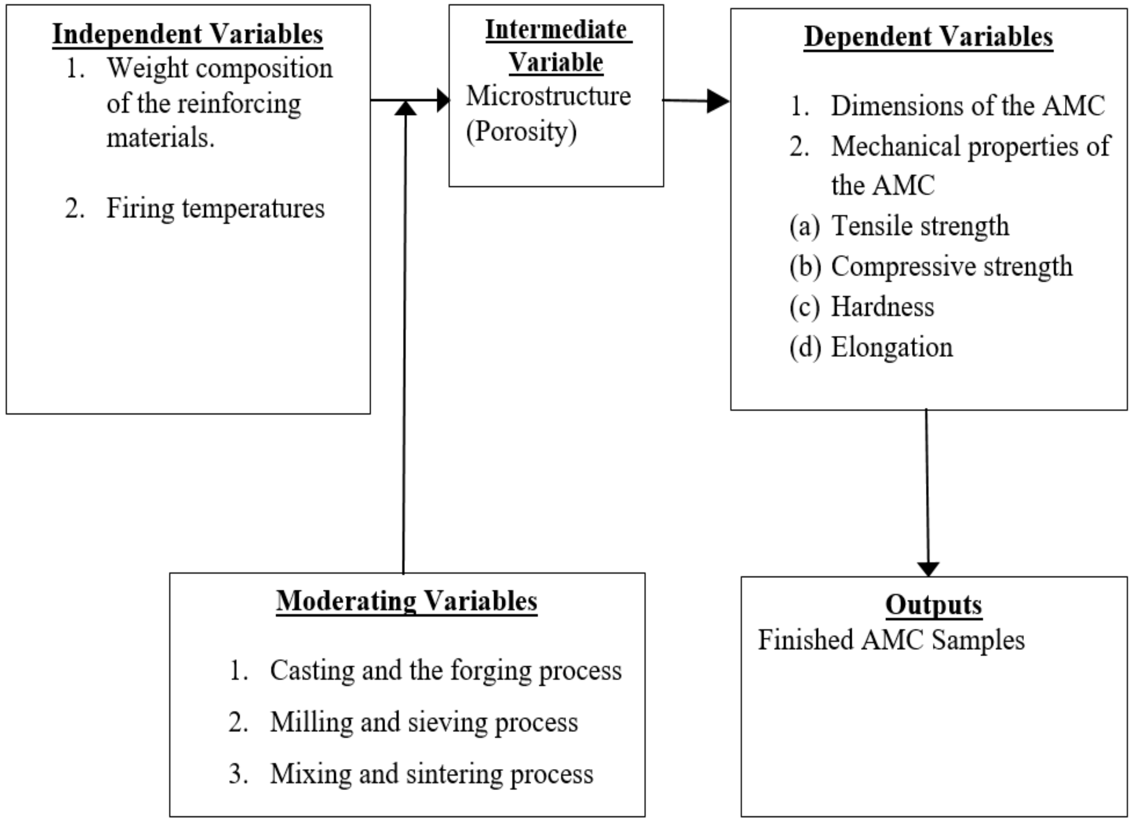

Figure 1.1: Conceptual Framework

CHAPTER TWO: LITERATURE REVIEW

2.1 Introduction

This section presents literature on aluminium and its composites, crushed gravel powder, coconut shell ash, the chemical composition of raw materials, casting methods, microstructure testing equipment, and the mechanical properties of test equipment with a global perspective in order to develop a proper understanding of AMCs fabricated for various applications.

2.2 Composite Materials

Composite materials can be defined as the combination of two or more distinct materials that produce superior qualities than the individual parts used. The composite materials are made of resins, reinforced to enhance mechanical strength. According to Sharma et al., (2020), the resin can be a metal matrix, polymer matrix or a ceramic matrix which is selected based on its mechanical, chemical or thermal properties as shown in Figure 2.1. Metal matrix composites (MMCs) are well known as advanced materials and the common metal matrix are Aluminium, Copper, Iron, Magnesium, Nickel, and Titanium. Metal alloys are combinations of two or more metals or non-metals that can be mixed to produce a new material with unique properties (H. Liu et al., 2023).

Reinforcement materials can include, gravel, and biomass waste such as coconut shell ash powder (CSAp), peanut shell ash, bamboo leaf ash and rice husks ash. The choice of suitable reinforcements and resins enables the composite materials to exhibit better mechanical properties than the resin and reinforcement alone (Naito et al., 2021). The reinforcing materials can make a composite material be chosen based on its unique mechanical properties. They include strength, stiffness, toughness, durability, hardness, elongation, and corrosion resistance.

Aluminium matrix composites (AMCs) have attracted a lot of interest lately because of their remarkable mechanical qualities and several potential uses in various industries. Stojanovic et al., (2018) stated that one of the best ways of making improvements in the properties of aluminium alloys is to create hybrid composites. Aluminium alloys are created by mixing pure aluminium with other elements, such as copper, magnesium, zinc, among others. As mentioned earlier, the addition of these elements alters the properties of aluminium. Due to their distinctive qualities, ultra-lightweight aluminium alloys like AA6061 and AZ31B find their use in a variety of significant applications more so in the construction industry (Manickam etal., 2023). This literature review explores the special characteristics of aluminium, crushed gravel, and coconut shell powder concerning the investigation into an aluminium matrix composite reinforced with these materials.

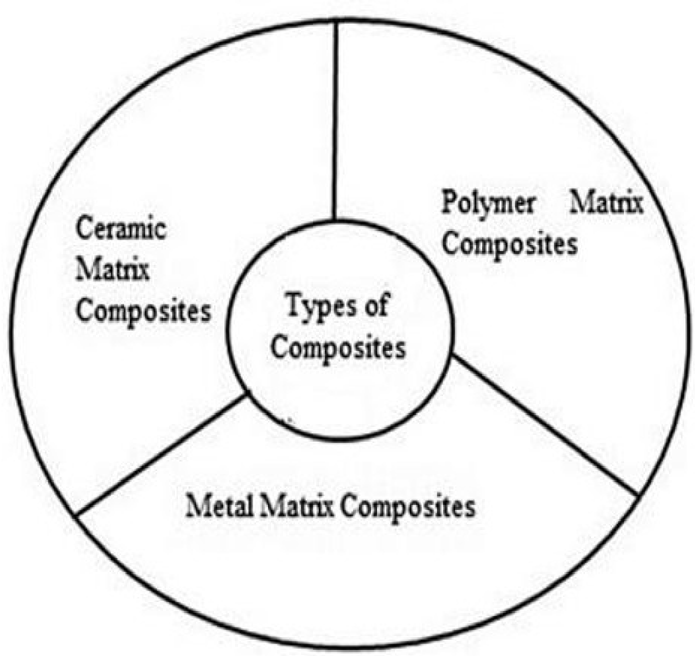

Figure 2.1: Classification of Composites According to Matrix Materials.

2.3 Raw Materials

2.3.1 Aluminium

Aluminium as a metal itself belongs to the group of chemical elements called the post-transition metals, whose density is about 2.7 g/cm3, with a melting point of 660.32 0C. They are characterized with a low specific gravity and a boiling point of 2467 0C (J. Liu et al., 2023). Additionally, aluminium is a silvery-white metal that is widely used in conventional and novel applications due to its unique properties such as its light weight, high strength and resistance to corrosion (S. Kumar & Kumar Jha, 2021). Due to the development of a thin oxide coating on its surface, aluminium is highly resistant to corrosion as this layer prevents further oxidation of the metal. The metal is highly ductile and it is a relatively soft metal, making it malleable, but upon being alloyed, it can be made significantly stronger. Aluminium finds extensive application in the manufacturing of machinery and tools, building construction, transportation infrastructure development, food and beverage packaging, building construction, and transmission of energy (Naito et al., 2021).

2.3.2 Chemical Properties of Aluminium

Aluminium is a highly reactive metal and can easily form chemical compounds with a variety of elements. Aluminium reacts with oxygen in the air to produce a thin coating of aluminium oxide, which shields the metal underneath from additional oxidation and corrosion. Additionally, aluminium is resistant to many acids, including hydrochloric acid, sulphuric acid, and nitric acid, but on the other hand can react with strong alkaline solutions. In terms of alloying, the metal can easily be alloyed with other metals to form a wide range of metal alloys with unique properties. Further, it is worth to note that aluminium is not highly combustible and therefore this makes it a suitable metal for a wide range of applications. However, finely divided aluminium powder can ignite when exposed to relatively very high temperatures.

2.3.3 Special Characteristics of Aluminium as Matrix Material

Aluminium possesses several unique characteristics that make it a preferred choice as a matrix material in composites:

i. Lightweight: This makes it vital for applications like aerospace and automotive industries where reducing weight is critical.

ii. High Strength-to-Weight ratio making it suitable for structures requiring strength and durability

iii. Corrosion resistance: Long-term endurance is ensured by the natural oxide coating of Aluminium.

iv. Thermal conductivity: High thermal conductivity enables efficient heat dissipation.

v. Malleability and ductility: These properties facilitate the fabrication and forming of composite structures.

2.3.4 Characteristics of Aluminium Matrix Composites

Aluminium metal matrix composites (Al-MMCs) and its alloys are generally used for producing metal matrix composites. Because of their exceptional mechanical qualities, ductility and strong resistance to corrosion, aluminium and its alloys have drawn the most attention when used as the matrix material in metal matrix composites in many engineering applications (Muley et al., 2015). Additionally, aluminium matrix composites are extensively utilized more frequently than competing materials because they are inexpensive, readily available, machinable, durable and have superior resistance to wear and corrosion. In fact, Sharma et al., (2020) further states that the addition of nonmetallic materials such as fly ash, Silicon carbide and Boron carbide, can improve their machining, tribological and mechanical properties. Zhu et al. (2023) states that a material's microstructure has a significant impact on its mechanical qualities.

2.3.5 Coconut Shell Ash

Coconut shells are the hard-outer coverings of coconut fruits. They are composed of organic and inorganic materials, basically cellulose, lignin, and mineral compounds such as calcium carbonate. Cellulose being the primary component in the structure of coconut shells, it accounts for up to 50% of the shell's composition (Onyelowe, 2016). Additionally, cellulose is a complex carbohydrate made up of long chains of glucose molecules that provide the strength and rigidity of the shell. Lignin, another organic component found in coconut shells, makes up to 20-30% of the shell's composition. Since it's a complex polymer, it therefore provides extra strength and stiffness to the shell. In addition to the organic materials in the coconut shells, other compounds in the shells are mineral compounds, such as magnesium, potassium, phosphorus, and calcium carbonate and they are these minerals that give the shell its properties of hardness and durability. According to Shanmuga Priya and Padmanaban (2024) coconut shell powder, an agricultural waste product, offers distinctive characteristics for composite reinforcement such as low density due to its light weight, biodegradability, and low cost.

2.3.6 Crushed Gravel Powder

Gravel is basically, a naturally occurring sedimentary rock composed of small fragments of various minerals and rocks and its physical nature can vary depending on the size and shape of its individual fragments in addition to its composition. In terms of size, the particle nature of gravel can literally range from 2 mm to more than 75 mm. In terms of shape, gravel particles can take up angular and rounded shapes or a combination of both (irregular shapes). Gravel is generally hard and durable, though its hardness would definitely depend on the particular type of minerals and rocks that make up the gravel. Because of its physical nature, gravel is basically widely utilized for different structural purposes like in the construction industry. Crushed gravel, typically derived from natural rock formations, possesses unique characteristics relevant to composite reinforcement:

- **i.** High hardness: it adds to the composite's hardness and resistance to wear.
- **ii.** Abrasion resistance: It improves the composite's resistance to abrasive forces, which qualifies it for use in brake lining applications.
- **iii.** Inert nature: Gravel is chemically inert, which reduces the risk of chemical reactions within the composite.

2.4 Chemical Composition

2.4.1 Aluminium

Qiu & Wang, (2023) used the energy dispersive spectrometry (EDS) to examine the composition of 2024 aluminium alloy substrate. The EDS spectra showed that Al, O and Si were the major elements in the composition of anodized aluminium. Similarly, Santhosh et al., (2022) also used the EDS to ascertain the composition of an aluminium composite and the EDS point analysis gave distinct peaks of Al, Si, and Mg alongside elements such O and C which form compounds with Al. Wang et al., (2023) investigated the chemical composition of 6092 aluminium alloy and results showed that the alloy comprised of elements such as Mg, Cu, Si, O, Fe, and Ti with Al being the principle element present with a weight percentage of more than 95%.

2.4.2 Coconut Shell Ash

The coconut shell is a tough part that is found between the coconut fresh and the coconut husk categorized as one of the hard-agricultural wastes and regarded as a high-potential material due to its excellent strength and modulus qualities (Somashekhar et al., 2018). Furthermore, the authors noted that when compared to other materials, coconut shell powder has excellent qualities including low cost, renewability, high specific strength-to-weight ratio, low density, less machine abrasion, and environmental friendliness. Yadav et al., (2021) stated that coconut shell ash powder (CSAp) has a high content of silica and can act as a potential source of silica and activated carbon. A study by Aku et al. (2013) on the coconut shell ash particulates using an X-ray fluorescence analysis revealed that SiO2, Al2O3, MgO, and Fe2O3 were the major compounds in the CSAp with weight percentages of 45.05%, 15.6%, 16.2%, and 12.4% respectively. The results still revealed the presence of flux oxides such as CaO, K2O, Na2O. Similar results were obtained by Isnaini (2012) and Yadav et al. (2021). An EDX spectrum of the CSAp is shown in Figure 2.2. Aku et al., (2013) further stated that the ash from coconut shells contains oxides of Si, Al, and Fe, meaning that they can be used as particulate reinforcement in metal matrix.

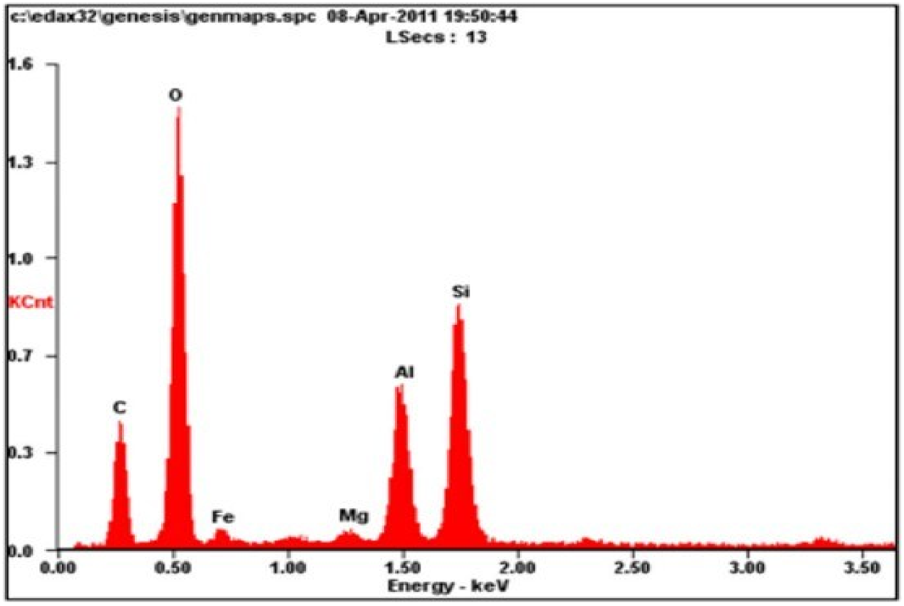

Figure 2.2: An EDX spectrum of the Coconut shell ash particulate.

2.4.3 Crushed Gravel Powder

A study by Zhang and Luo (2019) on a new technique for calculating the surface free energy of extremely wettable mineral powders revealed that SiO2, Al2O3, and Fe2O3 were the principle oxides present in the gravel aggregate, with other oxides such as Na2O, CaO, MgO, and SO3 present but with low weight percentages. Furthermore, Tzibulsky and Frid (2023) used SEM coupled with the EDS analysis to understand the chemical compositon of gravel and the study results revealed that the rocks were composed of silica, oxygen, and small amounts of calcium, for which silicon and oxygen were the principle elements present that give rise to SiO2.

2.5 Casting Methods

The casting process involves pouring liquefied material such as molten metal into a mold that has been specially prepared, then cooling the metal to solidify or harden it (Li et al., 2024). After solidification, the workpiece is drawn from the die and it undergoes several finishing treatments to achieve the desired shape and size. According to Aynalem (2020), there are different casting methods used in the development of complex solid shapes and cast products, and different research studies have been conducted on the different casting methods which include; sand casting, high-pressure die casting, flux casting, stir casting, solid-state powder metallurgy, and squeeze casting.

2.5.1 Sand Casting

This is one of the most prominent, low cost, and conventional techniques used in foundries that basically rely on silica-based materials such as sand which can be strengthened with addition of clay. Typically, this method uses spherical particles of finely crushed sand that are firmly packed together to create a smooth molding surface. However, Xu et al. (2022) claimed that pore defect and interfacial response in sand castings are extremely important issues that lower the quality of the cast work piece. B. Liu et al. (2024) conducted a research study on the impact of hollow sand molds on the mechanical characteristics and microstructure of aluminium alloy casting. The researchers developed a large aluminium alloy conical cabin and research results showed that the tensile strength and elongation of the hollow mold structure increased by 1.1% and 41.1% respectively when compared to the dense mold.

2.5.2 High Pressure Die Casting

This is currently one of the most efficient and effective manufacturing technique because of its simple operation, high casting rate, and quick production capacity (Dudek et al., 2023 ; Jiao et al., 2023). This process often works with non-ferrous metals and alloys and entails molding the materials under high pressure. However, the technique is prone to the formation of massive gas pores in the material under development hence affecting the mechanical properties of the materials. Zhang et al., (2020) found out that porosity was unavoidable in an aluminium alloy developed using high pressure die casting, which finally affected the mechanical properties of the alloy. According to Di et al. (2024), die casting molds are capable of withstanding complex mechanical loads during use. According to Pellizzari et al. (2023), die casting mold needs to have exceptional qualities including strength, toughness, wear resistance, high temperature performance, and heat fatigue resistance in order to guarantee the mold's active life under demanding working conditions. In the fabrication of Al2O3- reinforced MMCs using the die-casting technique, the evaluation done showed that ultimate tensile strength, elastic modulus, and Rock-well hardness of the fabricated MMCs increased with an increase in the reinforcement materials.

2.5.3 Stir casting technique

This technique is used to develop composites by mixing reinforcing materials such as silicon carbide (SiC) and Cu, high carbon steel chips, among others, with an aluminium matrix using a stirrer that is either driven manually or automatically with the help of a motor (Vineeth Kumar & Jayahari, 2018). Stir casting technology is relatively easy to use and inexpensive when fabricating AMCs than its alternatives. Al matrix hybrid composites developed by this casting technique with the use of bamboo leaf ash and silicon carbide as reinforcements was investigated by Alaneme et al. (2013). In the study, silicon carbide (SiC) particulates added with 0, 2, 3, and 4 wt% bamboo leaf ash (BLA) were utilized to prepare 10 wt% of the reinforcing phase with Al-Mg-Si alloy as a matrix using two-step stir casting method. The performance of the composites was evaluated through microstructural characterization and mechanical property evaluation. The study's findings demonstrated that the hardness, ultimate tensile strength, and percent elongation of the hybrid composites all decreased as the amount of bamboo leaf ash increased. However, Sarada et al. (2015) produced an aluminium hybrid MMCs (LM 25+ Activated Carbon+ Mica) by stir casting method and study results showed an increase in hardness of hybrid composite material by 14.285% when compared with activated carbon metal matrix composite.

2.5.4 Squeeze Casting

The liquid metal forging process, commonly referred to as squeeze casting, is a casting method that combines the benefits of gravity permanent mold casting, high pressure die casting, and conventional forging technology (Aynalem, 2020). This technique is a combination of both casting and forging processes in which a slurry of molten matrix and reinforcement is poured into the bottom half of the preheated die and pressure is then applied while the metal solidifies. Mohan Kumar et al. (2018) used preheated fly ash particulates with 3 and 5wt% to make an Al composite by squeeze casting technique. After being poured into the heated die cavity and squeezing it with a load of 120 MPa, the molten liquid composite solidified inside the mold. The final mechanical property test findings demonstrated that adding more fly ash particles to the composites increased their hardness, yield strength, and UTS linearly. Okafor and Aigbodion (2010) studied the effect of zirconium silicate reinforcement on Al-Cu alloy matrix prepared by squeeze casting. The molten matrix was mixed with preheated reinforcing particles, then poured and solidified under a 10 MPa squeezing load. Hardness, apparent porosity, yield strength, and ultimate tensile strength of the composite were increased by 107.65%, 34.2%, 156.52%, and

155.8%, respectively, when 15wt% zirconium silicate ($ZrSiO_4$) reinforcing particulates were incorporated.

2.5.5 Flux Casting

This is a casting technique that permits the incorporation of a number of reinforcements into molten Aluminium without the need for vigorous stirring. In the fabrication of an Al-TiC MMC using the flux casting technique, the study results showed that the technique permits well distribution of reinforcement in commercial Al-Al_2O_3 and the manufactured composites. The study results still showed that the composites exhibited better properties such as ultimate tensile strength and stiffness than the commercial Aluminium.

2.6 Microstructural Characteristics

The microstructure of a composite material refers to the arrangement of its constituent materials at the microscopic level (Padmavathi et al., 2020). Since there are two or more constituents in the composite material, its microstructure can significantly affect its mechanical, electrical, and thermal properties (Wan et al., 2022). In general, the microstructure of composite materials is typically characterized by the size, shape, and orientation of the reinforcing fibers or particles within the matrix material. The reinforcing material, which can typically be stiffer or stronger than the matrix material, provides improved and better mechanical properties of the composite, as the matrix material holds the reinforcements in place and provides the desirable properties, such as corrosion resistance, toughness, and wear resistance.

2.6.1 Microstructure of Aluminium

In recent years, research on the uniformity of the microstructure of forging has been conducted with two main practical methods for the grain refinement utilized (HU et al., 2022). The first method is to attain grain refinement through the dynamic crystallization approach and the second one is to improve uniformity through isothermal die forging process (Guo et al., 2015). The approach of refining grains through plastic deformation is widely utilized in the production industry. Sakai et al. (2009) performed a high temperature massive deformation of 7074 aluminium alloy with a total strain of 6.3 using a multi-directional die forging procedure. The findings demonstrated that when the strain rate was smaller, the alloy underwent continuous dynamic crystallization, which realized grain refinement. HU et al., (2022) studied the evolution of the microstructure during hot die forging process of aluminium alloy. The authors found that dynamic recovery and dynamic recrystalisation were the primary mechanisms of microstructure change during the heat deformation process of the aluminium alloy 7A85. Zupaniˇc et al. (2023) studied the microstructure and mechanical properties of aluminium alloy AA 6086 and the results showed that, according to the ASTM E112 standard, the micrograph of billet in the transverse and longitudinal directions showed crystal grains of the matrix solid solution that possessed a fibrous microstructure with long elongated grains in the extrusion direction. Qiu & Wang, (2023) observed the surface morphology of 2024 aluminium alloy using SEM and the microstructural results suggested that the alloy substrate had grinding marks and pits as shown in Figure 2.3.

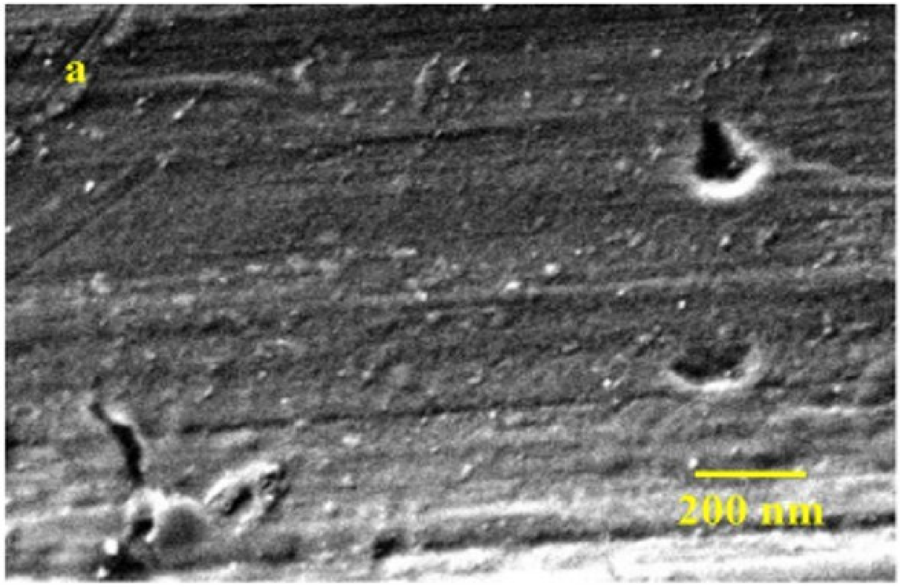

Figure 2.3: Surface morphology of 2024 aluminium alloy substrate.

2.6.2 Microstructure of Coconut Shell Ash

According to Zhao et al. (2023), the microstructural characteristics determine the performance of the materials and thus a need for an identification of the material's microstructure. Apasi et al., (2016) investigated the microstructure and mechanical properties of aluminium alloy reinforced with 0-15 wt% coconut shell ash powder. In the study, microstructural analysis revealed that the composite had a homogeneous distribution of coconut shell ash particulates within the matrix. As mentioned earlier, a microstructural observation by Aku et al., (2013) in Figure 2.4 showed that the CSAp can reasonably distribute in the aluminium alloy. The researchers stated that the fair wettability of the molten metal and the fair interfacial bonding between the coconut shell particles and matrix material affected the distribution of the coconut shell ash particles. Additionally, the mechanical properties of the developed composite, such as hardness increased with increasing weight of the coconut shell ash powder, and so did the tensile and yield strength of the composite. Similarly, in a study by Refaai et al. (2022) to optimize the mechanical properties of aluminium 8079 composite materials reinforced with peanut shell ash, study results showed that there were pockets of agglomerated reinforcement particles inside the aluminium matrix where the peanut shell ash reinforcements were more evenly distributed.

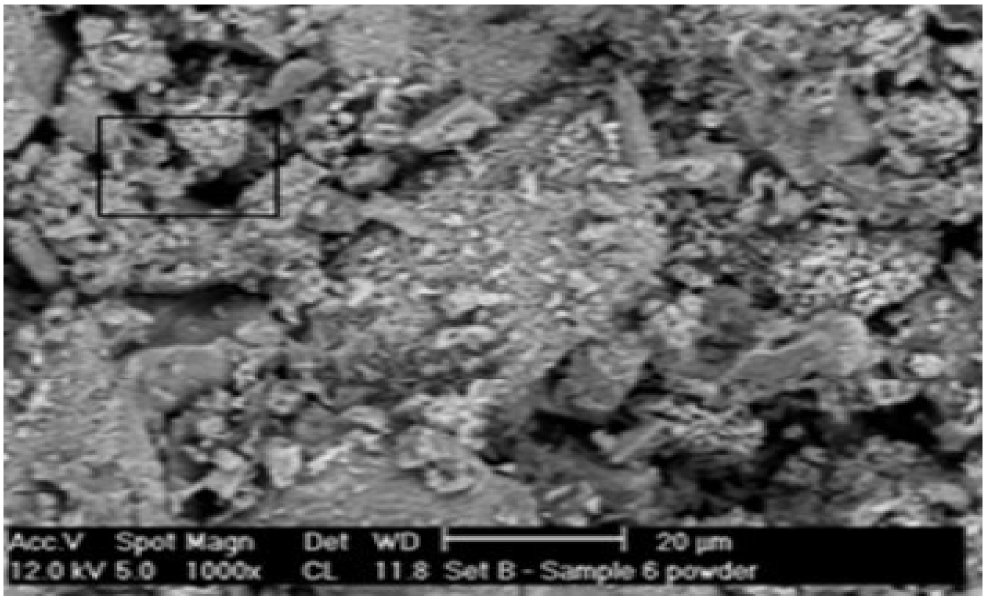

Figure 2.4: Microstructure of CSAp (Aku et al., 2013).

2.6.3 Microstructure of Crushed Gravel Powder

To understand the morphology of gravel, Tzibulsky & Frid, (2023) used SEM (quanta 200) for the characterization and results revealed that the chert rock is characterized by a banded structure. Wu et al. (2017) carried out a mineral composition and microstructural analysis of gravel aggregate using SEM. In the study, the authors examined several gravel aggregates, including basalt, sandstone, gneiss, and quartzite. After performing a microscopic scanning of rock aggregates with varying amplification times, 50,000 times of rock images were obtained. The findings demonstrated that, at a magnification of 50,000 times at the 200 nm scale, different types of rock particles exhibited distinct microscopic morphology, with irregular protrusions on the surface of limestone particles. While the quartzite surface featured some uneven protrusions, the basalt particle surface displayed exfoliated features.

2.6.4 Microstructure of Composites

Numerous microscopic techniques including optical microscopy, scanning electron microscopy, and transmission electron microscopy, can be used to observe and analyze the microstructure of composite materials (Padmavathi et al., 2020; Wan et al., 2022; Liang HU et al., 2022). It is worth noting that the performance goals of any composite material can be optimized by adjusting the composition, size, and shape of the reinforcing materials.

In the study by Abdulrazaq et al., (2023), Scanning electron microscopy was employed examine the surface morphology and structure of the two reinforced aluminium composites (dolomite and date palm seeds) at different proportions of reinforcing materials. The appearance of the 2.5% date palm seeds with a magnification picture (500×) showed the distribution of date palm seed ash particles in the AMC, with the darker areas corresponding to the ash in form of carbon agglomerates, as shown in Figure 2.5 below.

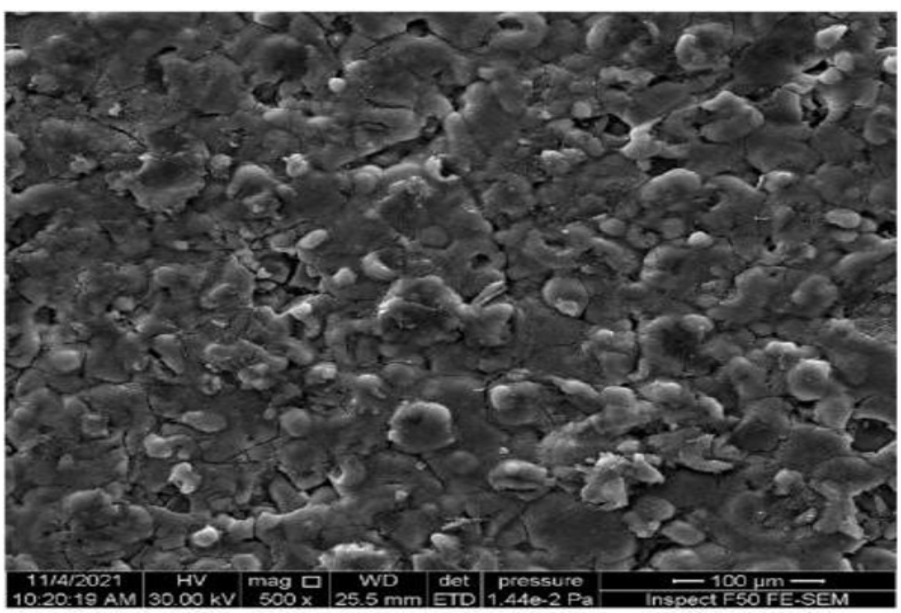

Figure 2.5: Surface Variation of 2.5% Date Palm Seeds Reinforced Aluminium Composite (Abdulraaq et al., 2023).

2.6.5 Microscopic Defects

Microscopic forming defects are imperfections or irregularities that occur during the manufacturing process of materials such as metal composites or plastics. These defects can be caused by a variety of factors, including but not limited to improper tooling, inadequate lubrication, use of wrong or incorrect temperatures, or improper material handling. The most common types of these microscopic defects include porosity, cracks and inclusions. In most cases, porosity occurs when gas or air bubbles become trapped in the material during forming process. Shao et al. (2022) using the probability functions and the statistical continuum theory, developed a methodology to construct a 3D microstructure for an isotropic porous material with a given porosity. In the study, it was possible to rearrange the isotropic porous material into an anisotropic material with desired physical properties and pore connectivity. On the other hand, cracks can occur due to high stress or strain in the material and voids are areas within the material where no material exists. For the case of inclusions, these are foreign particles that become embedded or trapped in the material during forming. The materials can negatively affect the mechanical properties of the composite formed thereby reducing its strength, ductility, and other important characteristics. In a study conducted on efficient aluminium depositing using additive manufacturing by Xie et al. (2023), study results suggested that microscopic forming defects can be prevented by choosing the right process parameters. Therefore, it is important to carefully monitor and control the forming process during manufacturing to minimize the occurrence of these defects by using high-quality tools, proper lubrication, and precise control of temperature and other forming parameters that come into play.

2.6.6 Fatigue in Composite Materials

Among the main underlying reasons for structural breakdown of composite structures in different applications is fatigue failure. In a study to quantify fatigue damage in fiber composite materials, Eder et al. (2021) developed an innovative and reliable methodological approach employing thermal imaging to evaluate damage progression stages in fiber-reinforced composite materials under fatigue loading and study results showed that the method was useful to determine fatigue damage in composite materials. Zupaniˇc et al., (2023) carried out quasi-static and fatigue tests on aluminium alloy AA 6086 using a 100kN servo-hydraulic test machine controlled with a mechanical extensometer (McKenna et al., 2023). Test results showed higher quasi-static strength of the alloy, and those for compressive fatigue showed relatively good fatigue resistance.

2.7 Mechanical Characteristics

The ability of a material to withstand loads and mechanical forces is referred to as its mechanical property. They entail a response to an applied load. The mechanical characteristics of metals define a material's anticipated service life. They include strength, stiffness, elasticity, plasticity, ductility, brittleness, malleability, toughness, resilience, creep and hardness.

Aluminium and its alloys allow the use of various reinforcement. H. Liu et al., (2023) suggested that it's of great importance to practically understand the shear response of composite materials as any shear loading can significantly limit the load-bearing capability of the composite materials thereby limiting their utilization. However, due to the availability of the low cost agricultural wastes such as coconut shells, groundnut shells, peanut shells, rice husks, palm oil clinkers, among others, their use as reinforcement materials has significantly increased and greatly affects the mechanical properties of the composite (Abdulrazaq et al., 2023). Furthermore, according to Wan et al., (2022), the mechanical properties of aluminium composites are highly dependent on the composite's microstructure, and the elemental com- position of the reinforcement materials.

2.7.1 Tensile Strength

Tensile strength is an important property in material science and engineering, as it is a critical factor in designing and selecting of materials for structures and components that will be subjected to tensile loads. it is the highest stress a material can withstand before cracking or irreversibly deforming under tension. It is, thus, a measurement of the material's resistance to breaking apart. For composite materials, their tensile strength depends on the properties of constituent materials and the way they are combined. The constituent materials that have different properties such as stiffness, strength, and toughness, when combined lead to the formation of a new material with superior properties such as higher tensile strength. Khazaal et al.(2022) conducted a study on the material properties of the hybrid metal matrix composites and the study results showed that best mechanical properties of the composites were 61%, 37% and 7% for compression strength, hardness, and radial crushing strength respectively considering 97% Fe and 3% (80% Al_2O_3 + 20% ZrO_2).

During formation of a composite material, the particles in the material are arranged in a specific orientation being held together by a matrix material, which provides the required support. This arrangement allows the composite to distribute the tensile load more evenly across the material thereby reducing on the stress concentration thus preventing premature failure. However, Gusev et al. (2021) stated that the process of formation of the structure of a composite material is anti-persistent and at a volume defect concentration of 65%, structural transition leads to high decrease in the relative strength of a material. Nevertheless, the tensile strength of these composite materials can be improved by selecting the right combination of materials, optimizing volume fraction and orientation of the constituent materials, and using appropriate and advanced manufacturing techniques. In a comparative study by Manoharan et al. (2022) on the tensile strength of hybrid aluminium matrix composites, a mathematical model for predicting the tensile strength of nano composites was proposed and physical experimental results showed that the nano particulate reinforced composites presented an improvement in the ultimate tensile strength by 53.4% of the unreinforced matrix and by 8.5% of the micro-composite at reinforcement levels of 15% weight percentage of silicon carbonate. Daramola et al. (2015) evaluated the mechanical properties of Al 6063 alloy-coconut shell composite. The researchers discovered that when the percentage weight of the coconut shell increased, the composite's tensile strength and hardness also increased.

2.7.2 Compressive Strength

This is the material's ability to bear loads before failure. The property can give valuable information about the characteristic behavior of a material under study. Abdulrazaq et al. (2023) used aluminium powder as a matrix material to develop aluminium matrix composites using reinforcements such as ash of date palm seeds and dolomite rocks. The composites were subjected to hardness and compressive strength tests from which the study results showed that for the compressive strength, the date palm seeds composite resisted 23.8 MPa at 7.5% reinforcement compared to 16.68 MPa for a dolomite reinforced aluminium composite.

2.7.3 Hardness

Obianyo (2019) defined hardness as the capacity of a substance to withstand abrasion or penetration when subjected to an applied load. According to Khazaal et al., (2022), the Rockwell test is one of the most widely used experiments used to measure the hardness of metals and it's applied to measure material's resistance to indentation under a static force. Abdulrazaq et al. (2023) reported that the composite reinforced with 7.5% date palm seeds possessed a higher hardness of 50 HRV while that reinforced with dolomite had a hardness of 48.3 HRV. However, Deshmanya and Purohit (2012) stated that the hardness of composites steadily decreases as reinforcement size increases because a larger grain size results in a less dense distribution of Al2O3 particulates in the aluminium matrix. Elangovan and Ravikumar (2014) evaluated the factors that affect the wear behavior of aluminium reinforced with fly ash using stir and squeeze technique. The researchers reported that addition of fly ash in the matrix material improved the hardness and wear resistance of the composite. Similar results were obtained by Refaai et al., (2022) when the researchers reinforced aluminium 8079 with peanut shell ash for which study results revealed that there was an increase in the hardness of the composite as the reinforcing weight percentage rises. Furthermore, Subramaniam et al. (2019) stated that a 3 wt% coconut shell fly ash and 12 wt% boron–carbon ceramic (B4C) reinforcements in the Al7075 metal matrix increased the hardness of the composites by 33%.

2.7.4 Elongation

In an investigation on the mechanical properties of aluminium 7075-boron carbide reinforced with coconut shell fly ash, Subramaniam et al., (2019) discovered that as the weight percentage of fly ash from coconut shells increased in the matrix, the composites' elongation reduced. Alaneme et al. (2018) also studied the mechanical properties of groundnut shell ash and silicon carbide particle reinforced aluminium composites, in ratios of 0:10, 2.5:7.5, 5:5, 7.5:2.5, and 10:0 for the a particulate combination of groundnut shell ash (GSAp) and silicon carbide. Study results revealed that the bigger rise in the percentage elongation that was attained was compatible with the higher concentration of GSAp.

2.7.5 Work Hardening

The mechanical properties of a material, such as hardness and strength, can be improved through plastic deformation, a process well known as work hardening. The use of plastic deformation processes such as bending, stretching, or rolling, can help in the work hardening of aluminium composites. This is because during plastic deformation, the dislocations in the material become more tangled and entangled, resulting in an increase in the hardness and strength of the material. A review paper by Das et al. (2014) on the properties of ceramic- reinforced AMCs stated that the density, toughness, hardness, and compressive strength increased with increasing reinforcement fraction. However, it is further stated that these properties may reduce with the existence of porosity in the material, and it is further stated that the particle size of the reinforcement material can adversely affect the hardness of the material.

2.7.6 Impurities

Impurities in any given material do significantly have a wide range of effects and can therefore affect the properties of the materials, depending on the nature and quantity of impurities. These effects can affect the mechanical properties of the material (Pearce, 2014). To minimize the diverse effects of impurities in materials, it is of great relevancy to often use various purification techniques, such as chemical treatment, filtration, and distillation to reduce or completely remove the impurities.

2.8 Testing Machines and Methods

2.8.1 Scanning Electron Microscopy

This testing method also recognized as SEM analysis is used worldwide in many disciplines. It is regarded as an effective method in the analysis of materials on a nanometer to micrometer scale and is extensively employed to study and offer detailed information on the specimen's size, surface topography, chemical composition, and electrical behavior. According to Abdullah and Mohammed (2019), SEM works by scanning a sample with a concentrated electron beam that interacts with the atoms in the sample to produce a three-dimensional surface topography. The authors further stated that SEM can reach magnifications of 300,000x and that can provide a more detailed field with gray-scale images. Conventionally SEM operates in a high vacuum and necessitates intricate and thorough sample preparation (Apasi et al., 2016).

2.8.2 Universal Testing Machine (UTM)

This is a versatile machine used to test the tensile and compressive strength, elasticity, compression, yield strength, strain hardening, bend compression, elastic and plastic deformation of a range of materials, components, and structures. This puts the UTM in a position to handle a wide range of materials, including flexile items like rubber and textiles and hard samples like metals and concrete. Different models of the UTM have different load capacities ranging from 5 kN and above with tests conducted in a controlled environment at extreme temperatures from -196 oC to over 1000 oC. Luo et al. (2022) used a tensile testing machine (SHIMADZU AGS-X 50 kN) at an engineering strain rate of 10-3 s-1 at room temperature to perform a tensile test for an aluminium composite reinforced with silicon carbide.

2.8.3 Rockwell Hardness Testing Machine

According to Obianyo, (2019), Rockwell hardness test involves application of a standard load using a standard indentor for a standard amount of time. The purpose of this test is to measure the permanent increase in indentation depth caused by an increased load by forcing the indentor into the surface of a test item. Once the extra load is removed, the indentation is measured and the Rockwell hardness number is derived from the measurement of the depth of the impression.

CHAPTER THREE: METHODOLOGY

3.1 Introduction

This chapter explains the methodological techniques used in the creation of the aluminium matrix composite as well as the process of evaluating the mechanical characteristics of the finished product, which included hardness, elongation, compressive strength, and tensile strength. The composites are made of aluminium alloy as the matrix material and pulverized gravel and coconut shell ash as the reinforcing materials. The chapter also describes the procedures involved in the preparation of coconut shell ash, crushed gravel and aluminium alloy as the primary materials involved in the fabrication of the composite.

3.2 Research Design

The study employed an experimental research design whereby tests were carried out on the fabricated composite. As mentioned earlier, the tests included; tensile strength, compressive strength, hardness and elongation of the material. The stir casting method was employed for the development of the composite. Microstructural characterization was carried out using the scanning electron microscopy (SEM). For the elemental composition of the reinforcing materials, SEM coupled with the Energy dispersive X-ray spectroscopy (EDS) was used. The mechanical tests were done using the universal testing machine and the brinelle's hardness machine.

3.3 Process Description

The procedure followed in developing the AMCs are depicted in the schematic flow diagram in Figure 3.1. As it can be seen, the preparatory steps include gathering the raw materials and their preparation, mixing of the raw materials, casting, molding and machining of the fabricated composite into the desired round shapes measuring 25 mm in diameter and 250 mm in height. Finally, the finished product was subjected to various mechanical tests.

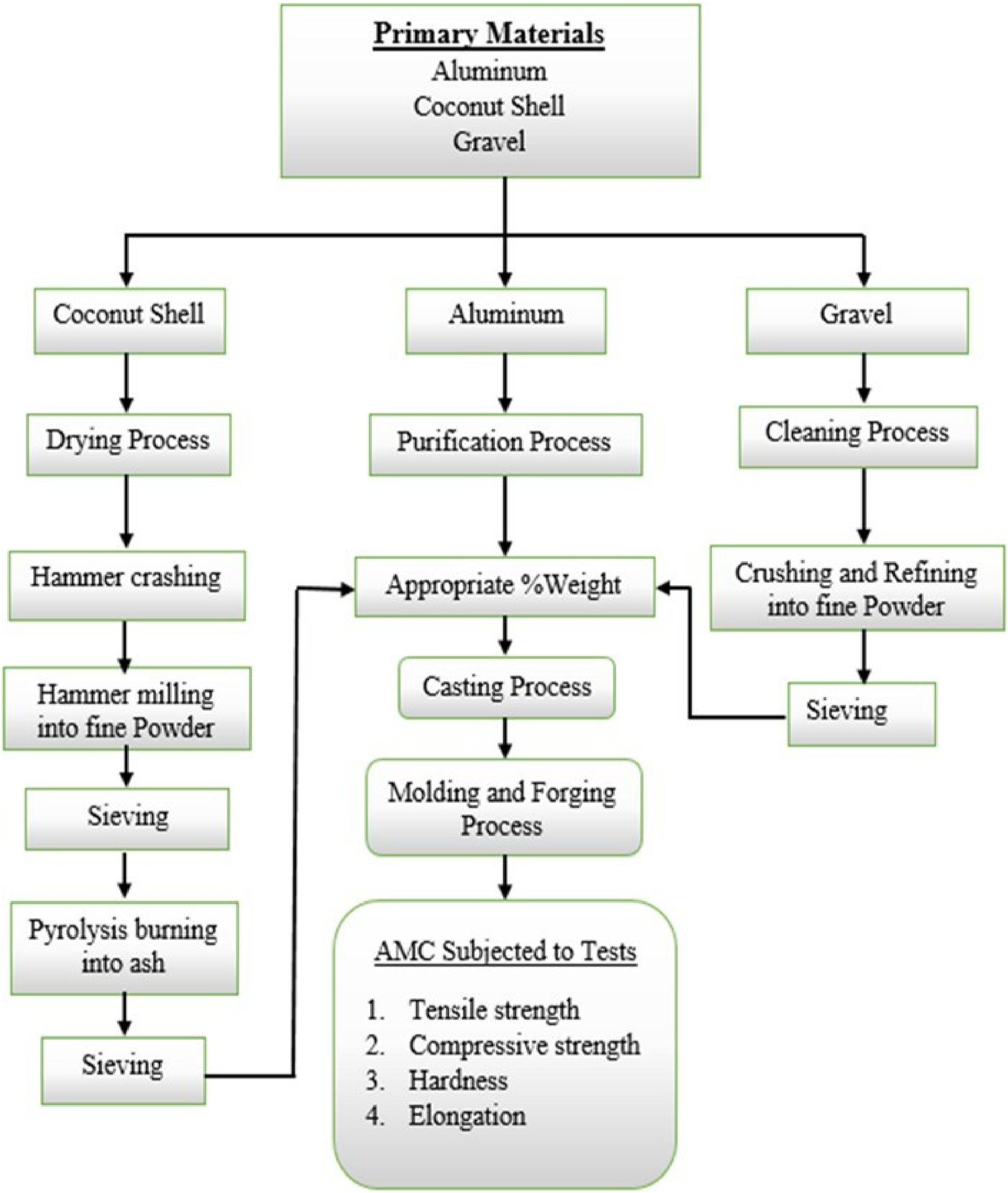

Figure 3. 1: Schematic flow diagram showing processes followed.

3.4 Preparation of the Raw Materials

The raw materials used in this study included; aluminium, crushed gravel and coconut shell ash. Before the materials were considered appropriate for use in the stir casting process, they went through numerous steps of preparation. The steps taken and techniques employed are described in subsections 3.4.1 and 3.4.2.

3.4.1 Coconut Shells

The coconut shells utilized in this investigation were purchased from Nakasero Market in Kampala. The coconut shells were dried using direct sunlight for 6 days to drive away the moisture. The dried coconut shells were first crushed to a size between 10- 15 mm as shown in Figure 3.2 (a). The shells were further processed to powder form using a hammer mill shown in Figure 3.2 (b). Subsequently, the pulverised coconut shells were sieved using conventional 0.3 mm and 0.16 mm mechanical sieves to form powder samples shown in Figure 3.3 (c) to guarantee a distribution size of particles. To obtain coconut shell ash, the coconut shell powder was subjected to a slow pyrolysis process in a ceramics furnace to a firing temperatures of 800 0C. The coconut shell ash was then passed through a standard mechanical sieve with a mesh size of 0.08 mm to obtain fine powder as seen in Figure 3.2 (d).

Figure 3.2: (a) Crushed coconut shells before milling, (b) Hammer milling process, (c) Coconut shell powder after milling and (d) Coconut shell ash after pyrolysis.

3.4.2 Gravel

The gravel used in this study was sourced from Mukono with a net weight of 6 kg in total. The gravel was first washed using clean water in order to remove any solid particles from them. The stones were then left under direct sunlight for 3 days in order to allow them dry. After the cleaning process of the gravel in Figure 3.3 (a), the stones were taken to a grinding machine (stone crusher) shown in Figure 3.3 (b) for crushing to desired fine particle sizes. Subsequently, the crushed gravel was sieved using a 0.08 mm mechanical sieve shown in Figure 3.3 (c) to produce the finely powdered form shown in Figure 3.3 (d).

Figure 3.3: (a) Gravel, (b) Stone crushing machine, (c) The sieving process and (d) Fine crushed gravel powder.

3.5 Chemical Composition of Raw Materials

The elemental composition of coconut shell ash and crushed gravel was carried out using a scanning electron microscope (SIGMA 300 VP) coupled with the Energy dispersive X-ray spectroscopy (EDX). Here an EDX system is installed on the SEM apparatus to enable chemical analysis of the characteristics being shown in the SEM monitor. EDX adds essential compositional information to the electron microscopy pictures in order to provide a thorough morphological and elemental composition of the materials.

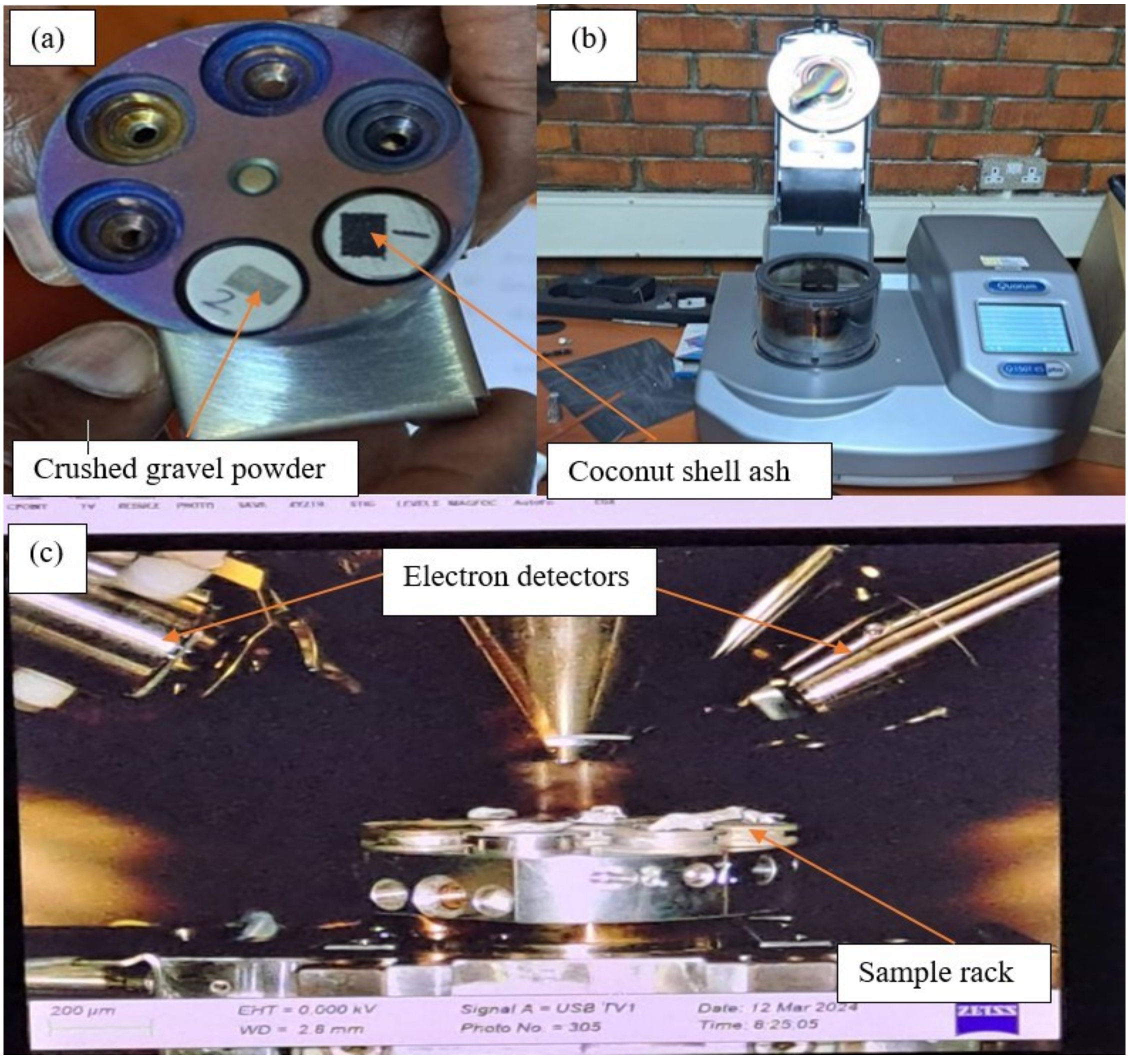

Figure 3.4: (a) Sample holders on a sample rack, (b) The sample coater for chemical analysis and (c) Detectors for electron generation in SEM Equipment.

3.5.1 Sample Preparation

Samples of coconut shell ash and crushed gravel were placed on the sample holder that sits on the sample rack using a carbon tape as shown in Figure 3.4 (a). The setup was placed in the sample coater (Q 150T ES) for two minutes as seen in Figure 3.4 (b). In the sample coater chromium was vaporized to ensure that the samples are more conductive. The samples were then removed from the sample coater and placed in the SEM equipment to provide an electrically conductive thin coating that accurately depicts the samples surface topography for viewing. The detectors that generate electrons in the chamber of SEM apparatus direct them to the sample to get the image of the sample on the SEM monitor as seen in Figure 3.4 (c). The EDS file is then extracted to stimulate the distinctive X-rays from the sample and ascertain the sample's elemental composition.

3.6 Fabrication of the AMC

Creating an aluminium matrix composite using coconut shell ash and crushed gravel involved a careful balance of materials to achieve the desired properties. According to Apasi et al. (2016), the percentage weight composition of reinforcement materials in any matrix composite can range from 0-18%. Increasing it beyond 18% may lead to decrease in the tensile strength. Based on this observation, this present study employed aluminium as the matrix material with a percentage weight composition ranging from 85-100%. Coconut shell ash as one of the reinforcing filler material had a percentage weight ranging from 4% -10%. Similarly, the percentage weight of the crushed gravel was varied from 5%-7.5% depending on the desired properties.

3.6.1 Mixing of Raw Materials

Aluminium served as the matrix material during the fabrication of AMCs, and a pre-determined weight proportion of reinforcement materials was combined with it. The mixing ratios were put into consideration in the fabrication of each of the seven samples of AMCs. The actual quantities of the raw materials that were purchased to be utilized for the development of the composite are shown in Table 3.1. These materials underwent several steps of preparation to produce crushed gravel powder and fine coconut shell ash powder, as described in sections 3.4.1 and 3.4.2.

Table 3.1: Quantities of materials purchased

Material	Quantities
Aluminium	25 kg
Coconut Shells	40 kg
Gravel	6 kg

Table 3.2 shows the mixing ratios and the weight composition of raw materials for the fabrication of composites samples (S1-S7). The mixing ratios were based on the study by Apasi et al.,(2016) which gave good results for the mechanical properties. More information about the mixing method is found in section 3.6.3.

Table 3.2: Percentage weight of materials used in preparation of different composite samples

Material	Weight of the Components in Samples (%)						
	S1	S2	S3	S4	S5	S6	S7
Aluminium	90	85	85	95	95	93	100
Coconut Shell ash	4	7.5	10	5	-	-	-
Crushed Gravel Powder	6	7.5	5	-	5	7	-

3.6.2 The Molding Process

The steps followed during the casting process to develop the AMCs include; pattern making, molding, melting and pouring, shakeout, heat treatment and inspection.

Pattern making involved creating a replica of the developed product. The mold cavity was shaped and precise dimensions of 25mm diameter and 250mm height of the composite required were provided using this wooden template. The next phase was sand preparation, which entailed using a sand moller to refine the sand. The sand was sieved using mechanical sieves of 0.3mm and 0.16mm to achieve fine particles shown in Figure 3.5 (a).

Subsequently, sieved sand was mixed with a little film of water until the mixture was able to keep its solid shape. At this point, the mixture didn't stick to the hands, which was the ideal texture for sand casting. The molding process involved shaping materials into desired forms. This was achieved by introducing a pattern into a mold that specified the shape and size of the final product. During this process, treated sand was tightly packed around the pattern design and placed in a support box as shown in Figure 3.5 (b). At this point, the prepared mold was ready to receive the molten metal.

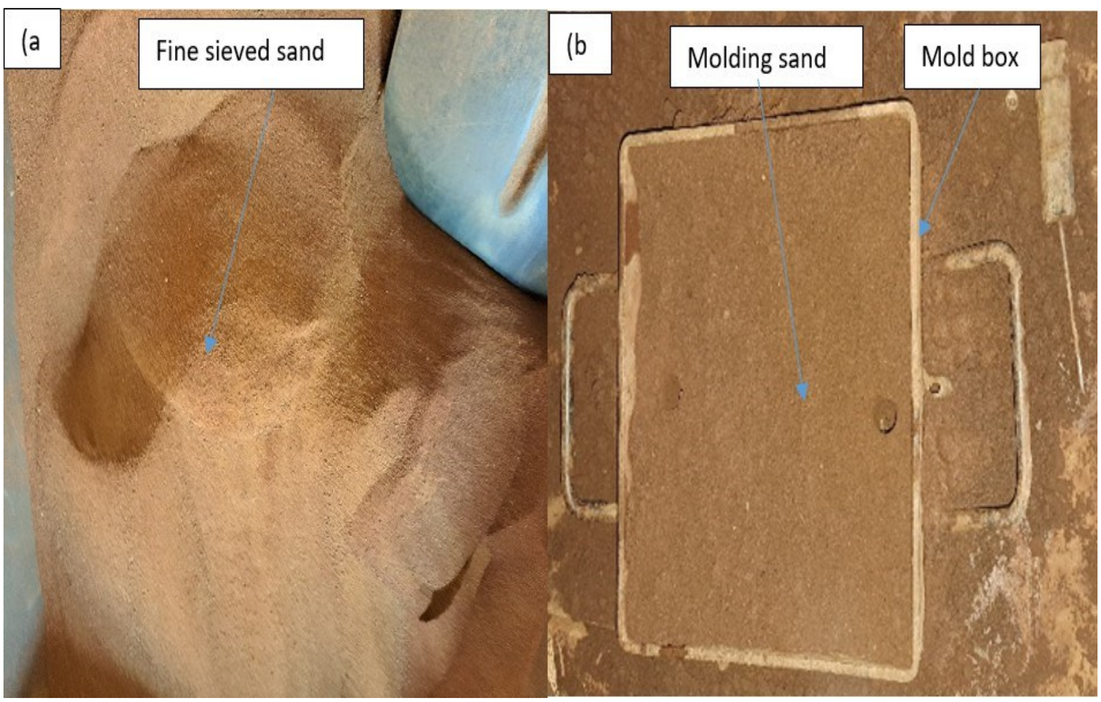

Figure 3.5: (a) Fine-sieved sand using a sand moller and (b) The molding process with a cavity ready to receive molten material

3.6.3 Casting of the AMCs

In this study, aluminium was used as a matrix material to produce the different samples of the composites. Coconut shell ash and crushed gravel powder were used as the reinforcing materials. The casting process was carried out at the foundry workshop located at the

Department of Mechanical and Production Engineering (DMPE), Kyambogo University. During the casting process, fire was started at the forging place where the burning chamber was located followed by placing of aluminium in the crucible as seen in Figure 3.6 (a) and (b). Mixing of raw materials was done as per the specified weight ratios shown in Table 3.2 and the measurements were done using a weighing scale shown in Figure 3.6 (c). Aluminium was fired up to a melting temperature of 650 0C that was recorded with a temperature gun in Figure 3.6 (d). Maintaining a specific temperature range was crucial for achieving a uniform distribution of the reinforcement materials. The pre-weighed powder samples of the reinforcement materials (coconut shell ash and crushed gravel powder) were heated at a different fire spots to eliminate impurities at the time of mixing them with molten aluminium. They were then poured into the molten aluminium and stirred continuously for five minutes to ensure uniform mixing.

The molten mixture shown in Figure 3.6 (e) was then poured into a permanent mold cavity so as to form desired AMCs measuring 25mm diameter and height 250mm as illustrated in Figure 3.6 (f). At this point the molds were filled and left to cool and harden. Sand was removed from the casting by vibrating the mold after the molten metal had solidified. Throughout the cleaning procedure, all extra metal was eliminated, with the aid of a chipping hammer. This was done to all sets of samples produced. After the molding process, machining of the composites was done and the final product was subjected to tests in a materials laboratory. The stop watch was used during the casting process by precisely measuring the timing of various stages. It aided in monitoring and recording the casting process duration, including the time required for mixing the aluminium alloy with the crushed gravel and coconut shell powder. This was done to ensure consistence in the process time for all the seven samples fabricated hence aiding accurate results.

Figure 3.6: (a) The forging area, (b) Fire setup for melting aluminium, (c) The weighing scale, (d) The temperature gun, (e) Molten aluminium in the crucible and (f) Appearance of the fabricated AMCs before machining.

3.7 Microstructural Analysis of the AMCs

Microstructural examination was carried out using SEM to view and analyze the size, shape, and orientation of the particles within the structure of the AMCs. Different samples of the AMCs developed were each prepared for microstructure examination by first grinding them using rough sand paper to remove the debris as shown in Figure 3.7 (a). The samples were polished using aluminium oxide powder to smoothen their surfaces. The samples were then pulverised using a ball mill to achieve an average particle size of less than 75µm. Subsequently the pulverised samples were placed on the sample holder that sits on the sample rack using a carbon tape as seen in Figure 3.7 (b) and (c). This sample rack sits on the sample stage in the SEM equipment shown in Figure 3.7 (d). In the SEM, images of the samples were produced by scanning the surface with a concentrated electron beam using detectors. The interaction of electrons and atoms in the sample produced various signals that reveal details about the sample's composition and surface topography. The microstructural results of the samples were then analyzed to clearly understand the microstructure properties of the samples.

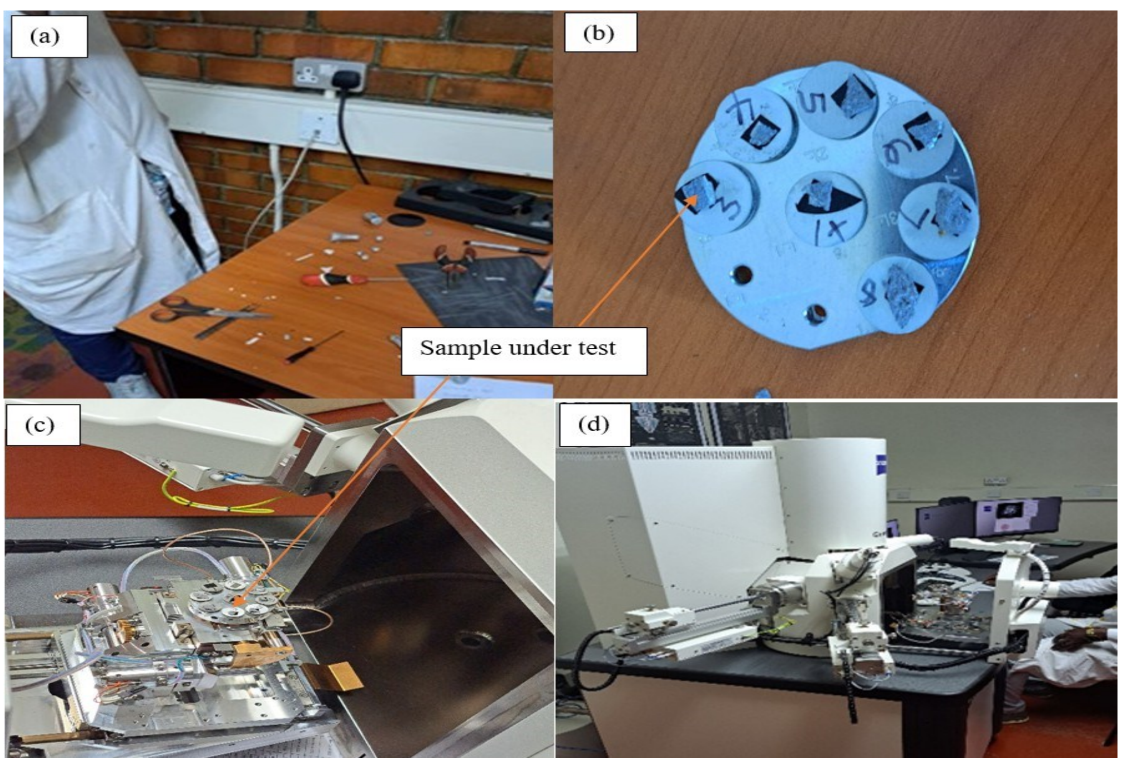

Figure 3.7: (a) Sample preparation process, (b) samples on the sample holder, (c) The sample rack on the sample stage and (d) The SEM equipment.

3.8 Mechanical Properties of AMCs

The material's mechanical characteristics show how it reacts to deformation caused by an applied load or force. Tensile strength, compressive strength, hardness, and elongation are the mechanical attributes that were examined in this investigation.

3.8.1 Tensile Strength

A universal testing machine (TORONTECH, TT-HW2-1000) was used to determine the tensile strength of the AMCs at a UNBS laboratory under conditions specified by ISO 6362-2:2014 standard. Other test parameters from the UTM include Yield strength and elongation. As shown in Figure 3.8 (a), each composite sample was positioned vertically between the two jaws and securely clamped. The samples were then subjected to a tensile force at a loading rate of 10KN/sec until they reached the fracture point. The maximum point of the graphs in Figure 4-5, Appendix A was considered as the breaking point of the AMCs. The tensile strength of the AMCs was obtained automatically from the monitor connected to the UTM machine (TORONTECH, TT-HW2-1000). Figure 3.8 (b) shows the nature of failure of samples after the tensile strength tests.

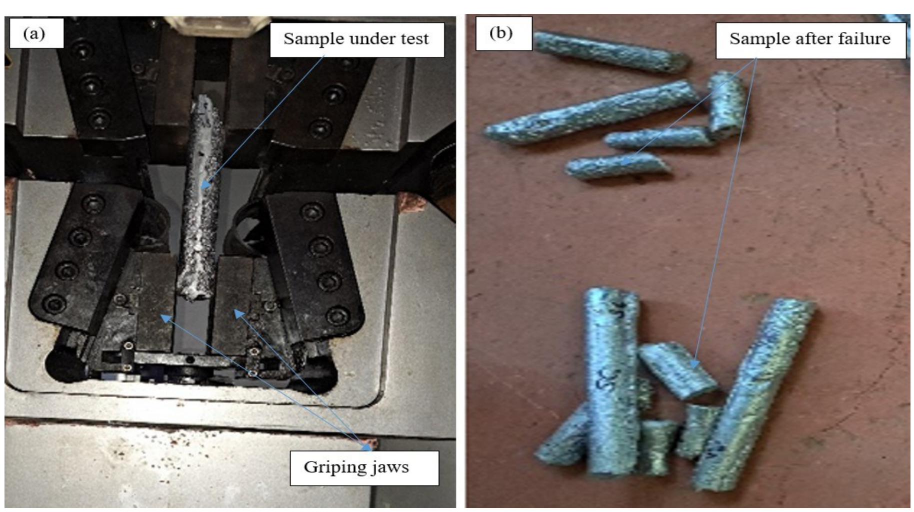

Figure 3.8: (a) Tensile tests on AMCs and (b) Material after fracture.

3.8.2 Compressive Strength

Compressive strength was determined using the universal testing machine (UTM) the same equipment that was used for tensile strength testing. Other test parameters include the Youngs modulus. The AMCs were ground using a stone grinding machine in order to have flat and smooth surfaces that could fit on the compressive plate of the UTM. The uniform distribution of load over the ends of the test piece was facilitated by the flatness of the compression plates. During the test, the base block was kept stationary while the central grip (compression plate) was subjected to a downward movement to apply a load of 10KN/sec on the AMCs as shown in Figure 3.9 (a). Various load intervals were used to measure the load and the accompanying contraction until the samples failed. The maximum point of the graph in Figure 6-12, under Appendix A was considered as the breaking point of the AMCs and the compressive strength of the AMCs was obtained automatically from the monitor connected to the UTM machine. Figure 3.9 (b) shows the nature of failure of the samples after the compressive strength tests. The compression test results are important in selection of the right materials for various applications in industries such as aerospace, automotive, and construction.

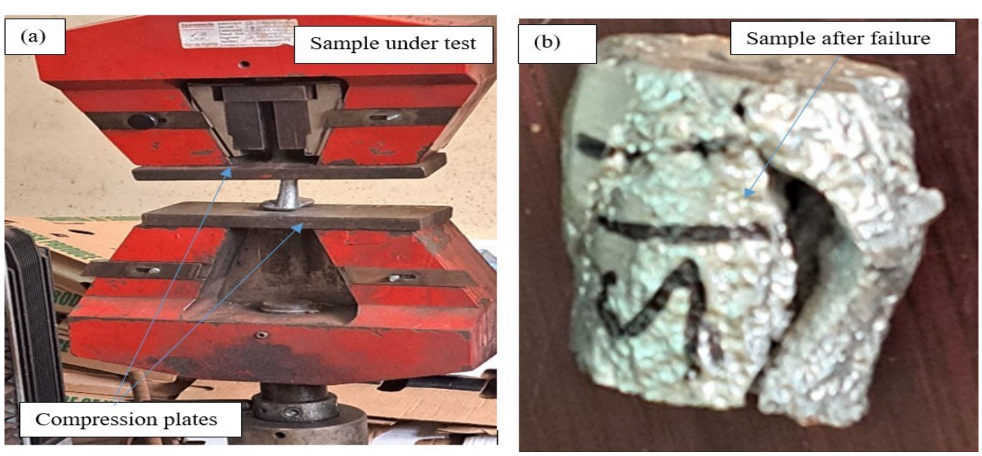

Figure 3.9: (a) Compressive strength test machine and (b) Nature of material after the tests.

3.8.3 Elongation

The elongation was achieved when the material was stretched under tensional forces on the universal testing machine. This measurement provides insight into the material's ductility, indicating how much it stretches before failure. The percentage that a material expands over its initial length before it breaks is known as percentage elongation and its given by equation 3.1. The grip/gauge length was the distance between the two griping points (jaws) of the tensile testing machine.

$$Elongation(\%) = \frac{L_2 - L_1}{L_1} \; x \; 100\%, \qquad (3.1)$$

Where L2 is the final gauge length after material failure and L1 is Initial gauge length before testing

3.8.4 Hardness

The depth of indentation made by an indenter of a plumbline shape with a given force applied for a specific amount of time was measured to determine the hardness value of AMCs. The hardness test was carried out using the Brinelle's hardness test machine (TORONOTECH, QualiBrineller QS T0061/283/20DE130918). The AMCs were ground using a stone grinding machine to achieve flat surfaces. The samples were then placed on a sample stage with the flat surface facing the 2.5 mm ball indenter. The sample plate was then raised so that the flat surface gets into contact with the loading ball indenter as seen in Figure 3.10. A standard force of 1839N was then applied on the flat surface of the AMCs for 9 seconds until the indentation mark was observed. The setup was then unlocked to remove the sample. The depth of indentation was measured and recorded using a displacement sensor embedded in the setup. The Brinell's hardness number of the AMCs was calculated using equation 3.2 (Apasi et al., 1970).

$$HBW = \frac{2P}{3.14D\left(D - \sqrt{(D^2 - d^2)}\right)} \tag{3.2}$$

where HBW is the Brinell's hardness number, P is the applied force (kgf), D is the diameter of the indenter ball in mm, d is the mean diameter of the indentation in mm.The Brinell's hardness values were then converted to Rockwell's hardness values of scale B using the hardness conversion chart in Appendix B.

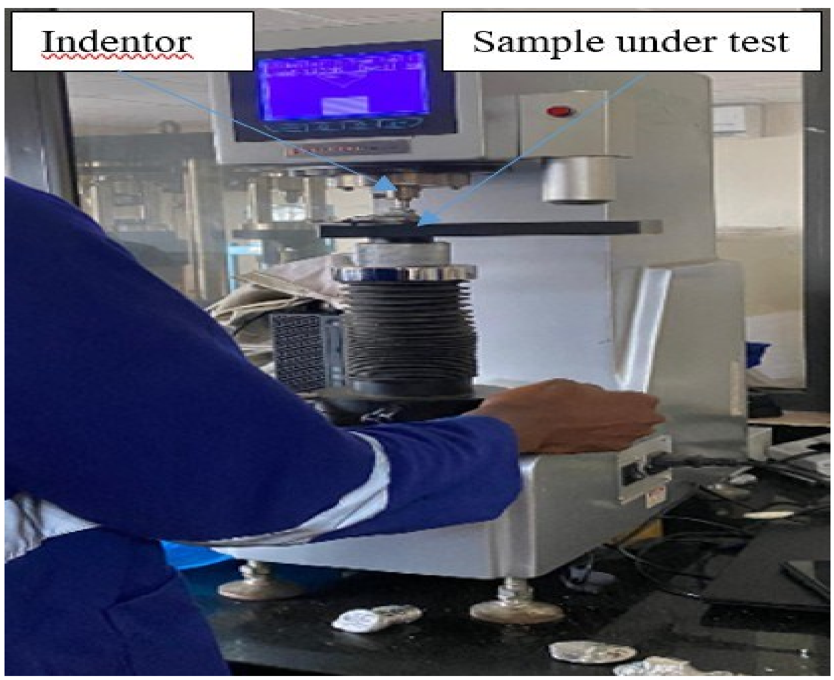

Figure 3.10: Brinelle's Hardness Machine making an Indentation

3.9 Comparison Process

In order to assess the versatility of the AMCs developed in this study, the mechanical properties of the developed AMC samples were compared with the findings of previous researchers. The ISO 6362-2;2022 standard for the mechanical properties of extruded bars, rods, tubes, and profiles made of wrought aluminium and aluminium alloy was also considered for comparison. However, the comparison was restricted to only rods with a diameter of 25 mm.

3.9.1 Data Analysis

The mechanical test results for the developed AMCs were analyzed using Origin Pro, a computer tool for interactive scientific graphing and data analysis. The software offers an easy-to-use interface for users combined with the ability to perform advanced customization. Graphs were produced and analysed using origin.

CHAPTER FOUR: RESULTS AND DISCUSSIONS.

4.1 Introduction

Numerical and microstructural results of developed AMC's are presented in this section. Before the development of the composites, coconut shell ash and gravel powder were subjected to chemical and microstructural analysis and the results are presented in this section. To assess how well the manufactured AMCs performed in comparison to pure aluminium and other aluminium alloys, mechanical tests were conducted on the samples. Results of these tests, which include tensile strength, compressive strength, hardness, and elongation, are presented and discussed in this section.

4.2 Chemical Composition

The elemental composition of coconut shell ash and crushed gravel was carried out using a scanning electron microscope (SEM) coupled with the Energy dispersive X-ray spectroscopy (EDS). The chemical composition for the AMCs was based on elemental and atomic percentage. The weight of an element as measured in the AMC sample divided by the weight of all the elements in the sample multiplied by 100 % is the weight percentage of that element. The atomic percentage, on the other hand, is calculated by dividing the number of atoms of an element at a specific weight percentage by the total number of atoms in the sample multiplied by 100 %. It helps to accurately measure the concentration of a substance in a solution.

4.2.1 Coconut Shell Ash

The elemental composition of coconut shell ash is shown in Table 4.1, and the corresponding micrographs can be seen in Figure 4.1. The results indicate that the coconut shell ash consisted of different elements with carbon (C) and oxygen (O) having the highest percentage by weight at 75.22 % and 12.65 % respectively. However, Nitrogen (N) had the least percentage weight mounting to only 0.01 %. A similar observation was made by Apasi et al. (2016). Other elements present include Na, Mg, Al, Si, Cl, N, Ca, and K. The data from the EDX spectral graph of the elemental analysis showed that 84.8% and 10.71% of the atoms were from carbon and oxygen respectively. The high carbon content assists in the reinforcement of metals for excellent mechanical properties. The presence of carbon as an element contributes to high stiffness, strength, and toughness, making the composite material suitable for structural applications where high mechanical performance is required. Additionally, the presence of carbon as an element in the composite increases on the weight reduction of the composite, since carbon has a relatively low atomic number (Sharma et al., 2020).

Table 4.1: Chemical composition of coconut shell ash.

Element	C	N	O	Na	Mg	Al	Si	Cl	K	Ca
Elemental composition (wt%)	75.22	0.01	12.65	0.23	0.25	0.13	0.97	1.23	8.20	1.10
Atomic percentage (%)	84.8	0.01	10.71	0.14	0.14	0.07	0.47	0.47	2.84	0.37

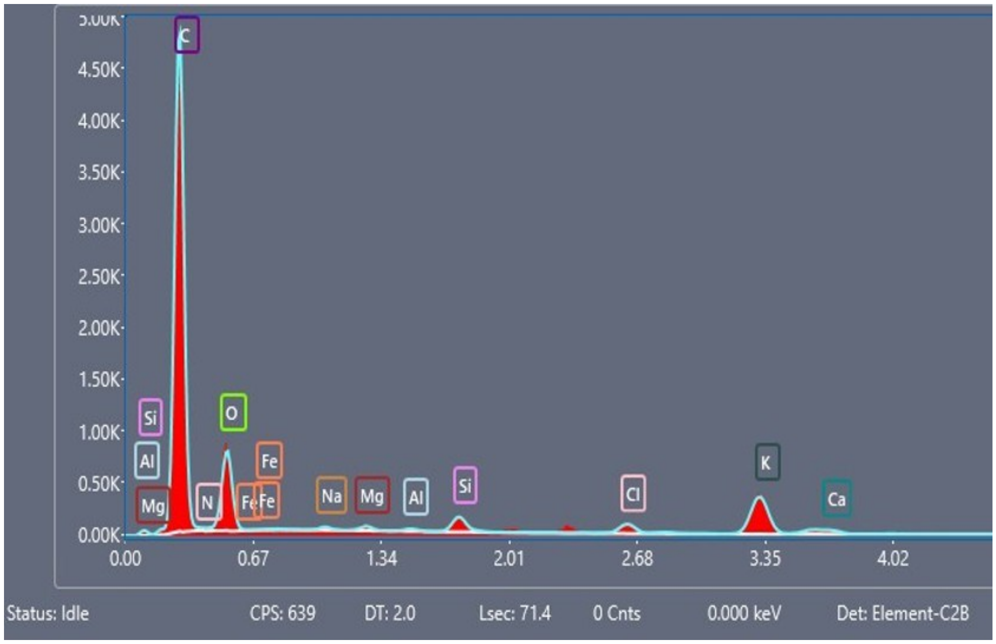

Figure 4.1: An EDS spectral graph for coconut shell Ash.

4.2.2 Crushed Gravel Powder

The results presented in Table 4.2 show the elemental composition of crushed gravel powder and the corresponding EDS analysis is shown in Figure 4.2. The data showed that O, Al, and Si were the main elements present in the crushed gravel powder. These elements exhibited the highest atomic percentage in the AMCs compared to the rest. Other elements such as Na, Mg, K, Ca, and Fe were present but in low contents. Aluminium as an element is a lightweight metal making it an excellent choice for applications where weight reduction is critical. Applications of aluminium can be found in aerospace and automotive industries (Kumar & Kumar Jha, 2021). Despite its low density, aluminium exhibits excellent strength to weight ratio meaning that a high content of aluminium can increase the strength of the composite while maintaining a relatively low weight, making them suitable for structural applications where both strength and weight are important considerations (Qiu & Wang, 2023). Aluminium (Al) and Silicon (Si) contents in the gravel contribute to better performance of AMCs in terms of strength, ductility, and corrosion resistance (Sharma et al., 2020).

Aluminium reacts with oxygen in air to produce a layer of aluminium oxide. This oxide provides natural corrosion resistance to the aluminium matrix, protecting it from further oxidation and corrosion (Abdulrazaq et al., 2023). However, there was low content of aluminium and silicon in coconut shell ash than in crushed gravel as seen in tables 4.1 and 4.2.

Table 4.2: Chemical composition of gravel powder.

Element	O	Na	Mg	Al	Si	K	Ca	Fe
Elemental composition (wt%)	63.1	2.60	1.61	12.03	12.64	3.37	0.33	4.31
Atomic percentage (%)	75.98	2.18	1.28	8.59	8.67	1.66	0.16	1.49

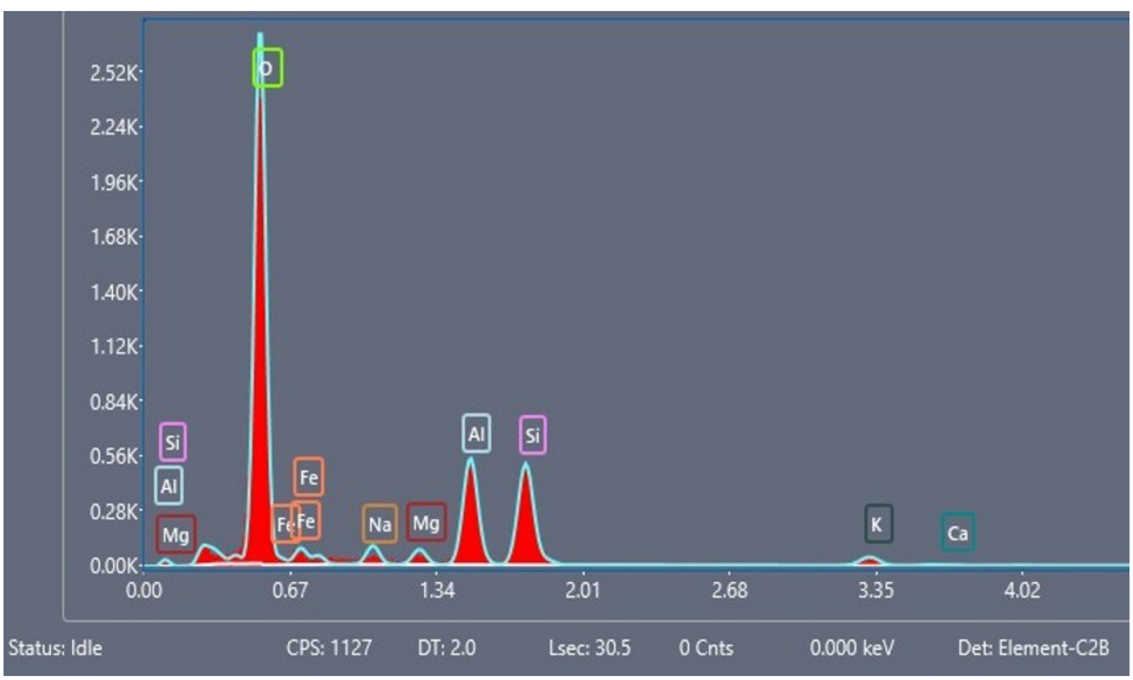

Figure 4.2: An EDS spectral graph for the elemental composition of gravel powder.

4.2.3 Chemical Composition of the AMC's

Table 4.3 presents the elemental compositions of the fabricated AMCs. The elemental compositions in terms of the weight percentage and atomic percentage in all the fabricated AMCs showed that Al and Si were the major elements present. Other elements such as Na, Mg, K and Ca were not present. A similar observation was reported in the study conducted by Das et al. (2014). Aluminium being the principle element was represented with the highest peak and then followed by Si as illustrated in Figure 1-2 under Appendix A. Other elements include O, C, and Fe. Sample S3 which was reinforced with 10% coconut shell ash and 5% gravel powder exhibited the highest composition of aluminium for both atomic and weight percentage. However, sample S4 exhibited the highest elemental composition of Si. The presence of silicon as an element in aluminium composites can help to enhance their fluidity during casting processes (Karpov et al., 2019). However, this property was not observed during the casting process since there was a reduction in pouring temperature of molten material. Furthermore, the presence of silicon in aluminium composites can influence their hardness (Muley et al., 2015).

Results in Table 4.3 show that silicon was the second most element present in the AMC samples by composition and the samples that had the highest wt% of silicon content produced higher values of hardness compared to their counterparts. This is because an increase in the silicon content increases the impact strength and hardness. Subsequently, presence of silicon reduces the pearlite content but increases the ferrite content which gives rise to impact strength and hardness (W. Arshad et al.,2018). Iron (Fe) was found present in sample 5 and sample 2. The presence of iron in the alloy resulted in a significant reduction in the elongation as the added reinforcement due to the Fe-rich compounds is at the cost of (reduces) the alloy ductility (Sharma et al., 2020).

Table 4. 3: Elemental composition of the fabricated AMC samples.

	S1	S2	S3	S4	S5	S6	S7
Element	**wt%**	**wt%**	**wt%**	**wt%**	**wt%**	**wt%**	**wt%**
Al	60.88	54.24	81.51	40.41	15.99	73.08	30.13
Si	39.12	42.3	18.49	59.59	35.89	26.92	59.62
C	-	-	-	-	36.6	-	-
O	-	-	-	-	10.34	-	10.26
Fe	-	3.46	-	-	1.18	-	-

4.3 Microstructural Analysis

4.3.1 Coconut Shell Ash

SEM investigation of the fabricated AMCs was conducted to examine the surface structure and morphology of the composite samples reinforced with different percentages of the reinforcing materials. Figure 4.3 shows the morphology of the coconut shell ash obtained when coconut shell was fired at 800 0C in a ceramics furnace. The microstructure consists of voids (denoted by V) and striations (denoted by S). The voids which are open spaces can be seen as dark spots within the microstructure. The striations and voids are more clearly visible in Figure 4.3 (b) at a scale of 50μm compared to that at a scale of 100μm in Figure 4.3 (a). According to Yekinni et al. (2020), voids can reduce the density of coconut shell ash particulate and disrupt its continuity, as well as production of microstructure discontinuities that facilitate the propagation of cracks under loads. Similarly, striations, which are linear marks or grooves on the surface of CSAp, can serve as initiation sites for crack propagation and these surface irregularities can weaken the mechanical properties of the material. Aluminium particles are also seen in the structure and since aluminium as an element is a lightweight metal, it brings in a property of strength making it an excellent choice for applications where reduced weight is required. (Bari et al., 2021).

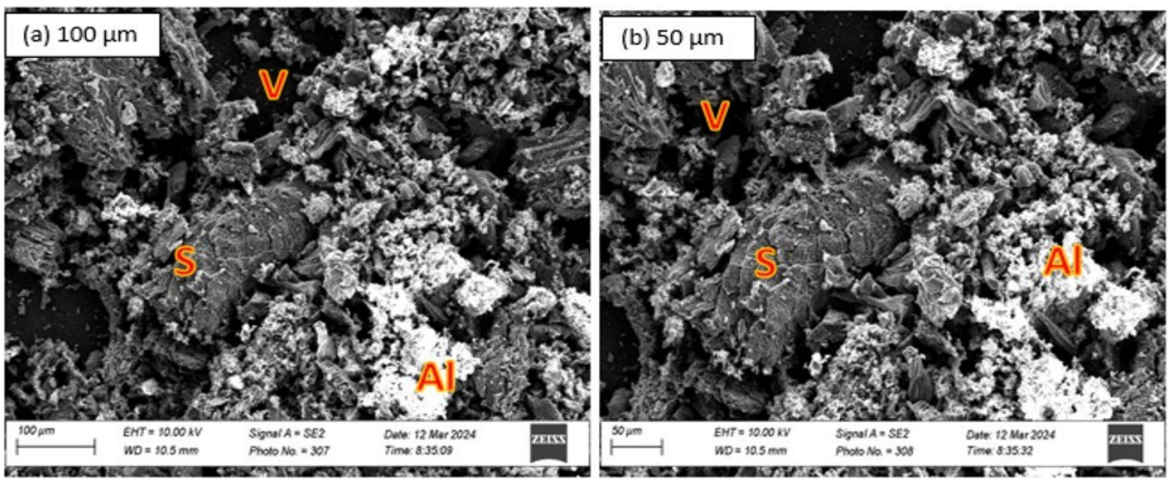

Figure 4.3: Microstructure of the coconut shell ash (a) At a scale of 100 µm, (b) At a scale of 50 µm.

4.3.2 Crushed Gravel Powder

The SEM Microstructural images of the gravel powder show large diamond-crystalline shapes with big spaces in between the crystals. The crystalline characteristic nature is that of the grains whose boundaries are clearly displayed in the SEM image. Figure 4.4 shows that the microstructure consists of consists of voids (denoted by V), and quartz crystals (denoted by C). The voids show the existence of big open spaces in the microstructure of the gravel represented by the dark regions. According to Mehdikhani et al. (2019), voids can weaken the overall structural integrity of the gravel and their presence implies that there is less gravel particulates to bear the load, thereby, potentially reducing the gravel's strength hence resulting in reduced strength. Since gravel was rich in O, Al, and Si (major elements), this means that quartz (SiO2) and Al_2O_3 may have been the main components of gravel and their presence can have a significant effect on the mechanical properties of the AMCs. The structure shows different particle sizes of elements. The presence of silicon and aluminium particles in the gravel can hinder dislocation movements thereby increasing the composite's tensile strength (Rana et al., 2022). A study by Karpov et al. (2019) on the effect of silicon content on mechanical properties of aluminium alloy showed that the tensile strength of the aluminium alloy increased with increased silicon content. The chemical stability of quartz means that its presence in aluminium composites might affect the material's hardness (Muley et al., 2015).

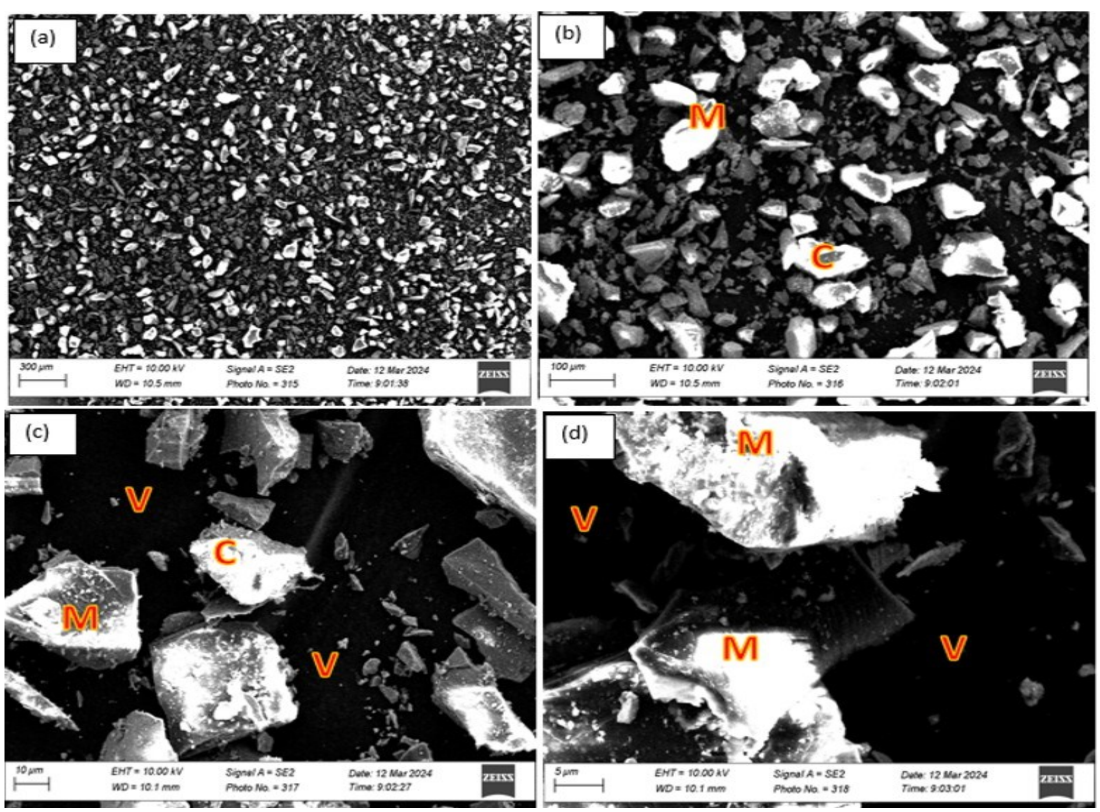

Figure 4.4: Microstructure of the crushed gravel powder at scales of (a) 300 µm, (b) 100 µm, (c) 10 µm, and (d) 5 µm,

4.3.3 Microstructural Analysis of the AMCs

The morphology of the fabricated AMC samples shown in Figures 4.5- 4.11 were observed using SEM. All the SEM images do indicate a rough texture of the AMCs samples, with voids and ridges observed in their microstructure. These voids can be seen as dark areas within the microstructure of the samples. Further, the formation of a series of ridges indicate the non- uniform distribution between the matrix particles of coconut shell ash and the crushed gravel powder. This non-uniform distribution of the particulates of the materials used in the fabrication of the AMCs arises from the mixing/stirring process during casting (Santhosh et al., 2022). The structural appearance of the samples is almost the same which results from the material composition and the way the samples were made and therefore had a direct effect on the mechanical properties of the developed AMCs. AMC sample 4 and sample 7 were the only samples that were not reinforced with crushed gravel powder (CGP).

However, it can be observed from Figure 4.8 (a) and (b) that the size of the voids (pores) in sample 4 (reinforced with 5% coconut shell ash) were smaller when compared to the voids in the micrographs of the other samples in Figure 4.5, 4.6 and 4.10. This means addition of coconut shell ash leads to a reduction in the size of pores and consequently an increase in mechanical strength. The voids in samples reinforced with crushed gravel are due to the existence of large crystals observed in the crushed gravel powder as described in section 4.3.2. Additionally, the samples can endure less impact energy because of the existence of voids, which decreases the matrix-dominated properties (Julen Mendikute et al. 2022). Figure 4.11 shows that sample 7 with no reinforcing material had larger voids when compared to sample 5 as seen in Figure 4.9. As a result, it affected the strength of the AMCs where by sample 7 exhibited 152Mpa (Figure 3, Appendix A) and sample 5 exhibited a value of 157.5Mpa. Therefore, the absence of the reinforcement materials has a negative impact on the mechanical properties of the composites.

On the other hand, addition of reinforcing material like in sample 5 with 5% CGP reduces on the size of the voids in the aluminium matrix by occupying some spaces if well mixed hence improving the tensile strength. As the particle size of elements and the presence of voids greatly impacts the mechanical properties of AMCs, it is also reported that high tensile strength of the composites is obtained by intense mixing during the casting process. (Stojanovic et al., 2018).

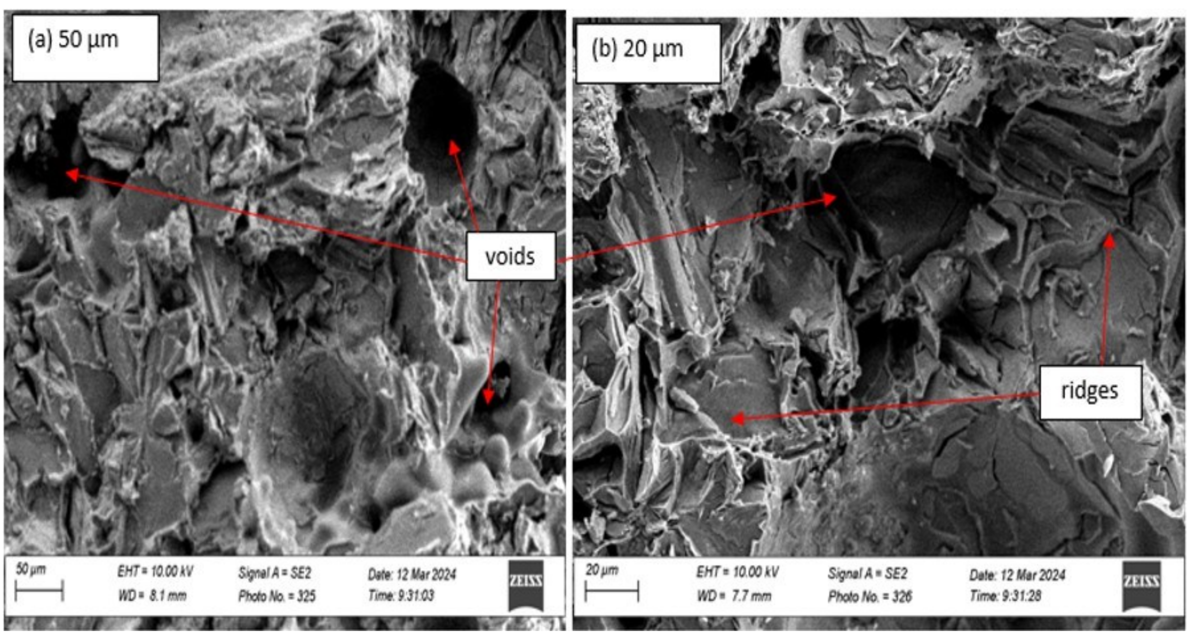

Figure 4.5: SEM images of the aluminium composite sample 1

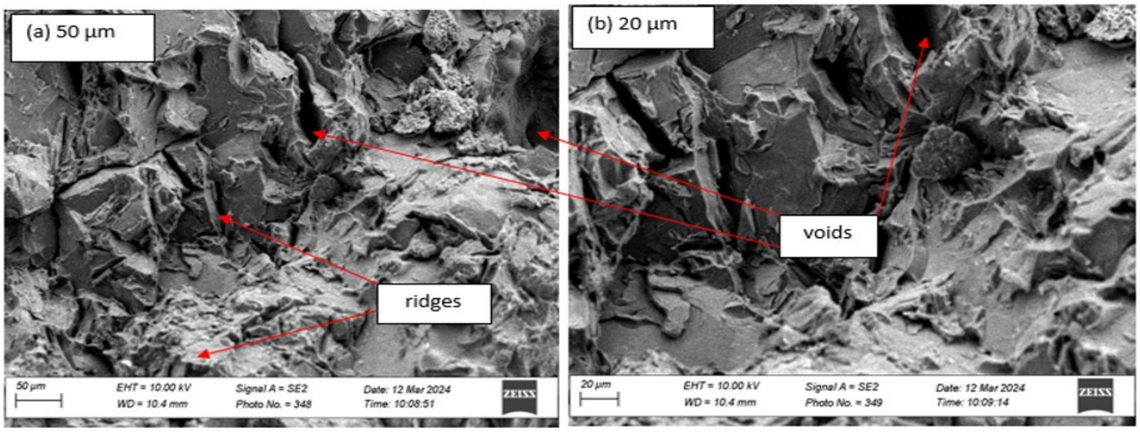

Figure 4. 6: SEM images of the aluminium composite sample 2.

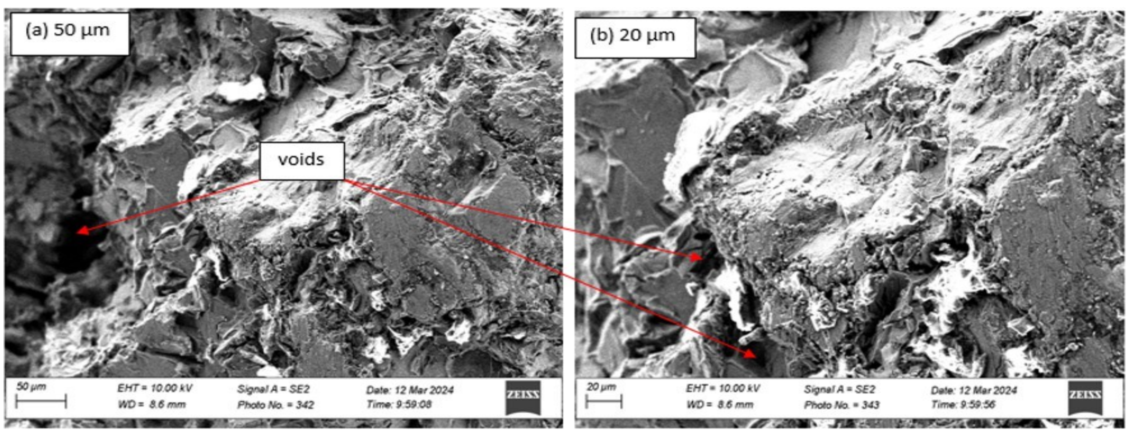

Figure 4. 7: SEM images of the aluminium composite sample 3.

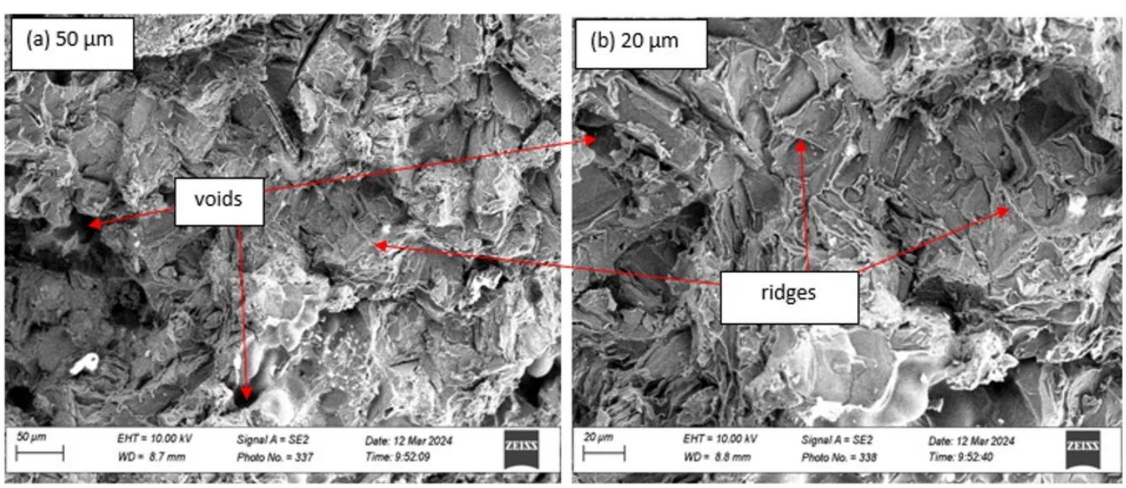

Figure 4.8: SEM images of the aluminium composite sample 4.

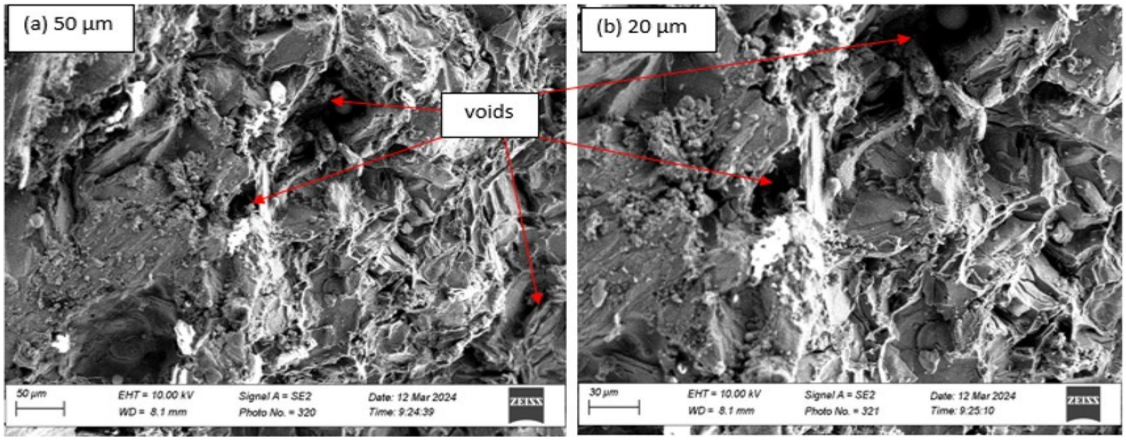

Figure 4.9: SEM images of the aluminium composite sample 5

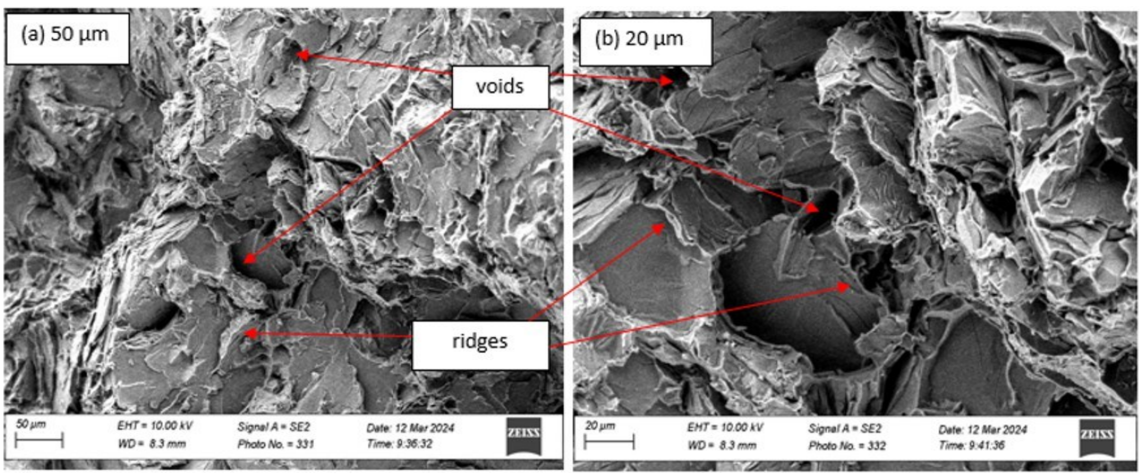

Figure 4.10: SEM images of the aluminium composite sample 6.

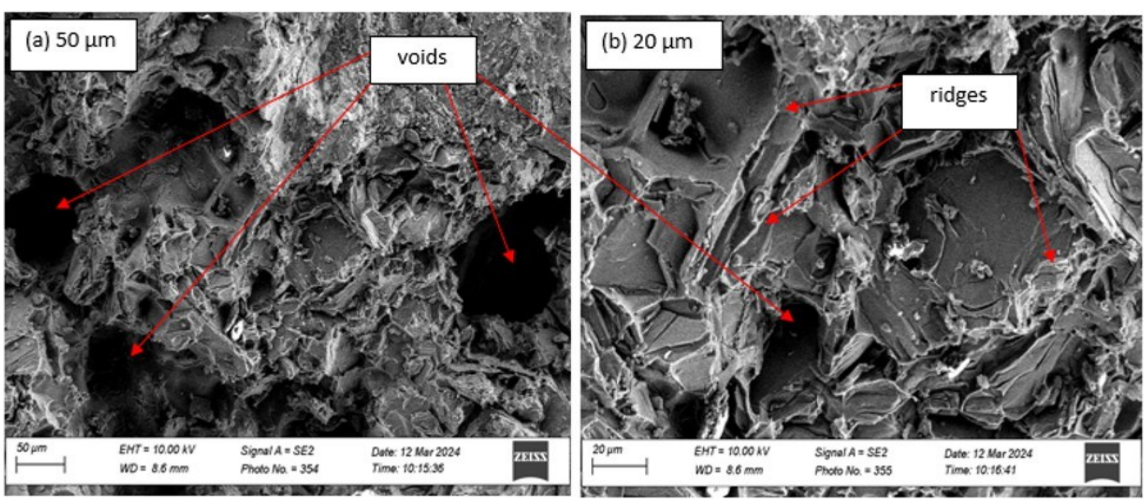

Figure 4.11: SEM images of the aluminium composite sample 7.

4.4 Mechanical Properties of the Developed AMCs

The seven fabricated AMC samples were each subjected to laboratory tests to determine their mechanical properties. The mechanical properties included; tensile strength, elongation, hardness, and compressive strength. Figure 3 in Appendix A shows the mechanical properties of each of the seven AMC samples.

4.4.1 Tensile Strength

The fabricated AMCs were subjected to a tensile strength test to determine the maximum load they could withstand without breaking. The fabricated AMCs' tensile strengths are shown in Figure 4.12, along with the ultimate tensile strength (90 MPa) for pure aluminium indicated by the reference line. All other manufactured AMCs, with the exception of sample 4, showed tensile strengths greater than those of pure aluminium with an average value of 130.71 MPa. The AMCs that had gravel as one of the reinforcing material exhibited higher tensile strengths. This behavior is attributed to the strengthening impact of the reinforcing particles in the aluminium matrix and the strong particle-matrix interfacial bonding (Apasi et al., 2016). The highest tensile strength of 157.5 MPa was exhibited by sample 5, which was reinforced with 5 wt% crushed gravel powder. Mansouri et al. (2021) stated that reinforced composites show better tensile properties due to the evenly distributed reinforcing particles during mixing, thereby, increasing densification levels and microstructural uniformity. A similar observation was made by Chang et al. (2015). Sample 1 which constitutes 4 wt% of CSAp and 6 wt% of CGP produced a tensile strength of 137.5 MPa which is higher than that produced by samples 2, 3, 4, and 6.

The high tensile strength is due to the enhancement with gravel which has a high content of silicon. The presence of silicon as an alloying element in aluminium composites helps to enhance their fluidity and homogeneity of particles during casting processes. This property is particularly beneficial for manufacturing complex-shaped components using casting techniques. AMC sample 4 exhibited the lowest tensile strength because aluminium was only reinforced with coconut shell ash which has a low silicon content compared to that in gravel powder. Additionally, the existence of dispersed voids and ridges in the microstructure of the AMCs led to low tensile strength. This is because the voids create stress concentration regions within the microstructure of the AMC thereby reducing its tensile strength. In fact, the data shows that addition of coconut shell ash as the only reinforcing material to the aluminium lowers the tensile strength of the composite which is not the case when reinforced with gravel powder. This is as a result of a mis-match along the grain boundaries of the matrix-reinforcing composition consequently resulting in the weakening of the load carrying capacity of the AMC (Hassan & Aigbodion, 2015). This result is in agreement with the findings of Apasi et al., (2016).

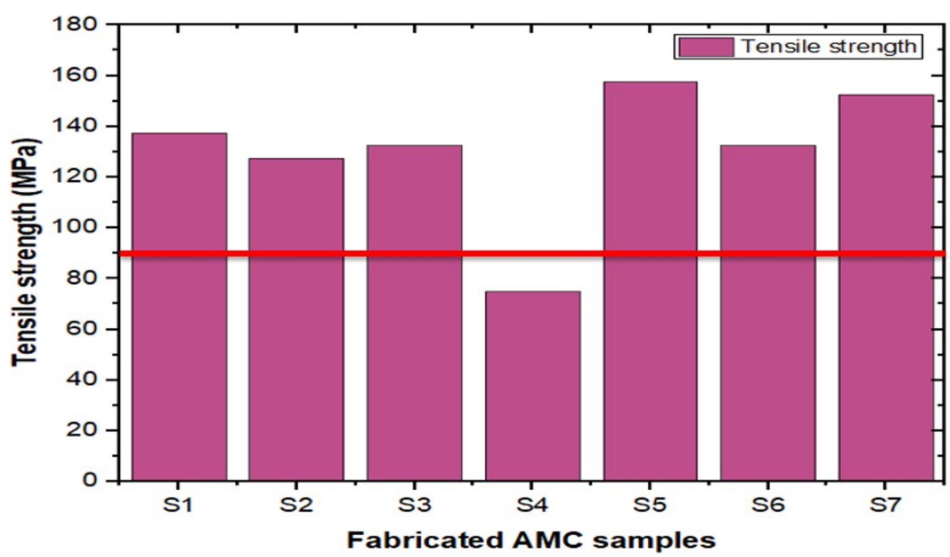

Figure 4.12: Tensile strengths of the fabricated AMCs.

4.4 2 Hardness

A Brinell hardness testing equipment was used to assess the composites' resistance to deformation and scratching when subjected to applied load. The Brinell's hardness values under Table 1, found in Appendix A were then converted to Rockwell's hardness values using the hardness conversion chart in Appendix B. The hardness results can help in assessing the AMCs suitability for specific applications like in the construction industry since different materials exhibit varying degrees of hardness. The test measures the depth of indentation produced by a specific load on the material's surface (Khazaal et al., 2022). The machine provides a numerical value representing the material's hardness hence the higher the value, the harder the material.

According to the study results the average hardness value for all the 7 samples was 91.14 HRB and the aluminium matrix becomes harder when reinforcing elements are added. The hardness of Sample 1 (S1), which consisted of 4% CSAp and 6% CGp was 66 HRB. When the compositions of CSAp and CGp were increased to 7.5% and 7.5% respectively, the hardness increased to 117 HRB in sample 2 (S2), which was the greatest hardness measured as shown in Figure 4.13. Daramola et al. (2015) reported a hardness value of 40.2 HRB, while Apasi et al. (2016) reported a value of 78.6 HRB. These hardness values are still lower than the 117 HRB exhibited by the fabricated AMCs in the present study.

The low hardness value produced in Sample 1 was due to the existence of large size of the voids in its microstructure (Figure 4.5) which create localized stress concentrations thus decreasing the composite's ability to resist deformation (Saenz-Castillo et al., 2019). When the CSAp was further increased to 10% and CGP reduced to 5% in sample 3, the

Rockwell hardness value reduced to 105 HRB. This signifies the impact of gravel as a reinforcement material on the mechanical properties of developed AMCs. The data still shows that a further reduction in the composition of one of the reinforcing materials in the matrix resulted in a further reduction in the hardness of the AMCs as portrayed in the AMC samples 4, 5, 6, and 7. Composite hardness increases due to the addition of the silicon and aluminium ceramic particles which are harder than the matrix (A. Kumar et al., 2013). This phenomenon matches with the previous work by Gireesh et al. (2018) and Akbar et al. (2020). The presence of Al and Si ceramic particles in the composite causes the Orowan's mechanism, a mechanism by which the ceramic particles are uniformly spread in the metal matrix to increase its strength and hardness (Srivastava & Chaudhari, 2018). The presence of the ceramic particles limits the movement of dislocations thus increasing the hardness of the composite (Rozhbiany & Jalal, 2019).

Furthermore, sample S4 reinforced with 5% CSAp, produced a hardness value of 102 HRB compared to a hardness of 82 HRB produced by sample S5 that was reinforced with 5% CGp. The higher hardness is attributed to a better dispersion of the coconut shell ash within the microstructure of the composite (Abdulrazaq et al., 2023). On the other hand the presence of the voids in coconut shell ash can increase the ductility of the material because the voids allow more flexibility and deformation before cracking or breaking (Dong, 2016). As noted by Apasi et al. (2016), this implies that, in contrast to crushed gravel, coconut shell ash increases the composite's hardness. Subsequently, the hardness of the AMC can be considerably raised by adding the proper quantities of reinforcement elements.

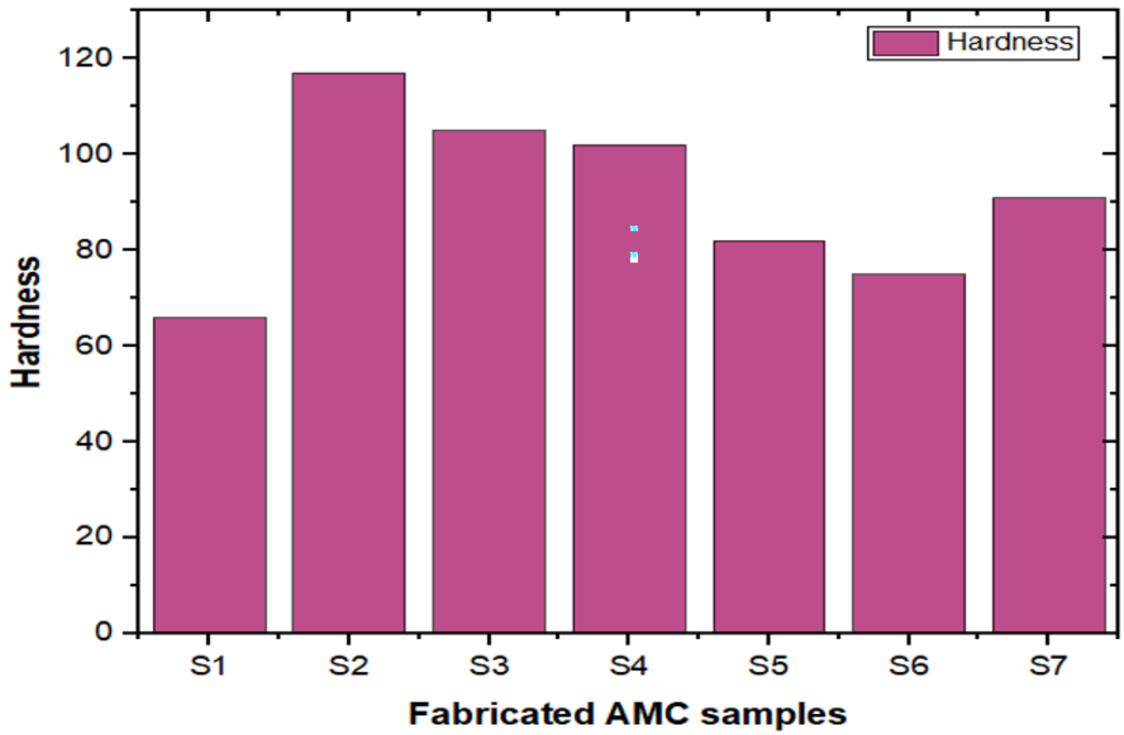

Figure 4.13: Hardness of the fabricated AMCs.

4.4.3 Compressive Strength

Compressive strength is a critical parameter in determining a material's ability to resist a reduction in size during loading without fracturing. Compressive strength tests were carried out on the fabricated AMC samples and the results are shown in Figure 4.14 with an average value of 232.45 MPa. Sample S4 reinforced with only CSAp at 5% had the maximum compressive strength, measuring 355.83 MPa, whereas sample 5 (S5) reinforced with only CGP at 5% had the lowest compressive strength, measuring 111.13 MPa. This is because the CSAp has fine particles throughout the matrix that can act as barriers to dislocations (Muraliraja et al., 2019). Subsequently, the voids present in the microstructure of sample 4 can generate dislocations on their surface, thereby obstructing void coalescence in the tensile phase hence reducing tensile strength and increasing compressive strength (Liebig et al., 2015). Additionally, reduced porosity due to uniform distribution of the reinforcements in the composite can enhance their compressive strength (Campbell, 2010). Results shows that when the percentage composition of CGp was increased to 7% (in sample 6) from 5% in sample 5, the compressive strength increased by 44.7%. Al2O3 and SiO2 particles which were found present in crushed gravel powder are well-known for improving strength of Al composites (Yekinni et al., 2020). Tests on an aluminium composite reinforced with CSAp in a related work by Muhib et al. (2020) revealed that the specimen's compressive strength rose when coconut husk ash was added in percentages of 7, 11, and 18.

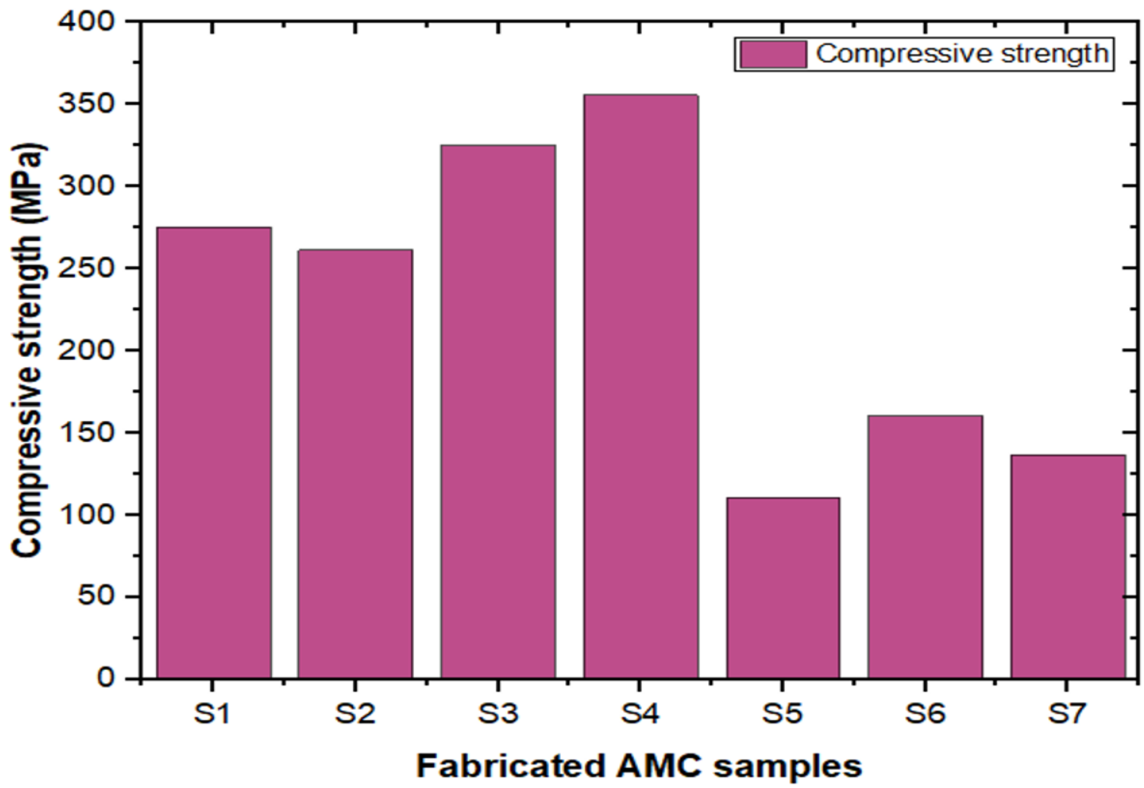

Figure 4.14: Compressive strength of the fabricated AMCs.

4.4.4 Elongation

To understand the ability of the fabricated AMCs to deform and stretch before failure, the samples were subjected to elongation tests using the universal testing machine. The results presented in Figure 4.15 show that the average elongation of the AMC samples was 6.99 and this elongation increases with an increase in the reinforcements. Composite sample 1 (S1) reinforced with 4% CSAp and 6% CGp produced a percentage elongation of 3.28 %. This elongation increased to 7.01% when the compositions of the CSAp and CGp in composite sample 2 (S2) were increased to 7.5%. Sample 3 also demonstrated an additional increase in the percentage elongation when the CSAp and CGp compositions were adjusted to 10% and 5%, respectively. However, the elongation began to reduce in absence of one of the reinforcing materials. This can be seen in Figure 4.15 in samples 4, 5, and 7. AMC sample 4 (S4), produced a lower elongation because the sample was only reinforced with CSAp. A further reduction in the elongation was observed in sample 5 (S5) when gravel was the only reinforcement material. Voids (see Figure 4.9) present in the microstructure of the AMC reduce its elongation by creating stress concentration areas and facilitating crack propagation as stated by Kosmann et al. (2015). However, when the composition of the crushed gravel powder was increased from 5% (in S5) to 7% (in S6), the elongation increased to 8.65% (see Figure A3 in Appendix). The elongation reduced in sample 7 (S7) in absence of any reinforcing material. This shows the effect of the reinforcing material on the elongation of the AMCs. Altering the ratio of aluminium to reinforcement material and temperature conditions during the fabrication, influences its microstructure, thereby, significantly affecting its elongation properties (Bhaskar & Singh, 2013). Furthermore, the presence of defects, such as voids, cracks, or striations in the microstructural surface, can act as stress concentration sites and decrease elongation by promoting premature failure (Liu et al., 2022).

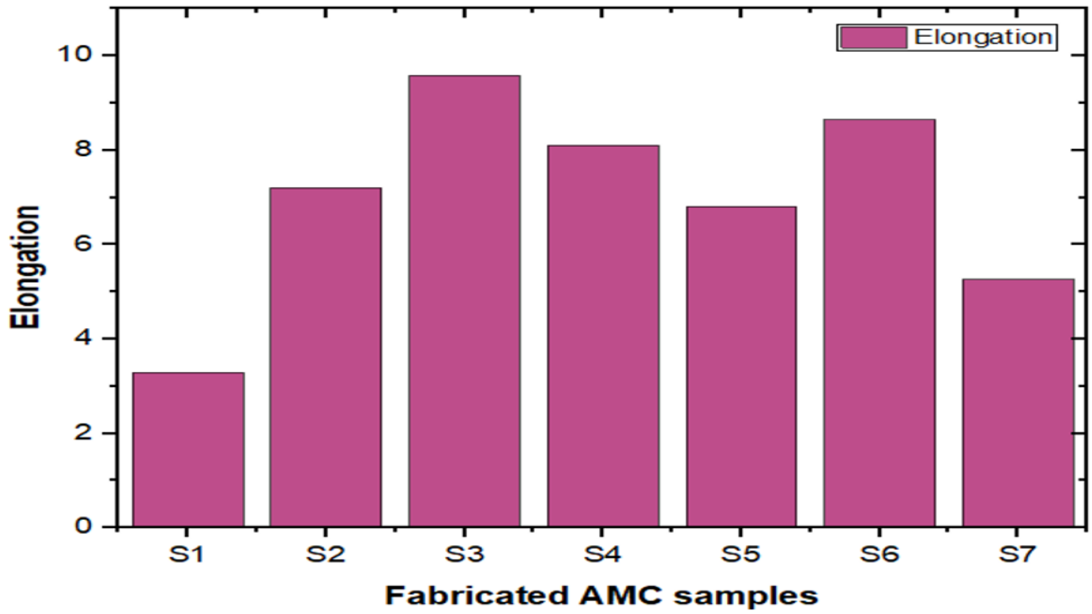

Figure 4.15: Percentage elongation of the fabricated AMCs.

4.5 Comparison of AMCs

In order to assess the versatility of the AMCs developed in this study, the mechanical proper- ties of the developed AMC samples were compared with the findings of previous researchers. The ISO 6362-2;2022 standard for the mechanical properties of extruded bars, rods, tubes, and profiles made of wrought aluminium and aluminium alloy was also considered for comparison. However, the comparison was restricted to only rods with a diameter of 25 mm.

Table 2 in Appendix A shows a comparison between the tensile strength and hardness of aluminium composite developed in this study and those developed by Daramola et al., (2015), Apasi et al., (2016) and aluminium alloy Al 6061-T6 from the ISO 6362-2;2022.

Figure 4.16 shows that in the present study, AMC sample S5 reinforced with 5 wt% crushed gravel powder exhibited the maximum tensile strength of 157.5 MPa. Daramola et al., (2015) reinforced Al 6063 alloy with only coconut shell ash and the maximum tensile strength obtained was 73.63 MPa. This tensile strength is lower by 83.9 MPa when compared to the maximum tensile strength produced in the present study. This indicates that addition of gravel powder has a positive impact on the strength of the AMCs. on the other hand, in a study conducted by Apasi et al., (2016), maximum tensile strength was 200 MPa obtained from aluminium alloy reinforced with 9wt% of coconut shell-ash particulate without gravel powder. The obtained maximum tensile strength value from the study conducted by Apasi et al., (2016) was slightly higher by 42.5 MPa when compared with the one obtained in this study. This was due to the superior procedures and the casting method that were employed by Apasi et al., (2016). Additionally, AMC sample S5 exhibited a higher tensile strength than the required tensile strength of 145 MPa for extruded bars/rods developed from aluminium alloy Al 6061-T6, according to ISO 6362-2;2022 standard. This implied that there was a high level of compliance of the present results with the International Organization of Standardization ((ISO) results for mechanical properties of wrought aluminium and aluminium alloy of extruded bars/rods, tubes and profiles.

For hardness, the maximum hardness recorded of 117 HRB in this study was attained from the composite sample S2 which constituted 85wt% aluminium and equivalent weight percentages of 7.5% for coconut shell ash and gravel, which is higher than those recorded in the referenced studies and the values of aluminium alloy Al 6061-T6, according to ISO

6362-2; 2022 standard as shown in Figure 4.16

This implies that AMCs can be utilized in similar applications in the building, construction and the automotive industry.

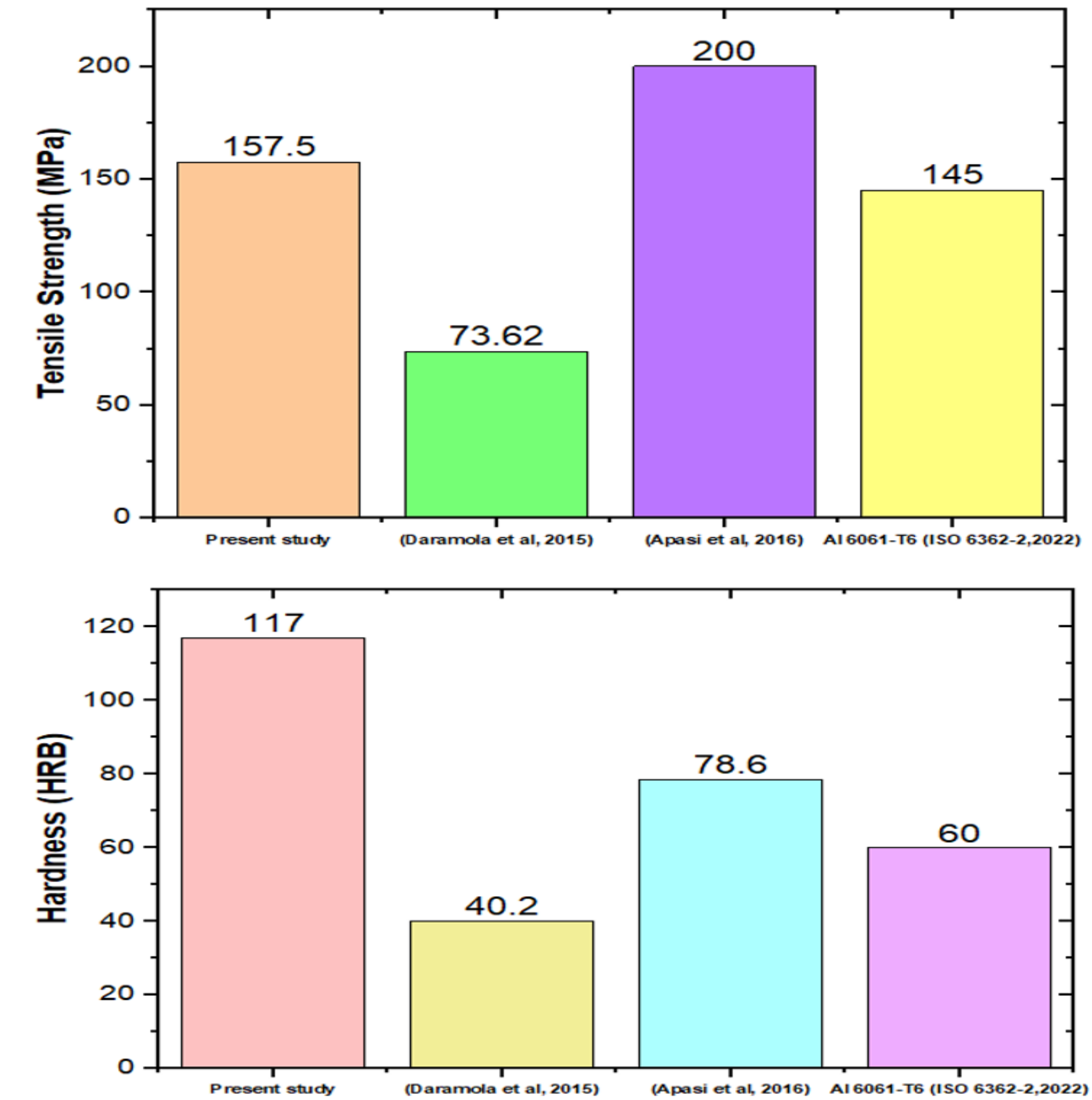

Figure 4.16: Comparison of mechanical properties of the AMCS with other aluminium alloys.

CHAPTER FIVE: CONCLUSION AND RECOMMENDATIONS

5.1 Introduction

Basing on the results presented and their discussion in the previous section, the following conclusions and recommendations were made.

5.2 Conclusion

A cost-effective aluminium matrix composite with high mechanical and physical properties was fabricated by utilizing coconut shell ash and crushed gravel powder as the reinforcement materials. The stir casting technique was used to fabricate the composites. The microstructure of the composites was studied using SEM and the elemental composition was analysed using SEM coupled with EDX. The mechanical properties of the AMCs including elongation, hardness, tensile strength, and compressive strength were studied. The obtained results were then compared with the already published work strictly involving the reinforcement of aluminium with biomass waste such as coconut shell ash and peanut shell ash. Therefore, the major findings in this study are summarized as follows;

Chemical analysis results showed the reinforcement materials; coconut shell ash and crushed gravel constituted of bigger percentage weights of 75.22% and 63.1% of mainly carbon and oxygen respectively which had a significant influence on the strength and hardness of the composites. Amongst the aluminium composites, the highest element present was aluminium followed by silicon. The presence of silicon as an element in aluminium composites can help to enhance their fluidity during casting processes hence improving on the harness.

Microstructural analysis revealed the presence of significant voids that are identifiable with dark patches which greatly affects the strength of the AMCs. For example, sample 4 reinforced with 5% coconut shell ash had smaller voids when compared to the voids in other samples. This sample exhibited the highest compressive strength of 355.83 Mpa because addition of coconut shell ash leads to a reduction in the size of voids and consequently an increase in mechanical strength.

The mechanical test results showed that using crushed gravel powder alone as the reinforcement material improves on the strength of the AMCs for example sample 5 reinforced with only crushed gravel at 5 wt% exhibited the highest tensile strength of 157.5 Mpa. This value was greater than that of 73.62 Mpa reported by Daramola et al. (2016). Also, the hardness values of the generated AMCs increased as the percentage weight of coconut shell ash additions increased for example when the percentage weight of coconut shell ash was increased from 4 wt% in sample 1 to 7.5 wt% in sample 2, the hardness value increased from 66 HRB to 117 HRB. This value was higher than the hardness values of 40.2 HRB and 78.6 HRB reported by Daramola et al. (2015) and Apasi et al. (2016) respectively. This is because coconut shell ash contains a hard-ceramic phase in the matrix.

In summary, the produced AMCs' tensile strength (157.5 Mpa) was greater than that of pure aluminium (90 Mpa) and the 145 Mpa recommended by the ISO 6362-2;2022 standard for extruded bars. The high degree of compliance of the study results when compared to the studies conducted by the previous researchers and the ISO standards indicates that these composites have the potential to serve as viable alternatives to existing materials on the market and provide promising solutions for a range of industrial applications including the aerospace and the building and construction sectors.

5.3 Recommendations

Based on the research findings and conclusion, the following areas are recommended for further studies;

It is important to pay close attention to the mixing ratios of the reinforcement materials because the mechanical properties of the developed AMCs rely on the percentage weight (wt%) compositions of the reinforcement materials. An imbalance in these proportions could either increase or decrease the value of one property over the other.

Ensuring constant stirring during the casting process is crucial to produce uniform dispersion of the matrix and its reinforcement components. Failure to do so may lead to the production of voids within the composite's microstructure. The creation of voids has a substantial impact on the mechanical characteristics that the composites display. Therefore, further studies should be carried out on the other various stirring methods.

In this study, sand casting technique was used in the development of the AMCs. However, it is recommended that better and modern casting techniques such as continuous casting, shell molding, lost-foam casting, and pressure die casting (Muley et al., 2015) can be used in similar future studies. Additionally, future research studies can be conducted by using Pea nut shell ash and crushed gravel as the reinforcement materials, increasing their percentage weights in equal proportions such that their adverse effects on the mechanical properties of the composites can be studied.

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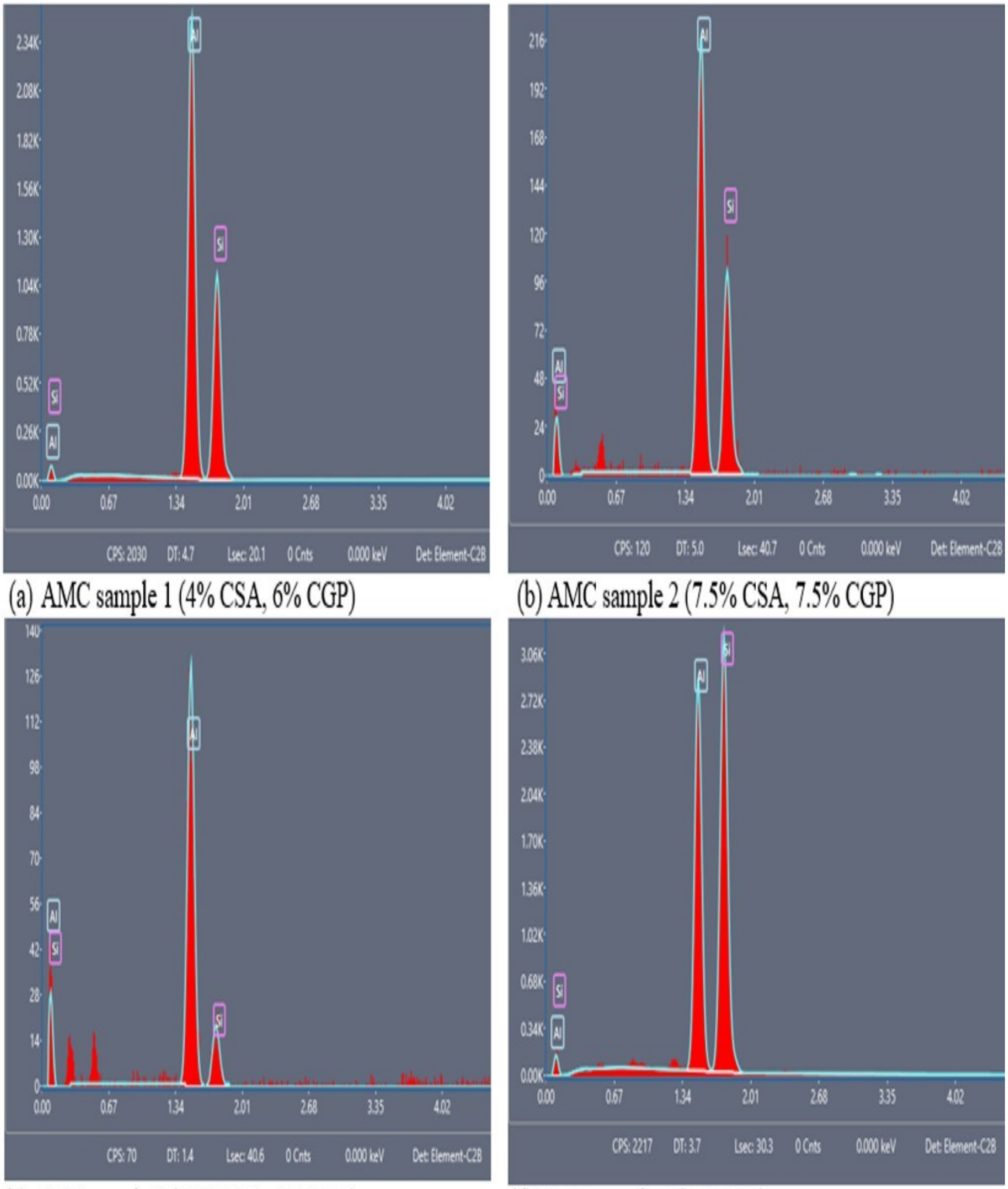
APPENDICES

Appendix A: Test Results and Graphs



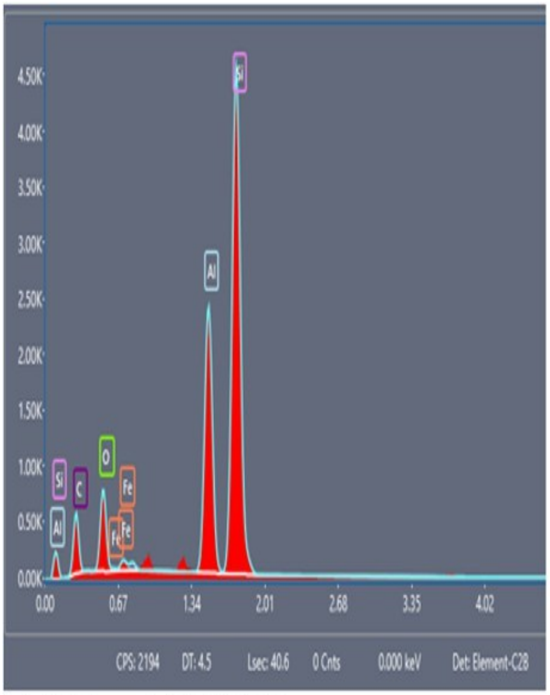
(a) AMC sample 1 (4% CSA, 6% CGP)

(b) AMC sample 2 (7.5% CSA, 7.5% CGP)

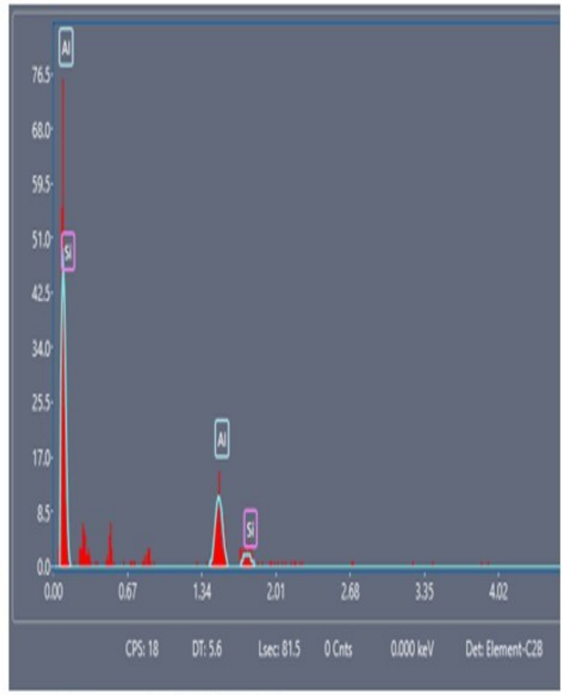
(c) AMC sample 3 (10% CSA, 5% CGP)

(d) AMC sample 4 (5% CSA)

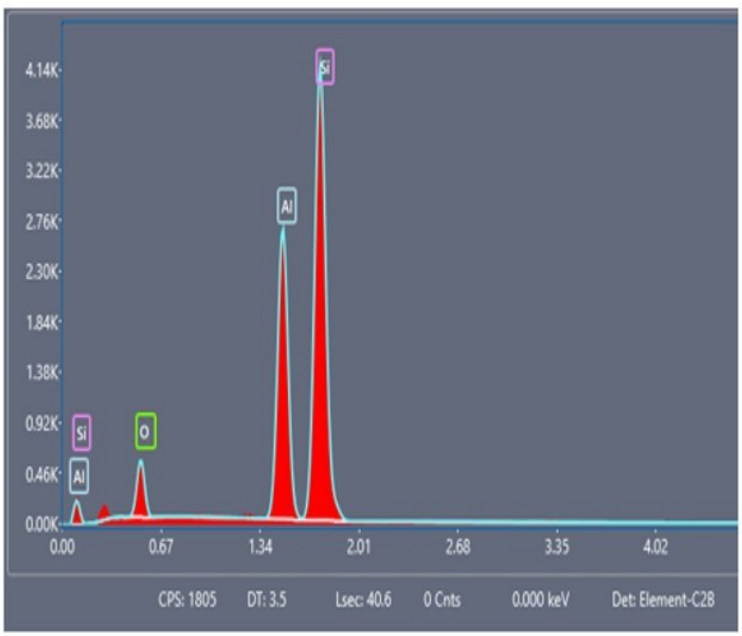
Figure 1: Spectral Graphs for samples 1-4



(e) AMC sample 5 (5% CGP)



(f) AMC sample 6 (7 %CGP)



(g) AMC sample 7 (No reinforcing material)

Figure 2: Spectral Graphs for samples 5-7

Mechanical Property	Unit	S1	S2	S3	S4	S5	S6	S7
Force	KN	61.45	57.55	60.05	33.85	71.10	60.80	68.25
Tensile Strength	MPa	137.50	127.50	132.50	75.00	157.5	132.50	152.50
Hardness (HRB)	-	66	117	105	102	82	75	91
Compressive Strength	MPa	275.54	261.61	325.27	355.83	111.13	160.88	136.92
Elongation	-	3.288662	7.207792	9.591326	8.108766	6.806184	8.653846	5.265568

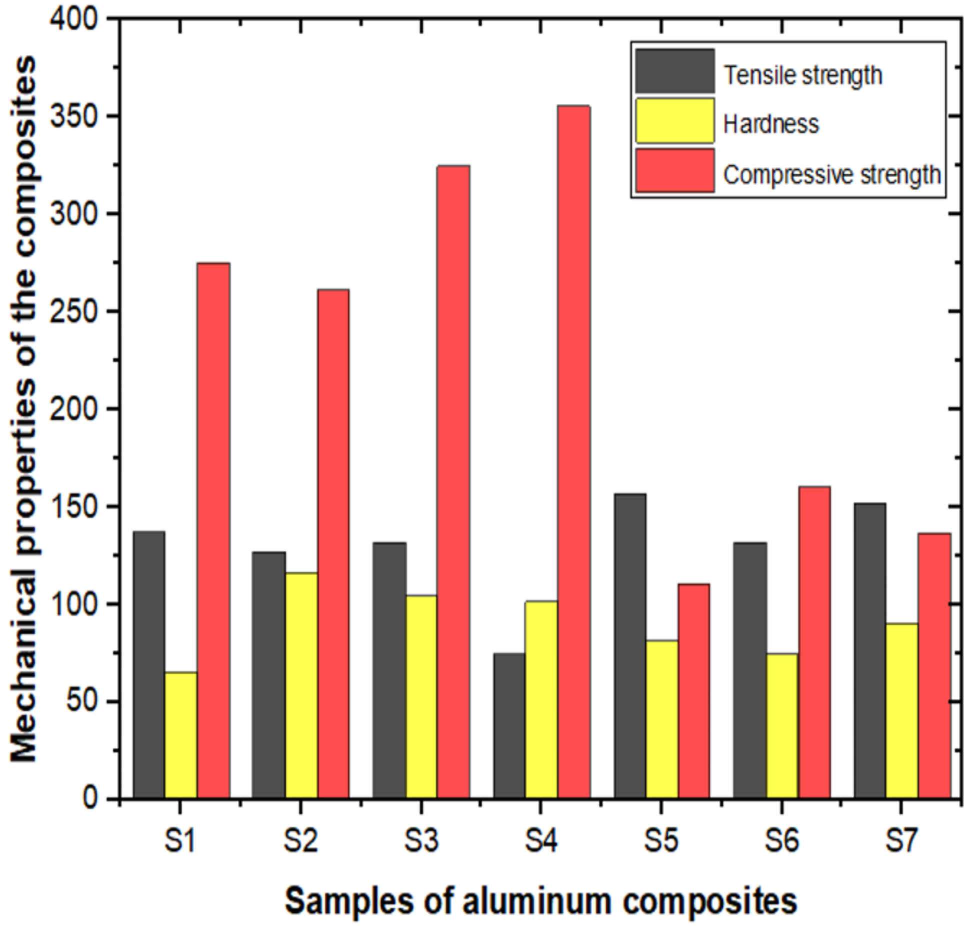


Figure 3: Mechanical properties of the different samples of aluminium composites

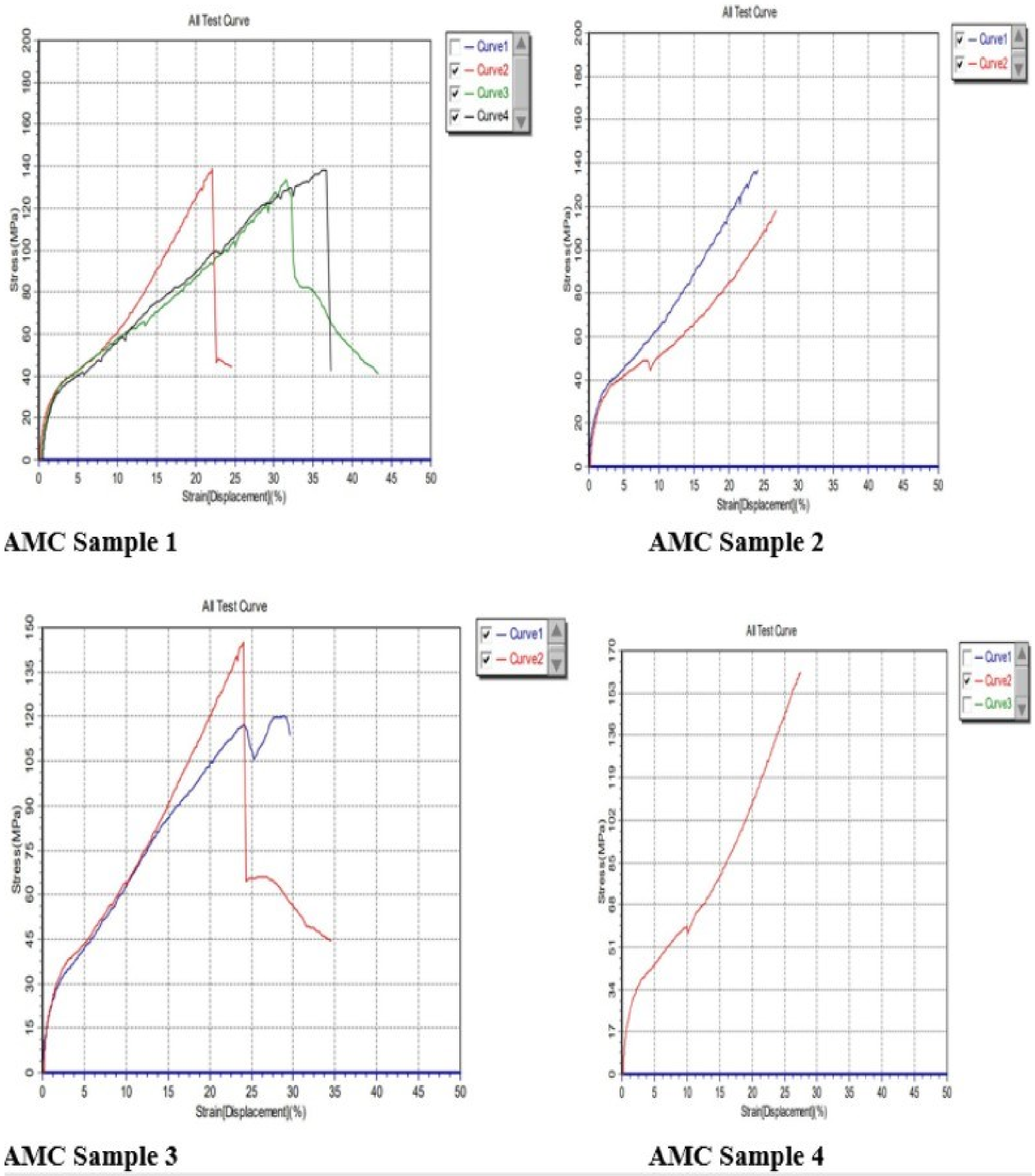
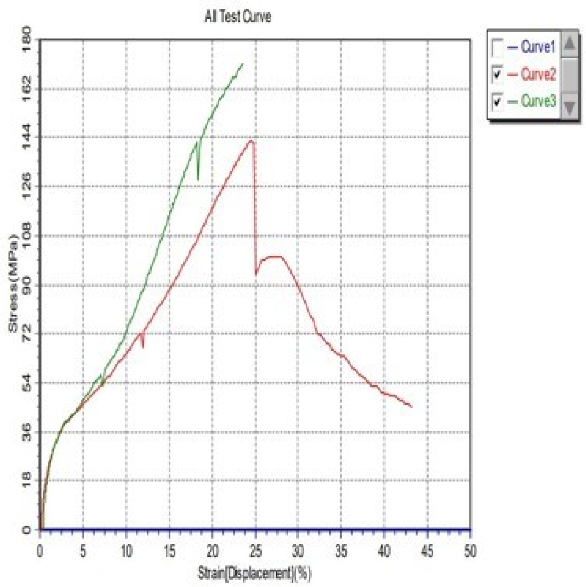
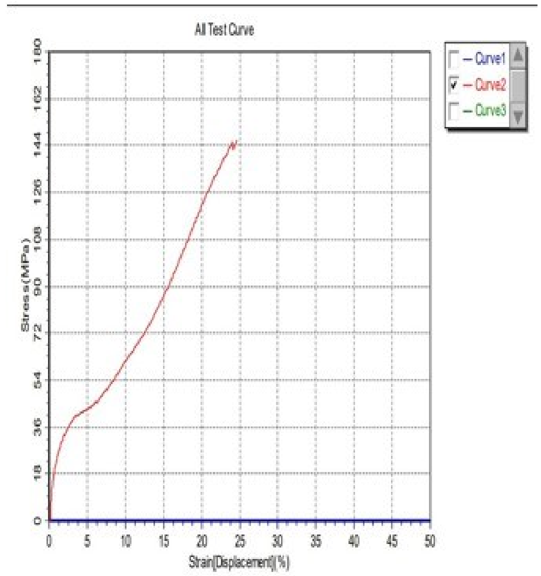


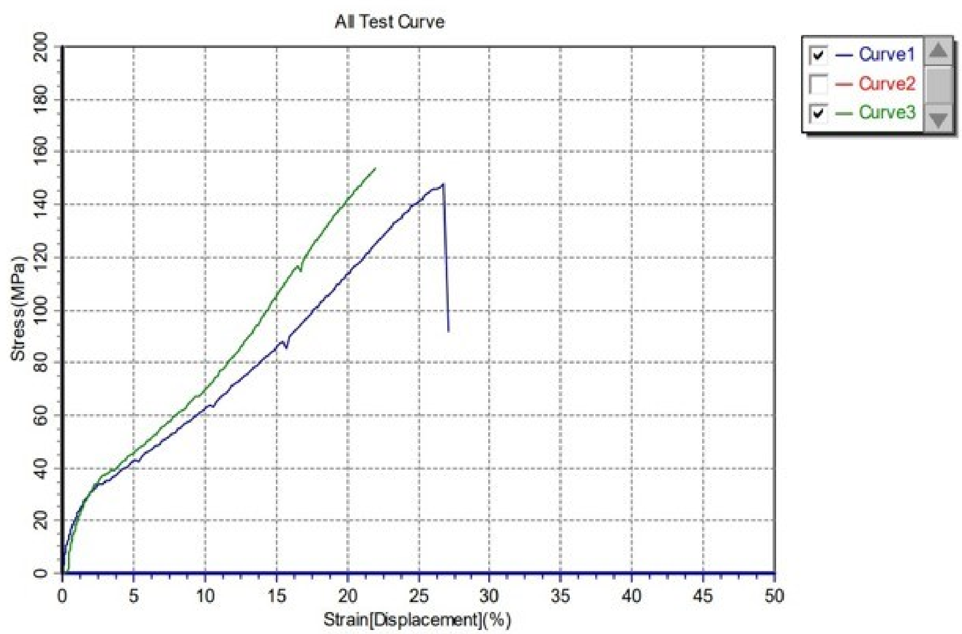
Figure 4: Tensile Strength Test Graphs for samples 1-4



AMC Sample 5



AMC Sample 6



AMC Sample 7

Figure 5: Tensile Strength Test Graphs for samples 5-7

o	Diameter (mm)	Breadth (mm)	Measured Mass (g)	Youngs Modulus (N/mm²)	Force @ Peak (N)	Force @ Upper Yield (N)	Stress @ Break (MPa)	Stress @ Lower Yield (MPa)	Stress @ Peak (MPa)
	24.500	24.500		1110.820	129897.995	33234.001	275.537	46.810	275.537

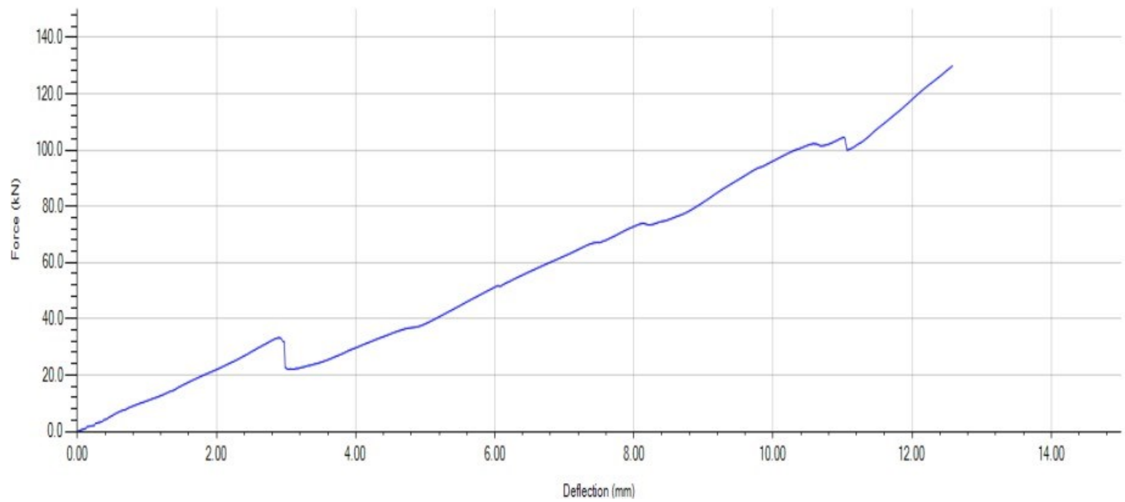


Figure 6: Compressive Test Graphs for sample 1

No	Diameter (mm)	Breadth (mm)	Measured Mass (g)	Youngs Modulus (N/mm²)	Force @ Peak (N)	Force @ Upper Yield (N)	Stress @ Break (MPa)	Stress @ Lower Yield (MPa)	Stress @ Peak (MPa)
	14.500	14.500		3375.372	43200.001	11056.000	-10.416	251.027	261.612

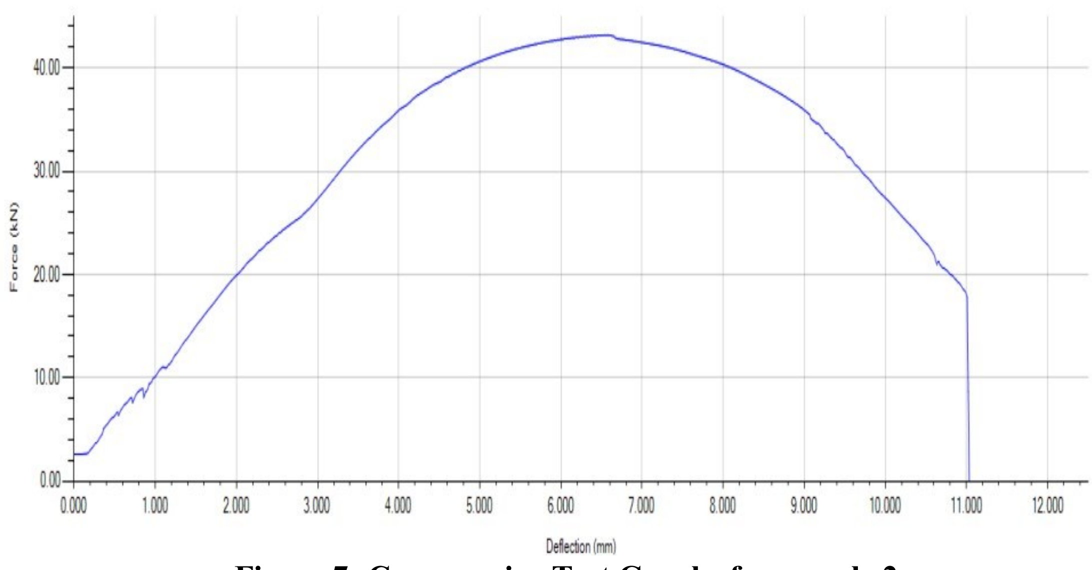


Figure 7: Compressive Test Graphs for sample 2

No	Diameter (mm)	Breadth (mm)	Measured Mass (g)	Youngs Modulus (N/mm²)	Force @ Peak (N)	Force @ Upper Yield (N)	Stress @ Break (MPa)	Stress @ Lower Yield (MPa)	Stress @ Peak (MPa)
	15.000	15.000		1928.356	57480.000	55897.999	103.879	316.018	325.270

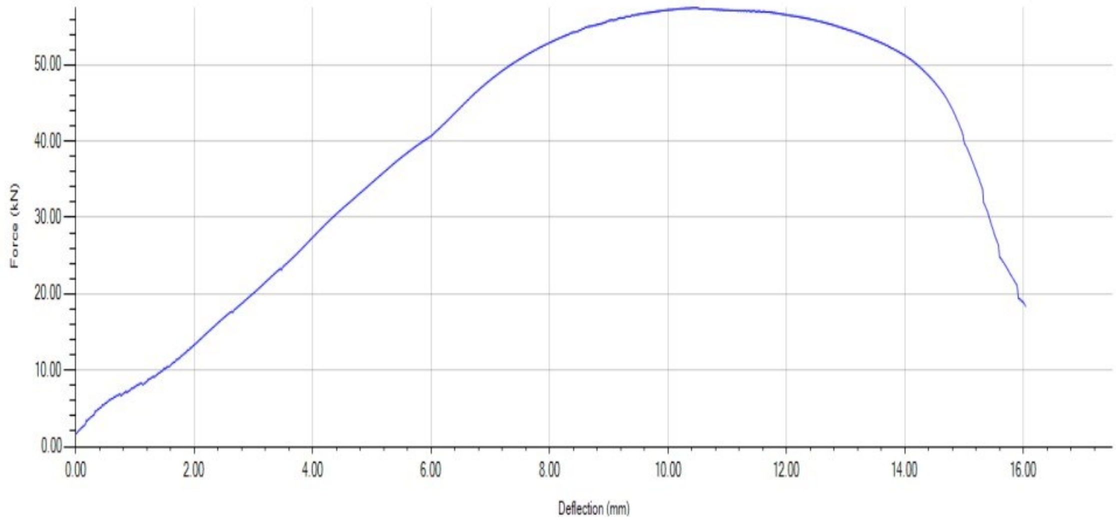


Figure 8: Compressive Test Graphs for sample 3

No	Diameter (mm)	Breadth (mm)	Measured Mass (g)	Youngs Modulus (N/mm²)	Force @ Peak (N)	Force @ Upper Yield (N)	Stress @ Break (MPa)	Stress @ Lower Yield (MPa)	Stress @ Peak (MPa)
	16.000	16.000		1986.587	71542.999	44057.999	275.522	84.357	355.826

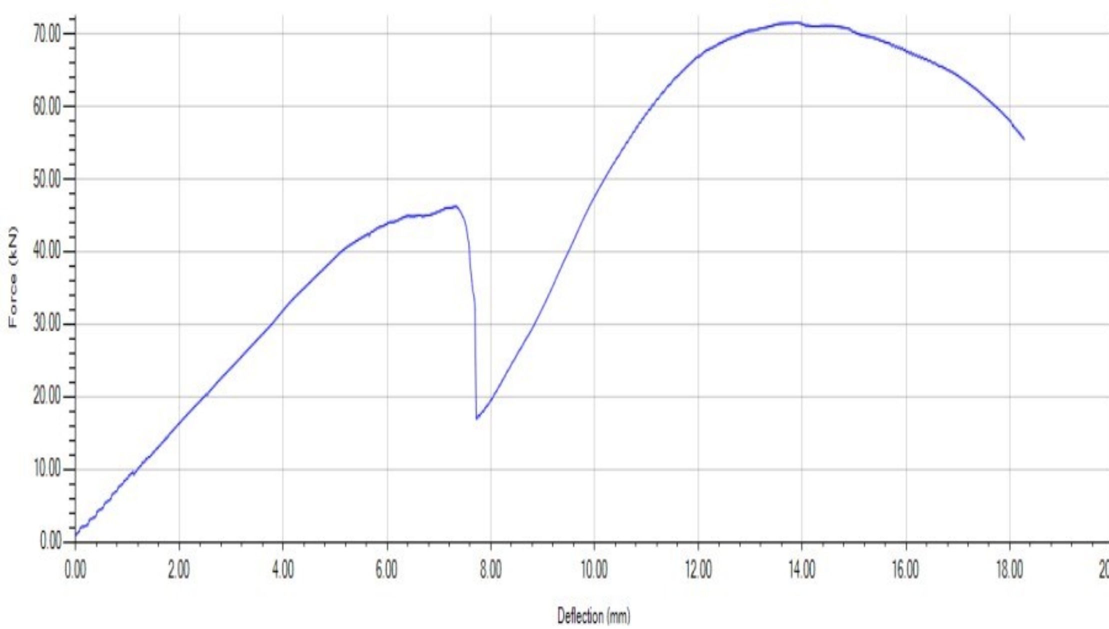


Figure 9: Compressive Test Graphs for sample 4

No	Diameter (mm)	Breadth (mm)	Measured Mass (g)	Youngs Modulus (N/mm²)	Force @ Peak (N)	Force @ Upper Yield (N)	Stress @ Break (MPa)	Stress @ Lower Yield (MPa)	Stress @ Peak (MPa)
	22.000	22.000		1995.822	42243.000	8783.000	67.369	23.463	111.127

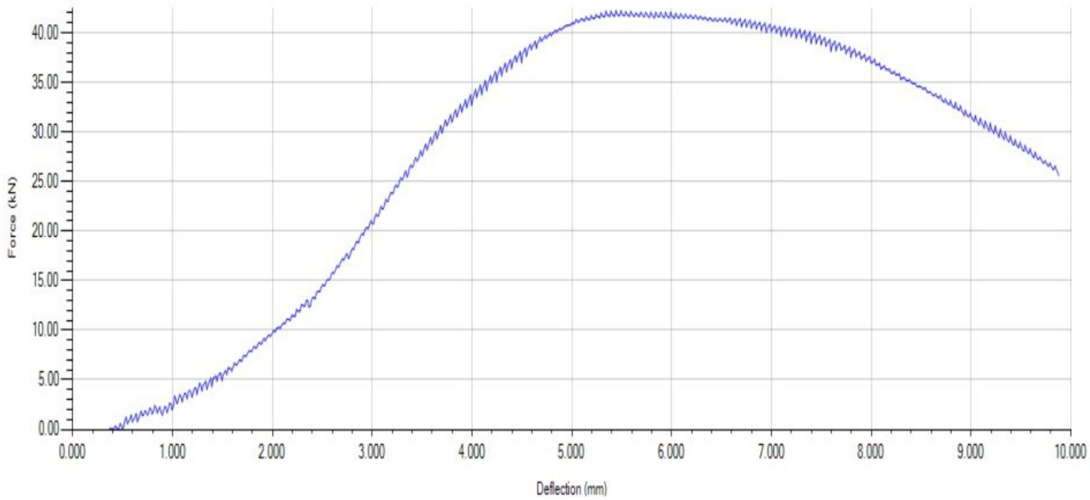


Figure 10: Compressive Test Graphs for sample 5

No	Diameter (mm)	Breadth (mm)	Measured Mass (g)	Youngs Modulus (N/mm²)	Force @ Peak (N)	Force @ Upper Yield (N)	Stress @ Break (MPa)	Stress @ Lower Yield (MPa)	Stress @ Peak (MPa)
	27.000	27.000		527.585	92114.998	20063.999	118.366	34.688	160.884

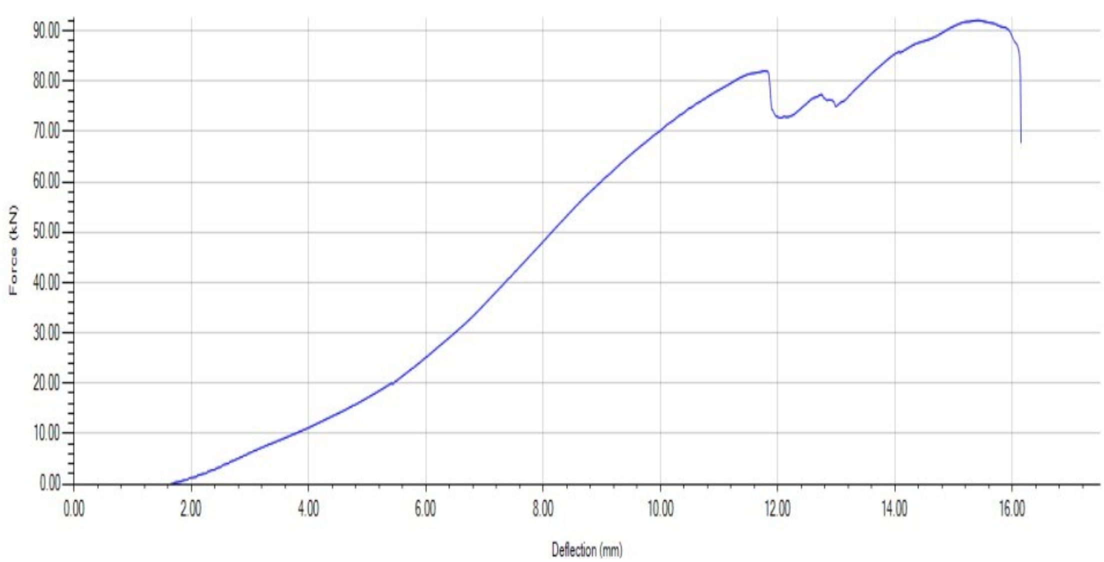


Figure 11: Compressive Test Graphs for sample 6

No	Diameter (mm)	Breadth (mm)	Measured Mass (g)	Youngs Modulus (N/mm²)	Force @ Peak (N)	Force @ Upper Yield (N)	Stress @ Break (MPa)	Stress @ Lower Yield (MPa)	Stress @ Peak (MPa)
	15.000	15.000		2215.641	24195.000	16250.999	-9.943	-10.859	136.916

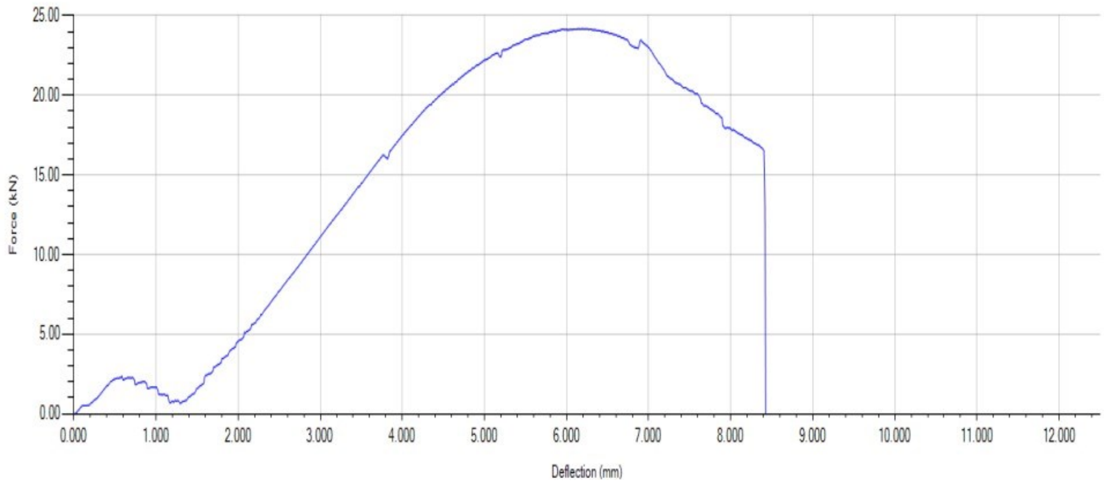


Figure 12: Compressive Test Graphs for Sample 7

Table 1: Hardness values of AMCs

Material Type	Hardness values						
	S1	S2	S3	S4	S5	S6	S7
Diameter of indentation (mm)	1.4	0.7	0.9	0.95	1.2	1.28	1.1
HBW	111	478	285	255	155.7	135.5	187.3
HRB	0	50	30	26	1	0	12
HRC	66	117	105	102	82	75	91
HV	118	505	285	258	152	137	184

Where

HBW: Brinelle's hardness number.

HRC: Rockwell's hardness number on scale C.

HRB: Rockwell's hardness number on scale B.

HV : Vickers hardness number.

Table 2: Comparison of the mechanical properties of aluminium composites

Research study	Tensile strength	Hardness
	(MPa)	HRB
Present study	157.5	117.0
(Daramola et al., 2015)	73.62	40.2
(Apasi et al., 2016)	200.0	78.6
Al 6061-T6 (ISO 6362-2;2022 ed.5)	145.0	60.0

Appendix B: Hardness Conversion Chart.

Steel Hardness Conversion Table

This table shows approximate hardness of steel using Brinell, Rockwell B and C and Vickers scales. These conversion charts are provided for guidance only as each scales uses different methods of measuring hardness. The right hand column show an approximate equivalent tensile strength.

Steel Hardness conversion calculator				
Brinell Hardness HB	Rockwell C - HRC	Rockwell B - HRB	Vickers - HV	
				Calculate
Enter a figure into any of the fields and click calculate, the nearest values in each scale is shown, or zero if out of range. Values are approximate and for guidance only.				

Reference Table: Steel hardness conversion chart - all values approximate.

Brinell Hardness HB	Rockwell HRC	Rockwell HRB	Vickers HV	N/mm^2
800	72			
780	71			
760	70			

752	69			
745	68			
746	67			
735	66			
711	65			
695	64			
681	63			
658	62			
642	61			
627	60			
613	59			
601	58		746	
592	57		727	
572	56		694	
552	55		649	
534	54	120	589	
513	53	119	567	
504	52	118	549	
486	51	118	531	
469	50	117	505	
468	49	117	497	
456	48	116	490	1569
445	47	115	474	1520
430	46	115	458	1471
419	45	114	448	1447
415	44	114	438	1422
402	43	114	424	1390
388	42	113	406	1363
375	41	112	393	1314
373	40	111	388	1265
360	39	111	376	1236
348	38	110	361	1187
341	37	109	351	1157
331	36	109	342	1118
322	35	108	332	1089
314	34	108	320	1049
308	33	107	311	1035
300	32	107	303	1020
290	31	106	292	990

277	30	105	285	971
271	29	104	277	941
264	28	103	271	892
262	27	103	262	880
255	26	102	258	870
250	25	101	255	853
245	24	100	252	838
240	23	100	247	824
233	22	99	241	794
229	21	98	235	775
223	20	97	227	755
216	19	96	222	716
212	18	95	218	706
208	17	95	210	696
203	16	94	201	680
199	15	93	199	667
191	14	92	197	657
190	13	92	186	648
186	12	91	184	637
183	11	90	183	617
180	10	89	180	608
175	9	88	178	685
170	7	87	175	559
167	6	86	172	555
166	5	86	168	549
163	4	85	162	539
160	3	84	160	535
156	2	83	158	530
154	1	82	152	515
149		81	149	500
147		80	147	490
143		79	146	482
141		78	144	481
139		77	142	480
137		76	140	475
135		75	137	467
131		74	134	461
127		72	129	451
121		70	127	431

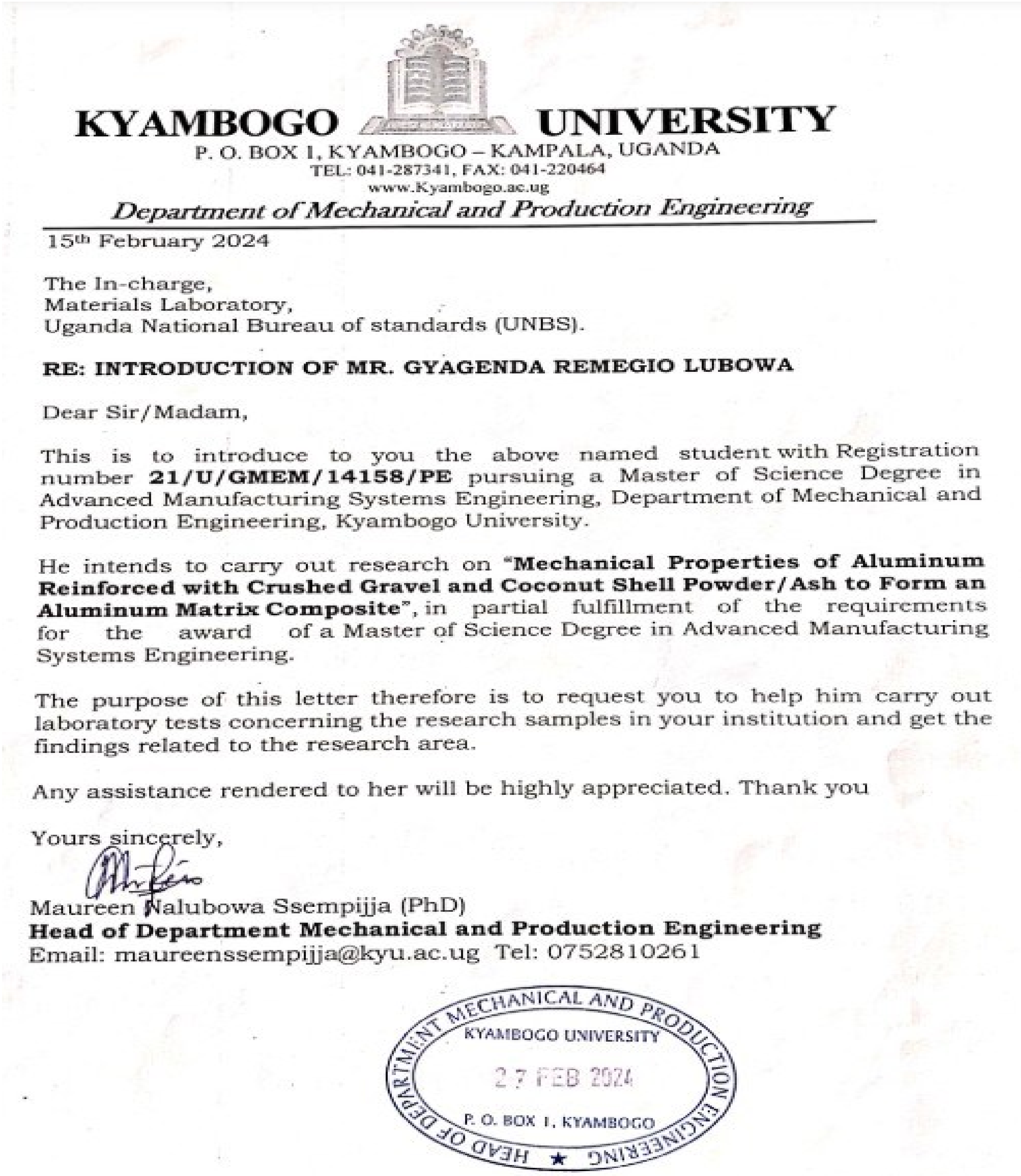
116		68	124	422
114		67	121	412
111		66	118	402
107		64	115	382
105		62	112	378
103		61	108	373
95		56	104	
90		52	95	
81		41	85	
76		37	80	
Brinell HB 3000kg 10mm Ball	**Rockwell HRC 150kg Brale**	**Rockwell HRB 100kg 1/16" Ball**	**Vickers HV Diamond Pyramid 120kg**	**N/mm² Tensile strength (Approx)**

Reference table: Steel Hardness conversion chart

Since the various types of hardness tests do not all measure the same combination of material properties, conversion from one hardness scale to another is only an approximate process. Because of the wide range of variation among different materials, it is not possible to state confidence limits for the errors in using a conversion chart.

Figure 13: Hardness Conversion Chart.

Appendix C: Introductory Letters.



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TEL: 041-287341, FAX: 041-220464
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Department of Mechanical and Production Engineering

15th February 2024

The In-charge,
Materials Laboratory,
Uganda National Bureau of standards (UNBS).

RE: INTRODUCTION OF MR. GYAGENDA REMEGIO LUBOWA

Dear Sir/Madam,

This is to introduce to you the above named student with Registration number **21/U/GMEM/14158/PE** pursuing a Master of Science Degree in Advanced Manufacturing Systems Engineering, Department of Mechanical and Production Engineering, Kyambogo University.

He intends to carry out research on **"Mechanical Properties of Aluminum Reinforced with Crushed Gravel and Coconut Shell Powder/Ash to Form an Aluminum Matrix Composite"**, in partial fulfillment of the requirements for the award of a Master of Science Degree in Advanced Manufacturing Systems Engineering.

The purpose of this letter therefore is to request you to help him carry out laboratory tests concerning the research samples in your institution and get the findings related to the research area.

Any assistance rendered to her will be highly appreciated. Thank you

Yours sincerely,

Maureen Nalubowa Ssempijja (PhD)
Head of Department Mechanical and Production Engineering
Email: maureenssempijja@kyu.ac.ug Tel: 0752810261

HEAD OF DEPARTMENT MECHANICAL AND PRODUCTION ENGINEERING
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27 FEB 2024
P. O. BOX 1, KYAMBOGO

Figure 14: Introduction letter UNBS

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Department of Mechanical and Production Engineering

15th February 2024

The In-charge,
Ceramics Department,
Uganda Industrial Research Institute (UIRI).

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KYAMBOGO UNIVERSITY
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Figure 15: Introduction letter UIRI

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www.Kyambogo.ac.ug

Department of Mechanical and Production Engineering

15th February 2024

The In-charge,
Chemistry Department,
Makerere University.

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MECHANICAL PROPERTIES OF ALUMINUM REINFORCED WITH CRUSHED GRAVEL AND COCONUT SHELL ASH FOR VARIOUS APPLICATIONS

GYAGENDA REMEGIO LUBOWA
BEng. Mech & Manuf. KyU
21/U/GMEM/14158/PE
2100814158

A DISSERTATION SUBMITTED TO THE DIRECTORATE OF RESEARCH AND GRADUATE TRAINING IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE AWARD OF MASTER OF SCIENCE IN ADVANCED MANUFACTURING SYSTEMS ENGINEERING DEGREE OF KYAMBOGO UNIVERSITY

OCTOBER, 2024