EFFECT OF DIFFERENT PRESSURE FORCES ON THE DENSE POROUS LAYER OF CERAMICS

NUR ASYILAH BINTI AWANG NGAH

B052010001

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

2024

EFFECT OF DIFFERENT PRESSURE FORCES ON THE DENSE POROUS LAYER OF CERAMICS

This report is submitted in accordance with requirement of the University Teknikal Malaysia Melaka (UTeM) for Bachelor Degree of Manufacturing Engineering (Hons.)

by

NUR ASYILAH BINTI AWANG NGAH
B052010001
000302-11-0038

FACULTY OF INDUSTRIAL AND MANUFACTURING
TECHNOLOGY AND ENGINEERING
2024

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

BORANG PENGESAHAN STATUS LAPORAN PROJEK SARJANA MUDA

Tajuk: **EFFECT OF DIFFERENT PRESSURE FORCES ON THE DENSE POROUS LAYER OF CERAMICS**

Sesi Pengajian: **2023/2024 Semester 2**

Saya **NUR ASYILAH BINTI AWANG NGAH (000302-11-0038)**

mengaku membenarkan Laporan Projek Sarjana Muda (PSM) ini disimpan di Perpustakaan Universiti Teknikal Malaysia Melaka (UTeM) dengan syarat-syarat kegunaan seperti berikut:

1. Laporan PSM adalah hak milik Universiti Teknikal Malaysia Melaka dan penulis.
2. Perpustakaan Universiti Teknikal Malaysia Melaka dibenarkan membuat salinan untuk tujuan pengajian sahaja dengan izin penulis.
3. Perpustakaan dibenarkan membuat salinan laporan PSM ini sebagai bahan pertukaran antara institusi pengajian tinggi.
4. *Sila tandakan (√)

☐ SULIT (Mengandungi maklumat yang berdarjah keselamatan atau kepentingan Malaysiasebagaimana yang termaktub dalam AKTA RAHSIA RASMI 1972)

☐ TERHAD (Mengandungi maklumat TERHAD yang telah ditentukan oleh organisasi/ badan di mana penyelidikan dijalankan)

☑ TIDAK TERHAD

Disahkan oleh:

Alamat Tetap:
P T4586 JALAN TENGGIRI
KG TEBING TEMBAH, 23100 PAKA,
TERENGGANU

Tarikh: 28 JUNE 2024

Cop Rasmi:
PROF. DR. MOHD WARIKH BIN ABD RASHID
Faculty of Manufacturing Engineering
Universiti Teknikal Malaysia Melaka
Hang Tuah Jaya, 76100 Durian Tunggal, Melaka

Tarikh: 28 JUNE 2024

*Jika Laporan PSM ini SULIT atau TERHAD, sila lampirkan surat daripada pihak berkuasa/organisasi berkenaan dengan menyatakan sekali sebab dan tempoh laporan PSM ini perlu dikelaskan sebagai SULIT atau TERHAD.

DECLARATION

I hereby, declared this report entitled “Effect Of Different Pressure Forces On The Dense Porous Layer Of Ceramics” is the result of my own research except as cited in references.

Signature : ....
Author’s Name : NUR ASYILAH BINTI AWANG NGAH
Date : 28 June 2024

APPROVAL

This report is submitted to the Faculty Of Industrial And Manufacturing Technology And Engineering of Universiti Teknikal Malaysia Melaka as a partial fulfilment of the requirement for Degree of Manufacturing Engineering (Hons). The member of the supervisory committee is as follow:

…………………….................................

Professor Dr. Mohd Warikh Bin Abd Rashid

ABSTRACT

The purpose of this study is to examine how different pressure forces affect the mechanical and structural characteristics of dense-porous layers in ceramic materials derived from a mixtures clay, Silica and Feldspar. Bi-layered ceramics have two layers in their structure which are a porous lower layer and a thick upper layer created by double pressing. The dense layer's function is to give the porous layer structural support. The pore-forming agent polymethylmethacrylate (PMMA) is added to the porous layer at weight percentage of 5%. The goal of the study is to clarify how various pressure levels throughout the fabrication process affect the final ceramics' microstructure, porosity, and mechanical strength. To do this, a controlled experimental setup was used to apply various pressure forces to a series of ceramic samples. To create dense, porous layers, ceramic powders were first compressed under various pressures and then sintering was performed. The microstructural properties were examined using X-ray diffraction (XRD) and scanning electron microscopy (SEM), which included pore size distribution and interconnectivity. Using established testing procedures, mechanical attributes like compressive strength and hardness were assessed. According to results, a pressure of 20 MPa is the best for the ceramic material to have the optimal balance of mechanical characteistics, density and smoothness under the tested conditions. Higher pressures are associated with less porosity and improved mechanical performance. This work offers important new insights into the optimization of dense-porous ceramic layer production, with potential applications in filtration, catalysis, and structural materials, among other areas. To fully comprehend the underlying principles and to improve the control parameters for customizing ceramic materials with particular qualities, more research is necessary. It is expected that the result of using the different pressure can improve their functionality for advance technology.

ABSTRAK

Tujuan kajian ini adalah untuk mengkaji bagaimana daya tekanan yang berbeza mempengaruhi ciri mekanikal dan struktur lapisan berliang tumpat dalam bahan seramik yang diperolehi daripada campuran tanah liat, silica dan feldspar. Seramik dua lapis mempunyai dua lapisan dalam strukturnya iaitu lapisan bawah berliang dan lapisan atas tebal yang dicipta dengan menekan dua kali. Fungsi lapisan padat adalah untuk memberikan sokongan struktur lapisan berliang. Ejen pembentuk liang PMMA ditambah pada lapisan berliang pada peratusan 5%. Matlamat kajian adalah untuk menjelaskan bagaimana pelbagai tahap tekanan sepanjang proses fabrikasi mempengaruhi struktur mikro, keliangan dan kekuatan mekanikal seramik akhir. Untuk melakukan ini, persediaan eksperimen terkawal telah digunakan untuk menggunakan pelbagai daya tekanan pada satu siri sampel seramik. Untuk mencipta lapisan padat, berliang, serbuk seramik mula-mula dimampatkan di bawah pelbagai tekanan dan kemudian pensinteran dilakukan. Sifat mikrostruktur telah diperiksa menggunakan pembelauan sinar-X (XRD) dan mikroskop elektron pengimbasan (SEM), yang termasuk taburan saiz liang dan kesalinghubungan. Menggunakan prosedur ujian yang ditetapkan, sifat mekanikal seperti kekuatan mampatan dan kekerasan dinilai. Mengikut keputusan, tekanan 20 MPa adalah yang terbaik untuk bahan seramik mempunyai keseimbangan optimum ciri mekanikal, ketumpatan dan kelancaran di bawah keadaan yang diuji. Tekanan yang lebih tinggi dikaitkan dengan kurang keliangan dan prestasi mekanikal yang lebih baik. Kajian ini menawarkan pandangan baharu yang penting tentang pengoptimuman pengeluaran lapisan seramik berliang padat, dengan aplikasi yang berpotensi dalam penapisan, pemangkinan dan bahan struktur, antara kawasan lain. Untuk memahami sepenuhnya prinsip asas dan menambah baik parameter kawalan untuk menyesuaikan bahan seramik dengan kualiti tertentu, lebih banyak penyelidikan diperlukan. Diharapkan hasil daripada penggunaan tekanan yang berbeza dapat meningkatkan fungsi mereka untuk teknologi maju.

DEDICATION

Only
my beloved father, Awang Ngah Bin Md Roshid
my appreciated mother, Salinah Binti Mohamed
my adored sisters Nur Syazliana, Nur Syazwani and Nur Syairah
my soulmate Siti Nurashikin Binti Mohamed Yazid
for giving me moral support, money, cooperation, encouragement and also understandings
Thank You So Much & Love You All Forever

ACKNOWLEDGEMENTS

In the Name of Allah, the Most Gracious, the Most Merciful

First and foremost, I want to express my gratitude and praise to Allah, the Almighty, who is also my Creator and Sustainer, for everything that has been provided for me from the dawn of time. I express my gratitude to Universiti Teknikal Malaysia Melaka (UTeM) for granting access to the research platform. We also acknowledge the financial support provided by the Malaysian Ministry of Higher Education (MOHE).

My supervisor, Associate Professor Dr. Mohd Warikh Bin Abd Rashid of Universiti Teknikal Malaysia Melaka (UTeM), has my sincere gratitude for all of his help, counsel, and inspiration. His unwavering patience in mentoring and imparting invaluable insights will always be cherished. Furthermore, to my academic adviser at Universiti Teknikal Malaysia Melaka (UTeM), Profesor Madya Ir. Dr. Lokman Bin Abdullah, who has always supported me on my journey. I would especially like to thank Mohamed Lokman Jalaluddin for all of his assistance and encouragement.

Last but not least, I would want to express my sincere thanks to my parents, Salinah Binti Mohamed and Awang Ngah Bin Md Roshid, for their unwavering support and encouragement throughout all of my achievements. My sincere gratitude to my large family for their unwavering love, support, and prayers is also forever. Lastly, I would like to express my gratitude to everyone who helped, encouraged, and supported me while I started my studies.

TABLE OF CONTENTS

LIST OF TABLES

TABLE **TITLE** **PAGE**

LIST OF FIGURES

LIST OF SYMBOLS

% - Percentage

°C - Celsius

g/cm^3 - grams per cubic centimeter

E - Young’s Modulus

g - Gram

Wc - Saturated Mass

ρ - Density

kg/m^3 - kilograms per cubic meter

GPa - Gigapascals

V - Volume

MPa - Mega Pascal

Wa - Dry Mass

Wb - Mass Suspended In Water

Pa - Pascal

5 °C/min - 5 °C per minute

m - Mass

mm - Millimetre

LIST OF ABBREVIATION

SI	-	System of Units
CTE	-	Coefficient of Thermal Expansion
HIP	-	Hot Isostatic Pressing
UTM	-	Universal Tensile Machine
TG/DTA	-	Thermogravimetric Analysis/ Differential Thermal Analysis
FESEM	-	Field Emission Scanning Electron Microscope
XRD	-	X-ray Diffraction Analysis
EDX	-	Energy Dispersed X-ray
PMMA	-	Polymethyl methacrylate

CHAPTER 1

INTRODUCTION

1.1 Research Background

For thousands of years, ceramic materials a broad class of inorganic, non-metallic compounds have been essential to human civilization. Ceramics, which are distinguished by a special set of characteristics, have been used for a variety of purposes, ranging from the use of sophisticated aerospace (Ozkan et al., 2022) components and cutting-edge medical devices to the production of building materials and ancient pottery. Metal and non-metal elements combine to form ionic or covalent bonds in a crystalline structure, which is the main component of ceramic composition and structure. Oxygen, nitrogen, carbon, and a variety of metallic cations (such as magnesium, silicon, aluminum, and more) are frequently found elements in ceramics. Depending on the particular ceramic material, atomic bonding in ceramics can be primarily ionic or covalent. Positively and negatively charged ions are created when atoms exchange electrons through a process known as ionic bonding. Atoms that share electrons form covalent bonds. The qualities of the material are influenced by the type of bonding.

The type of ceramic material can have a significant impact on the specific chemical composition. The crystal structure is what distinguishes ceramics. A ceramic material's atoms are arranged in a three-dimensional lattice pattern that repeats. The ordered arrangement of atoms in ceramics is responsible for their distinctive characteristics, such as their hardness, brittleness, and thermal stability. Ceramics frequently have several crystalline domains or grains in addition to the general crystal lattice (Abdul Hai Alami et al., 2023). Grain boundaries are the lines separating these grains. Grain structure influences both mechanical strength and electrical behavior, making it a crucial factor in ceramic properties. Not every ceramic has an only crystalline structure. Certain ceramics, like some types of glasses, can have a non-crystalline or amorphous structure . The more haphazard arrangement of atoms in amorphous ceramics accounts for these materials' distinctive transparency and absence of a clearly defined crystal lattice. Ceramics occasionally include impurities or purposeful additions to change their characteristics. These can be additives to modify electrical conductivity, sintering agents to speed up the manufacturing process, or other components to improve particular properties. Ceramics are known for their hardness, brittleness, and resistance to high temperatures because of this atomic arrangement. Ceramics are generally insulators and have superior resistance to wear and corrosion than metals and polymers.

Recently, there has been an increasing interest in tailoring ceramic materials for particular uses. The need for cutting-edge ceramic materials has grown as a result of the ability to customize ceramics to precisely match the needs of various industries. Owing to their resilient mechanical, chemical, and thermal characteristics, porous ceramic structures have been the subject of extensive structural and functional exploration in recent decades. Filter membranes, catalyst support, thermal insulators, solid oxide fuel cells, biomedical implants, and other industrial uses are among their many uses according to Venkata Sundeep Seesala et al. (2021).

"Dense ceramics" are ceramic materials with a high density, which indicates that there is little porosity, or open space, in their structure. These ceramics differ from porous ceramics in that they have particular properties and characteristics due to their relatively tight, solid, and compact structure. Dense ceramics are suitable for structural components in a variety of applications due to their increased mechanical strength due to the absence of porosity. In contrast to porous ceramics, dense ceramics are less permeable to liquids and gases. This feature is useful in situations where sealing or containment is necessary. Because porous ceramics trap insulating air pockets within their structure, dense ceramics are generally less effective as thermal or electrical insulators than porous ceramics. Dense ceramics are more wear-resistant when there is no porosity, which makes them appropriate for applications where there is friction and abrasive forces(Wu et al., 2023). Dense ceramics are useful in applications involving extreme heat because they frequently show high-temperature stability and resistance. When compared to porous materials, dense ceramics' compact structure can result in superior mechanical and thermal conductivity. Applications like heat exchangers and cutting tools benefit from this.

The term "porous ceramics" describes ceramic materials that have been purposefully engineered and designed to have a structure that has a network of voids, pores, or open spaces within their matrix. These voids, also known as pores, are made to give material particular qualities and functions. Porosity affects the mechanical, thermal, and electrical properties of ceramic materials, making it a crucial component. For example, low porosity is preferred for structural components, while high porosity is desirable in applications such as thermal insulation. The porosity can differ in size, shape, and distribution. Porous ceramics are fundamentally different from dense or non-porous ceramics in that they possess porosity. Heat transfer can be considerably inhibited by air or gas-filled voids in porous ceramic materials. Porous ceramics frequently serve as barriers to the passage of heat in thermal insulation applications. Because porous ceramics have a lower density by nature, they are lighter. This feature is helpful in applications like aerospace and automotive components where weight reduction is a crucial factor.

Porous ceramics are useful for noise control and acoustic insulation because of their capacity to absorb sound, which is facilitated by the voids within them (Lou et al., 2023). It is possible to design porous ceramics with a regulated pore size distribution, which makes them useful filters for removing materials or particles from liquids or gases. The porous ceramic are employed in processes like air and water filtration.Ceramics' porosity can be adjusted to resemble the structure of natural bone, which encourages tissue ingrowth and qualifies them for use in tissue scaffolds and orthopedic and dental implants. By expanding the area of contact between the implant and the bone and lowering the stress-shielding effect, porous implants with open pores may also encourage osteointegration (Venkata Sundeep Seesala et al., 2021). High surface area is provided by porous ceramics, which is advantageous for catalytic material support. The porous ceramic are employed in chemical processes, especially in catalytic converters, which reduce emissions in cars.

Pressure differentials between two sides of a material can be equalized with the use of porous ceramics. Applications like pressure sensors and protective barriers can benefit from this feature. It is possible to engineer the capillary action in porous ceramics for fluid transport applications, like wicking in medical devices or inkjet printing. Different porosity levels can be achieved in porous ceramics, ranging from low porosity with few voids to high porosity with a large amount of open space. The pore structure's design and management play a crucial role in customizing the material to fulfill the demands of various applications. Because of their distinct structure, porous ceramics provide a wide range of functionalities. Moreover, the porosity of these materials is a fundamental property that can be utilized to meet a variety of engineering and industrial needs.

Pressure forces have become an important factor in ceramic performance and fabrication. Comprehending the effects of various pressure forces on dense-porous ceramic layers has emerged as a crucial facet of material engineering. These pressures can come from a number of places, including harsh environments, high-temperature applications, and sintering procedures. The mechanical characteristics of ceramic materials can be directly impacted by changes in pressure forces. Comprehending the impact of pressure on attributes such as hardness, toughness, and tensile strength is crucial when creating ceramic materials that can tolerate particular mechanical strains in real-world scenarios. Ceramics' porosity and density can be changed by pressure forces. In ceramics, the degree of porosity is frequently a crucial design factor for uses like catalysis, filtration, and insulation (Venkata Sundeep Seesala et al., 2021). To achieve the best results, ceramic materials' porosity can be adjusted with the aid of this research. Different pressure forces can have an impact on dense-porous ceramics' structural integrity. This is especially crucial in situations where ceramics are subjected to dynamic loading or high pressures, like when armor or protective materials are being constructed. The thermal conductivity of ceramics can be affected by pressure. Knowing how pressure forces impact thermal properties is crucial for applications where effective heat transfer is required, such as heat exchangers and thermal management systems.

For electrical properties, pressure-induced changes in ceramic electrical properties are of great interest for applications involving electrical insulators or conductors, such as in electronic components. The impact of pressure on electrical resistivity, dielectric constant, and other pertinent properties might be investigated in this study. Understanding how pressure forces affect ceramics is essential for improving production methods. For example, methods for pressure-assisted sintering could be developed or enhanced to produce ceramics with particular characteristics. Knowing how pressure forces affect dense-porous ceramics makes it possible to modify them for a variety of uses. Ceramics can be customized by researchers to fit the unique needs of a variety of industries, including aerospace, energy, and biomedicine (Ozkan et al., 2022). Beyond useful applications, this research advances our basic knowledge of material science. It clarifies the connections between ceramic structure, properties, and pressure that also hold true for other materials. Overall, it is crucial to research how different pressure forces affect dense-porous ceramic layers in order to both improve current ceramic materials and uncover new opportunities for their use in a range of fields and applications. Researchers still don't fully understand how different pressure forces specifically affect dense- porous ceramic layers, despite the growing interest in customized ceramics and the acknowledged impact of pressure forces on ceramic materials. Previous studies have predominantly concentrated on traditional ceramics; therefore, it is imperative to investigate the unique characteristics and actions of dense-porous ceramics under varying pressure regimes.

1.2 Problem Statement

One of the most important aspects of materials science and engineering is comprehending the interaction between ceramic properties including porosity, thermal conductivity and strength, and external pressure forces. For a variety of applications in sectors where ceramics are important, an understanding of this relationship is necessary. The kind of ceramic material, the particular application, and the type of pressure applied are some of the variables that can affect how different pressure levels affect a material's porosity. The porosity of ceramic materials can be greatly impacted by external pressure forces. The voids, pores, or open spaces in ceramic materials tend to compress when external pressure forces are applied. Porosity is decreased as a result of this compression (Sylvain Meille et al., 2012). One of the main causes of the porosity reduction is the mechanical compression of the ceramic structure under pressure. The spaces between particles get smaller or closer together as pressure pushes them closer together. A crucial stage in the production of ceramics, sintering, occasionally involves the application of pressure. A heat treatment called sintering aids in the densification and strengthening of ceramics. Porosity is further decreased by applying pressure during the sintering process, making the material more robust and compact.

In materials science and engineering, the relationship between external pressure forces and ceramic properties such as thermal conductivity is an important field of research. To optimize ceramics for applications where heat transfer efficiency is critical, it is imperative to comprehend the relationship between pressure and thermal conductivity. Ceramics' internal voids and pores have a tendency to compress under the influence of external pressure. Densification, the process of forcing the ceramic particles closer together, is the outcome of this compression. Thermal conductivity usually increases with densification. Heat can move across the material more effectively since there are fewer voids and thermal barriers between the particles. Increased thermal conductivity results from increased particle-to-particle contact, which allows phonons the heat carriers to travel more freely. Ceramics can undergo structural alterations under high pressure, which can impact their thermal conductivity (Cha et al., 2023). Phase transitions, atomic rearrangements, or modifications to the crystal lattice are a few examples of these structural changes. These structural modifications have the potential to either increase or decrease thermal conductivity, depending on the particular ceramic material. Ceramics can undergo structural alterations under high pressure, which can impact their thermal conductivity. Phase transitions, atomic rearrangements, or modifications to the crystal lattice are a few examples of these structural changes. These structural modifications have the potential to either increase or decrease thermal conductivity, depending on the particular ceramic material.

The link between external pressure forces and ceramic properties particularly strength is crucial to materials research and engineering. Designing and utilizing ceramics in applications where mechanical integrity and resistance to external pressure are critical requires an understanding of this relationship. Ceramics can be subjected to external pressure forces, particularly compressive forces, which can increase the material's compressive strength. The capacity of a material to tolerate axial loads that tend to decrease its volume is referred to as its compressive strength. Particle packing becomes closer as a result of the compression of the ceramic structure under external pressure forces, which lowers the risk of crack initiation and propagation (Sylvain Meille et al., 2012). Enhanced compressive strength is frequently the outcome of this compression effect.

Densification, or a closer packing of the ceramic with fewer voids or pores, is usually the result of applying pressure. Particularly in compression, densification can help to raise the material's overall strength. Anisotropic means that the response of external pressure forces to ceramic strength can vary within the material in different directions. The strength behaviour can be affected by how the pressure force is oriented in relation to the crystallographic axes. Applying pressure can improve strength in some directions while having a different effect in other directions, depending on the particular ceramic material. Ceramics can undergo structural changes when exposed to high pressure (Venkata Sundeep Seesala et al., 2021). Phase transitions and modifications to the crystal lattice structure are two examples of these changes. The strength properties of the material may be impacted by these structural alterations. Brittleness is a well-known characteristic of ceramics. Pressure may not have a substantial effect on their tensile or flexural strength, but it can increase their compressive strength. In actuality, microcracks or other defects that lower tensile or flexural strength may arise as a result of external pressure forces. The particular application and loading circumstances must be taken into account when evaluating how pressure affects ceramic strength.

On the other hand, the precise effects of various pressure forces on critical ceramic properties including mechanical strength, thermal conductivity, and porosity are not well understood. This information is crucial for optimizing ceramics in a variety of industries, including manufacturing, aerospace, and energy production, where these qualities are vital to material performance and efficiency. Specifically, researcher will look into how pressure forces affect various pressure conditions and ceramic properties like strength, porosity, and thermal conductivity. Therefore, how do different pressure forces affect the porosity, thermal conductivity, and strength of ceramics is the main research question that motivates this work. By clarifying this connection, researcher hope to find knowledge that can guide the engineering and design of ceramics for particular uses, improving their functionality and advancing technology. This study aims to investigate the effects of different pressure forces on the properties of ceramics, specifically porosity, thermal conductivity, and mechanical strength, in light of the existing knowledge gaps. It is anticipated that the findings of this research will offer significant perspectives that can be utilized to enhance ceramics for various uses in sectors where these characteristics are critical.

Although a substantial amount of information has been written about how ceramics behave under various pressures, there is still a clear knowledge vacuum when it comes to the particulars of dense-porous layers. Although a great deal of study has been done on how ceramics respond to pressure in general, little of it has been done to thoroughly examine the subtle effects of various pressure forces on ceramics that include dense-porous layers. The peculiar features of dense-porous ceramics, which can greatly affect their mechanical and structural reactions to external stresses, make this knowledge gap noteworthy. The extant literature predominantly concentrates on homogeneous ceramics or porous materials, with a deficiency of clarity on the interaction between pressure forces and the particular properties of densely porous layers.

Furthermore, a wide range of pressure levels are rarely systematically examined in existing studies, which limits our comprehension of the ways in which differences in the magnitude of pressure might result in a variety of consequences concerning mechanical properties, microstructural changes, and thermal behavior. In order to close this knowledge gap, this study focuses on dense-porous ceramics under a range of pressure forces. By doing so, it hopes to clarify the complex interactions and provide fresh perspectives that will benefit the larger field of materials science and engineering. The work intends to close this knowledge gap and promote the field of material design and applications by improving our understanding of the intricate behavior of ceramics with dense-porous layers under various pressure settings.

1.3 Objectives of the study

The objectives are as follows:

a) To study the effects of different pressure forces on the dense porous layers of ceramic.
b) To investigate the correlations between ceramic layers' properties such as porosity, thermal conductivity, and strength with pressure forces.

1.4 Scopes of the research

The research focuses on understanding how applied pressure affects the properties of ceramics, with layers. The goal is to conduct a set of experiments that use 43.27g of clay, 10.07g of silica, 46.65g of feldspar and 5g of PMMA to analyze how different pressure forces impact the thermal and structural characteristics of ceramics that have layers of dense porous material. Researcher will explore a range of pressure levels which are 10 MPa, 15 MPa, 20 MPa, 25 MPa and 30 MPa to get an understanding of how the material responds in different situations. By using techniques researcher will examine the microstructure of the ceramics to identify any changes caused by varying pressure forces.

The research will evaluate the properties of the layers including their strength, hardness and resilience. This evaluation aims to provide insights, into how these ceramics perform under pressure conditions. Additionally thermal analysis will be conducted to examine the heat conductivity and stability of the ceramics. There are a few different types of forming methods.

Due to the equipment provided in the lab, the types of equipment that can be used is limited. X-ray diffraction analysis (XRD), field emission scanning electron machine (FESEM), universal tensile machine (UTM), and density porosity are among the tests and analyses that were performed. All of this testing and analysis were done to help determine the best appropriate parameter or approach to utilize.

The findings from this study can have applications in industries like manufacturing, aerospace and energy by enabling the development of materials. Understanding how pressure affects ceramics can lead to performance and durability, in these sectors. Ultimately this research seeks to advance the field of materials science and engineering by enhancing our understanding of how pressure influences the characteristics of ceramic layers.

1.5 Thesis Organization

In order to give a thorough and structured investigation of the "Effect of Different Pressure Forces on the Dense-Porous Layers of Ceramics," the thesis will be divided into multiple clearly defined sections. The introduction will lay out the background information, explain the importance of researching the effects of pressure forces on ceramics particularly those with dense-porous layers and outline the goals of the study. The literature review that follows will offer a thorough examination of pertinent research, theories, and techniques relating to the behavior of ceramics under pressure, with a focus on the knowledge gaps that currently exist with regard to dense-porous layers. The experimental approach, including the steps and equipment used to carry out the experiments, will be covered in depth in the section that follows. The results presentation, which includes a methodical analysis and interpretation of the experiment outcomes, will come next.

After that, the results will be critically assessed within the framework of previously published research in the discussion section, which will also make links between the observed results and theoretical frameworks. Researcher will talk about the consequences of the research findings, taking into account their importance for future applications in many industries as well as for scientific understanding. The main findings will be outlined in the conclusion, together with any study limitations and potential directions for further investigation. Furthermore, an appendix with additional data sets, experimental techniques in detail, and other pertinent materials will be supplied. The goal of this well-structured thesis is to provide a comprehensive analysis of the impact of various pressure forces on ceramics with dense-porous layers, thereby making a significant contribution to the field of materials science and engineering.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Around 15,000 years ago, low-firing earthenware made its appearance as the first ceramic product. This is the beginning of the advancement of ceramics. About 200 years ago, the only products that could be classified as ceramics were clay pipes, roofing tiles, bricks, and tableware. These ceramic items are referred to as classic or traditional ceramics. The iron and steel industries in the nineteenth century demanded new refractory bricks, which differed from conventional fire clay bricks in that they contained silica, alumina, chrome-magnesia, and magnesia. Since then, ceramics have significantly impacted a variety of societal domains. A few terms, such as advanced, new, modern, special, and technical ceramics, can be used to describe ceramics that are opposed to classic or traditional ceramics. Modern and contemporary ceramics are in opposition to traditional or classic ceramics. Furthermore, because they were created using special porcelains or refractories, special ceramics share meaning with new and modern ceramics. Advanced ceramics places a special emphasis on advanced ceramic features ("Handbook of Advanced Ceramics: Materials, Applications, Processing, and Properties," 2013). Technical ceramics and advanced ceramics have comparable meanings. All industrial ceramics fall under the category of technical ceramics, with the exception of items like tableware, porcelain, and pottery that are connected to traditional ceramics.

Figure 2.1: Ceramic

Ceramics are a class of materials widely employed in various industries, owing to their unique combination of properties, including high-temperature resistance, electrical insulation, and mechanical strength. The design and processing of ceramic components often involve the manipulation of their microstructure, especially in dense-porous layers. Among the techniques used to tailor these structures, the application of pressure forces has gained significant attention. This literature review aims to provide an overview of existing research on the impact of different pressure forces on dense-porous ceramic layers.

2.2 Ceramic materials and properties

Among the most ancient and adaptable materials that humans have ever encountered are ceramics. Their diverse properties and limitless possibilities continue to fascinate and inspire innovation in everything from building bricks and pottery to advanced electronics and heat shields for spacecraft. A wide range of materials, including inorganic and nonmetallic materials, are shaped and fired at high temperatures to create ceramics. Strong, durable, and heat-resistant materials with distinctive qualities are produced by this process. Atoms joined by potent ionic or covalent bonds serve as their fundamental building blocks.

The intriguing materials known as ceramics, which originated from fire, are not a single category. They are available in an astounding variety of varieties, each with a distinct history and set of characteristics. The classics, the ones that have adorned our homes and cultures for ages, are traditional ceramics. Crafted from common clay and baked in kilns, they represent a variety of daily favorites. The versatile workhorse of the ceramic world, clay has strong thermal insulation qualities and is resistant to outside influences (Rumi et al., 2023). It can be fired and shaped into an infinite number of shapes, including roof tiles and pottery. For centuries, artisans have been enthralled with its inherent beauty and rustic appeal. Porcelain has a smooth, opulent feel and a translucent, white quality. It is delicate yet deceptively strong. It exudes elegance and refinement and is used for exquisite tableware, figurines, and even electrical insulators. Bricks are the foundation of many buildings because they are strong, long-lasting, and fireproof. They continue to be a classic architectural element, whether it's the delicate patterns of decorative brickwork or the raw warmth of exposed brick walls. Earthenware is a cheap, porous ceramic that is frequently coated to make it waterproof. Its earthy appeal makes it perfect for regular dishes, mugs, and planters, bringing a cozy touch to any house. Stoneware is denser and more waterproof than earthenware because it is fired at a higher temperature. Because of its durability, it is ideal for cookware, mugs, and even bathroom fixtures, providing functionality and style.

Not every ceramic has a historical foundation. Advanced ceramics is a cutting-edge field that uses science and technology to produce materials with remarkable qualities. Cutting tools, engine parts, and even armor are made of alumina, a ceramic that is extraordinarily durable and resistant to wear. It is a true champion of material strength, with a hardness that rivals that of diamonds. High strength, heat resistance, and biocompatibility are attributes of zirconia (Xu et al., 2023). Zirconia is a multifaceted star in the field of advanced ceramics. It performs exceptionally well in dental crowns, medical implants, and even high-performance engine parts. High-temperature applications are best served by silicon carbide, a ceramic that is both incredibly hard and heat-resistant. It can endure extremely high temperatures and severe wear and tear, which is why it is used in rocket engine nozzles and brake discs. Consider a substance that possesses both superior electrical and thermal insulation properties. The miracle material known as boron nitride finds application in lubricants, high-temperature components, and electronics.

Functional ceramics have been engineered to fulfill specific functions. Piezoelectric materials, on the other hand, use pressure or vibrations to convert them into electrical energy. This allows them to power a wide range of devices, from lighters and microphones to medical ultrasound machines, bringing sound and technology to life (Wenjing et al., 2023). Superconductors, on the other hand, are biocompatible ceramics that are specifically made for medical applications. They can be used in everything from high- speed trains to powerful magnets. Finally, bioceramics, which are specifically designed for medical applications, are biocompatible ceramics that are specifically made for the human body.

Ceramics are a broad class of materials with special qualities derived from their crystalline structure and inorganic makeup. Outstanding hardness, which protects against abrasion, wear, and deformation, is one of the qualities that distinguishes ceramics. This feature is especially helpful in applications like protective coatings, grinding wheels, and cutting tools where longevity is crucial (Chen et al., 2021). Nonetheless, one noteworthy feature of ceramics is their innate brittleness. Ceramics, in contrast to metals, have a tendency to fracture instead of deform when stressed, this characteristic can be both beneficial and restrictive. Brittleness is important in situations where preserving structural integrity is critical, even though it may present difficulties in other applications.

Additionally, ceramics have high melting points, which enable them to tolerate high temperatures without experiencing appreciable changes to their physical characteristics (Zhao et al., 2023). This characteristic is used to produce heat-resistant materials that are used in furnace linings and aerospace components, among other applications. Ceramics are also known for their corrosion resistance and chemical stability, which makes them appropriate for use in settings where exposure to abrasive chemicals is a concern. Another important characteristic of ceramics that makes them useful in applications requiring non-conductivity is electrical insulation. Their application as insulators for electrical wires, electronic parts, and materials used as insulators in high- temperature environments makes this clear. Moreover, ceramics are generally low in thermal conductivity, which makes them efficient heat-transfer insulators (Zhao et al., 2023). This feature comes in handy in situations where thermal insulation is needed, like in kilns and some industrial operations.

Ceramics frequently have low coefficients of thermal expansion, which means that when the temperature changes, their dimensions barely change. This feature is critical for maintaining stability in applications where exact measurements are required. Additionally, some ceramics are biocompatible, meaning that using them in medical implants won't result in negative side effects. Medical devices such as bone implants and dental prosthetics are developed using this biocompatibility. Glass and other crystalline ceramics have the ability to be transparent to visible light. They can be used in optical components like windows, lenses, and lasers because of their transparency. In conclusion, a variety of ceramic properties, such as electrical insulation, low thermal conductivity and expansion, biocompatibility, high melting points, chemical stability, hardness, brittleness, transparency, and low thermal conductivity and expansion, contribute to the versatility of ceramics in a wide range of industrial, medical, and technological applications(Huang et al., 2023).

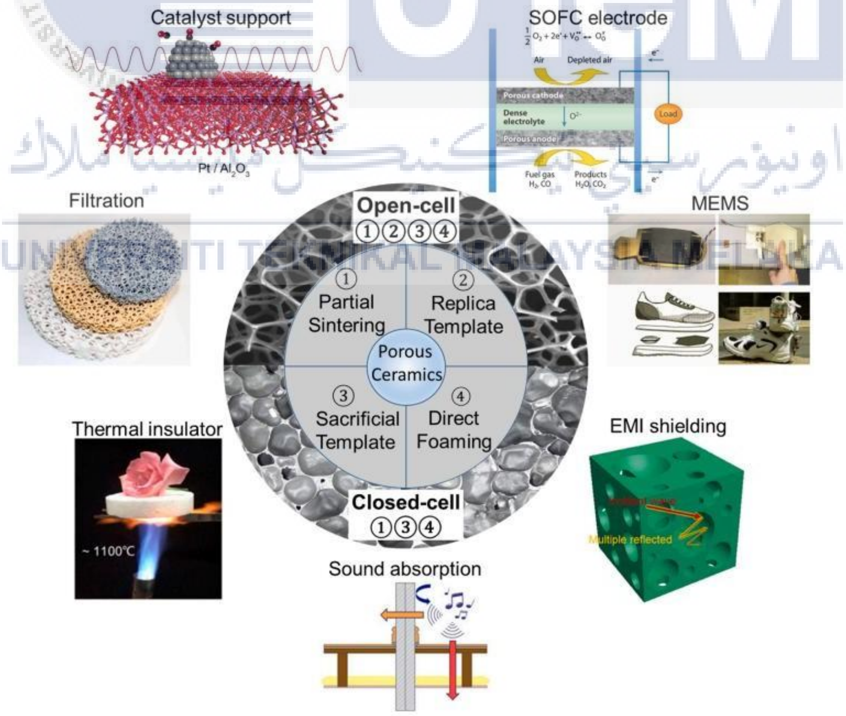


Figure 2.2: The four manufacturing techniques and the numerous energy and environmental related fields (Chen et al., 2021).

2.3 Porous ceramic materials

A specific class of ceramics known as porous ceramic materials is made specifically with the intention of having interconnected voids or pores in their structure (Kłosek-Wawrzyn et al., 2023). These materials have special qualities and functions due to the purposeful addition of porosity, which makes them especially adaptable to a wide range of uses. These ceramics have various types of porosity, such as closed pores that are isolated within the material and open pores that are connected and form a network that is accessible from the surface. Porosity can be precisely adjusted to satisfy certain needs, impacting important characteristics like permeability, density, and mechanical strength.

Figure 2.3: Structure of Porous Ceramic

Porous ceramics are widely used in filtration systems because of their ability to selectively allow some substances to pass through while effectively blocking others due to their porous structure. This is especially helpful for gas filtration, water purification systems, and other industrial uses where separation and purification are crucial. Because of their porous structure, these ceramics have a high surface area that is beneficial for uses like catalysis, where they can act as efficient supports for catalysts in chemical reactions.

Porous ceramics are used in thermal insulation in addition to their roles in filtration and catalysis. This is because they use their low thermal conductivity to prevent heat transfer (Guo et al., 2023). This makes them appropriate for use as insulating materials in electronic devices or in high-temperature industrial processes where thermal insulation is critical. Porous ceramics are also used in biomedical applications, particularly in tissue engineering and the creation of medical implants. These materials' porosity makes it easier for them to integrate with the surrounding tissues, improving their biocompatibility and encouraging the ingrowth of bone cells.

Porous ceramics are made using a variety of techniques, each designed to produce a particular pore structure. Techniques include additive manufacturing (3D printing), which allows for precise control over pore size and distribution, and foaming, which involves adding foaming agents into the ceramic mix to create bubbles that remain in the material after firing. During the manufacturing process, sacrificial templates like polymers or particles are used as templates to create pores.

Although purposeful porosity creation in ceramics increases their adaptability, it also presents difficulties. The mechanical strength of materials with higher porosity levels is frequently diminished, which restricts their use in load-bearing structures. It can be difficult to achieve exact control over porosity and pore size during the manufacturing process, necessitating careful processing parameter optimization. In brief, porous ceramic materials constitute a specific and versatile subset of the larger ceramics domain. Their deliberate porosity makes them indispensable in meeting a variety of technological and industrial needs. These applications range from filtration and catalysis to thermal insulation and biomedical uses.

2.4 Processing Techniques

A number of complex procedures are used during the ceramic processing process to turn raw ceramic materials into final goods with the desired qualities. Powder synthesis is usually the first step in the process, where ceramic powders are carefully created by ball milling, sol-gel processing, chemical precipitation, or spray pyrolysis. Revolving cylinders loaded with grinding media (balls) are used in ball milling to grind and crush raw materials in order to reduce particle size, increase surface area, and improve reactivity (Silva et al., 2020). The next step in the sol-gel processing process is to turn a solution or colloidal system into a solid gel, which is then dried and calcined. Subsequently, a chemical reaction between precursor solutions causes solid particles to precipitate, facilitating the carefully regulated synthesis of target compounds. This process is known as chemical precipitation. The chemical reaction of precursor solutions results in the formation of powders in the spray pyrolysis process. This is followed by the formation of droplets and their thermal breakdown. This method works well for creating consistent, fine powders.

The next stage is very important because it determines the properties and makeup of the ceramic material. Ceramic powders are formed into the required shape during the forming stage by a variety of methods including dry pressing, isostatic pressing, extrusion, or slip casting. A porous mold is filled with a liquid ceramic suspension called slip casting. Water from the slip is absorbed by the mold, leaving behind a solid layer of ceramic material (Li et al., 2013). This process works well for creating ceramics with complex geometries and is frequently used to create intricate or detailed shapes. In addition, pressing is the process of compacting powder into the desired shapes by applying pressure to it (Yin et al., 2023). A fundamental aspect of understanding the effect of pressure on ceramics is its role in compaction. Pressure forces applied during manufacturing processes can lead to the reduction of porosity and an increase in density. Harned et al. (2009) conducted a study on alumina- based ceramics and observed that increasing pressure forces resulted in a substantial decrease in porosity while enhancing mechanical properties. This compaction mechanism is significant in industries where high-density ceramics are required for improved performance.

Common techniques include isostatic pressing and dry pressing. Isostatic pressing applies pressure uniformly from all directions, usually using a flexible mold filled with powder, while dry pressing uses a mechanical press to compact dry powder into a specific shape. A popular method for creating simple to moderately complex shapes with good dimensional control is pressing. Extrusion comes next. A viscous ceramic paste is forced through a die to create continuous sections of predetermined profiles (Dreier et al., 2023). When creating materials like rods or tubes that have a constant cross-sectional shape, extrusion is very helpful. Both simple and complex shapes can be created using this ongoing process. Pressure is used on the powder particles during these procedures to produce a compacted green body with a predetermined shape. Pressure and forming technique affect the green body's density and porosity, which in turn impacts the final sintered ceramic's characteristics. Before moving on to later stages of the manufacturing process, like sintering, these forming techniques are essential for forming the material into the desired shape. The intricacy of the intended shape, the material's characteristics, and the intended use of the finished product all influence the choice of forming technique.

When a material, usually a powder or compacted powder, is heated to a temperature below its melting point, which causes the particles to stick together and form a solid mass is called sintering, is a crucial step in the ceramic processing process while densification is the process of a ceramic material's porosity being reduced, which raises its density. The green ceramic body may go through a drying phase after it has formed in order to eliminate extra moisture and improve its stability and strength. To guarantee the final product's structural integrity and avoid cracking during the ensuing firing process, the moisture must be removed from the green ceramic (Zhang et al., 2022). In order to convert shaped green bodies or powders into dense, solid ceramic materials with desired mechanical and physical properties, sintering and densification are essential steps in the ceramic processing sequence.

There are several drying methods used, including convection and microwave drying. Hot air circulation is used during convection drying to extract moisture from the green ceramic. The water evaporation process is aided by the placement of the shaped ceramic pieces in an area with warm air circulation. This technique is frequently used in ceramic processing because it works well for uniform drying. By gradually removing moisture from the material, the controlled application of heat reduces the likelihood of cracking. In microwave drying, the green ceramic is heated and moisture is evaporated using microwave radiation. When microwaves pass through a material, heat is produced inside the ceramic. The capacity of microwave drying to rapidly and effectively heat materials is well known. When considering energy efficiency and processing time savings over conventional convection drying methods, it can be beneficial. Achieving a high density is essential for improving mechanical characteristics like hardness, strength, and fracture toughness.

Because of the molten phase's surface tension, pressure is naturally applied to the ceramic particles during the sintering process. Alternatively, external pressure can be applied using specialized sintering techniques like hot isostatic pressing (HIP) (Venkata Sundeep Seesala et al., 2021). This pressure promotes more compaction, which helps the particles reorganize and bond. As a consequence, the porosity decreases and the density rises, improving the material's hardness, mechanical strength, and other characteristics. The final ceramic product's mechanical and thermal properties are greatly influenced by the microstructure and characteristics of the ceramic, such as its hardness, strength, and thermal conductivity, which is largely determined by the forming technique chosen.

Further processing steps like finishing, polishing, glazing, or coating can be used after sintering to achieve particular surface properties or functional improvements. The ceramic product's usefulness and visual appeal are enhanced by these techniques. Ultimately, a wide variety of ceramics, from traditional pottery to cutting-edge engineering components, can be created thanks to the complex interactions between these processing techniques, which include powder synthesis, sintering, and finishing.

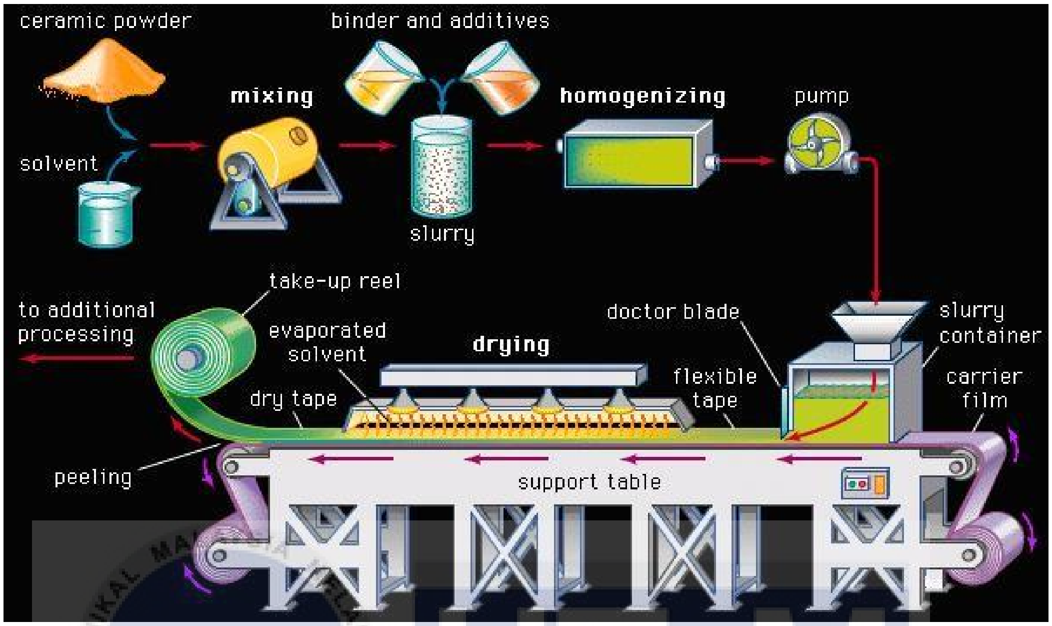


Figure 2.4: Ceramic Processing

2.5 Properties

2.5.1 Physical properties

The measurable and observable qualities that characterize how ceramics react to outside stimuli or circumstances without changing chemically are referred to as physical attributes in ceramics. These characteristics are essential for comprehending and applying ceramics in a variety of applications since they shed light on the material's behavior in diverse situations. Density, melting point, thermal expansion, electrical conductivity, thermal conductivity, translucency or transparency, chemical stability, and piezoelectric and ferroelectric properties are common physical characteristics of ceramics.

A fundamental physical parameter called density measures a material's mass per unit volume. Density is an important factor in ceramics since it affects the material's overall weight and, in turn, its mechanical and structural qualities. A ceramic material's density can be computed by dividing its mass (m) by its volume (V). Density (ρ) can be mathematically stated as $\rho = m/V$. Density is commonly expressed in grams per cubic centimeter (g/cm^3) or kilograms per cubic meter (kg/m^3). Generally speaking, ceramics are lighter than metals because they have lower densities. This feature is useful in situations when weight is an important consideration.

For instance, the use of low-density ceramics can help achieve goals such as fuel efficiency and total weight reduction in aeronautical engineering, where these are critical (Abdul Hai Alami et al., 2023). Similarly, low-density ceramics can offer strength and durability without needlessly adding mass to lightweight structural parts and automobile components. Ceramics have a reduced density, which affects their mechanical and structural properties. Low-density ceramics can help with lightweight designs in a range of engineering applications, improving dynamic system performance, fuel economy, and energy usage.

The temperature at which a substance changes phases from a solid to a liquid form is known as the melting point, which is a basic physical attribute. This change in ceramics refers to the change from a crystalline, hard structure to a liquid, amorphous condition.

When compared to many other materials, ceramics are often noted for having high melting points. This feature arises from the strong covalent or ionic bonds present in the crystal structure of ceramics (Abdul Hai Alami et al., 2023). Because ceramics usually have strong connections that must dissolve at high temperatures, the material melts. One important characteristic that sets ceramics apart from other materials, such as metals and polymers, is their high melting point.

A material's ability to vary its size (expand or contract) in response to temperature variations is known as its thermal expansion. Understanding thermal expansion is important for ceramics since it directly affects the material's dimensional stability at different temperatures. The amount that a material expands or contracts with each unit change in temperature is measured by the coefficient of thermal expansion, or CTE. Units of length per unit temperature change, such as parts per million per degree Celsius or microstrain/°C, are used to express it. The symbol α is commonly used to represent the CTE. For applications where dimensional stability is crucial, ceramics with low thermal expansion are a desirable property. Low CTE ceramics are less likely to undergo noticeable alterations in size or form when subjected to temperature variations. This is especially crucial for components used in electrical gadgets, optical systems, and aircraft, where exact dimensions must be maintained.

One essential characteristic that characterizes a material's ability to carry an electric current is its electrical conductivity. Depending on the precise makeup, structure, and processing of the ceramic material, the electrical conductivity of ceramics can vary greatly, from insulating to semiconducting or even conducting. A wide variety of ceramics work well as electrical insulators. This indicates that they prevent electricity from passing through them (Shanmugam et al., 2020). Ceramics' insulating qualities are particularly handy in situations where electrical separation is required, like in electronic parts and gadgets. A certain degree of electrical conductivity in certain ceramics is midway between that of insulators and conductors, a phenomenon known as semiconducting behavior. Temperature and the presence of specific impurities can have an impact on the electrical characteristics of semiconducting ceramics. Electronic devices, sensors, and other semiconductor technologies find use for these materials.

Certain ceramic materials have the ability to carry electricity, despite the fact that most ceramics are insulators. For instance, metallic conductivity may be present in some ceramics that have been doped with metal ions or that have particular crystal structures. These conducting ceramics are employed in high-temperature conductive ceramics for industrial heating elements. Moreover, bioengineering may be used in a variety of situations where both electrical and ceramic properties are required, such as the incorporation of electrically conductive materials that aid in tissue healing (Youness et al., 2023). A number of factors, including temperature, doping, chemical composition, and crystal structure, affect a material's electrical conductivity in ceramics. The crystal structure is electron mobility within a material can be influenced by the configuration of atoms in the crystal lattice. The composition of chemicals is the electrical properties that are dependent on the kinds of components present and how they link together. Doping the electrical conductivity of the ceramic structure can be changed by adding particular impurities or dopants. The temperature is certain materials show changes in conductivity with temperature variations, and the electrical conductivity of ceramics can be very temperature dependant.

The characteristic of a material that characterizes its capacity to conduct heat is called thermal conductivity. The effectiveness of a material's conduction of thermal energy serves as a proxy for it. High thermal conductivity ceramics can be used in thermal insulators, heat exchangers, and other thermal management systems because of their excellent heat transfer properties. These ceramics have the ability to transport or dissipate heat efficiently, which helps to prevent electronic equipment from overheating or to transfer energy efficiently in a variety of industrial operations (Gharibi et al., 2022). The ceramic's thermal conductivity can be influenced by its density, crystal structure, and the presence of specific elements or compounds.

A substance's translucency indicates how much light it can pass through. Certain types of materials allow light to pass through without scattering, but transparent materials also allow light to pass through without scattering. For many uses, ceramics' translucency and transparency are crucial characteristics. For use in dental ceramics, lenses, windows, and optical components, among other uses, transparency and translucency are crucial optical properties in ceramics. Dental ceramics, for example, need to be translucent to mimic real teeth and allow light to pass through for a more realistic aesthetic (Kim et al., 2023). This trait is highly important in cosmetic dentistry and dental restorations, where a lifelike appearance is necessary. It is often preferable for windows, lenses, and other optical components to be transparent.Since transparent materials allow light to pass through without changing or dispersing, they are suitable for applications where precision and clarity are essential.

Chemical stability is the capacity of a material to resist chemical reactions or degradation when subjected to different substances. The integrity, structure, and qualities of a material that is chemically stable will not be affected by substances that could be reactive or corrosive. Chemical resistance is crucial for ceramics in instances when the material comes into contact with corrosive substances. Because of their strong chemical resistance, ceramics are frequently used in chemical processing industries (Wang et al., 2022). Ceramics are widely utilized in pipelines, containers, and other equipment used in chemical processing because of their resistance to chemical attack. This feature ensures the dependability and longevity of the ceramics under demanding chemical conditions. This is especially crucial in sectors of the economy where equipment integrity and the avoidance of leaks and contamination are vital to overall process success as well as safety and efficiency.

When mechanical stress is applied to piezoelectric materials, an electric charge is produced. The ceramic generates an electric charge when pressure or tension is applied, and it deforms mechanically when an electric field is supplied. An external electric field has the ability to reverse the spontaneous electric polarization that occurs in ferroelectric materials. Electronic gadgets, actuators, and sensors all use piezoelectric and ferroelectric ceramics. Piezoelectric materials have application in energy harvesting systems, pressure or acceleration sensors, and ultrasonic transducers (Wenjing et al., 2023). Ferroelectric ceramics find application in electronic components such as capacitors and non-volatile memory devices.

2.5.2 Mechanical Properties

The collection of traits or behaviors known as a material's mechanical properties define how the material reacts to loads or applied forces. These characteristics reveal information about a material's ability to tolerate stresses and external pressures as well as how it deforms and breaks. It is essential to comprehend a material's mechanical properties while designing and engineering devices, components, and structures for a variety of industries. The mechanical properties of ceramics, including hardness, brittleness, strength, elastic modulus, toughness and fatigue resistance are highly dependent on the processing conditions, including pressure forces. Research by Smith and Patel (2017) on silicon carbide ceramics showed that pressure-assisted sintering not only led to increased density but also resulted in a remarkable improvement in hardness and strength. These findings emphasize the potential for tailoring ceramics to meet specific mechanical requirements.

The basic physical characteristic of hardness is a material's resistance to abrasion, scratching, indentation, and surface deformation. Hardness is an important property in ceramics since it establishes how resilient the material is to abrasion in different applications. Standardized tests, such the Mohs scale or the Vickers hardness test, are commonly used to quantify hardness. A qualitative measure called the Mohs scale is used to evaluate how resistant minerals, particularly ceramics, are to scratches. On a scale of 1 (the softest, like talc) to 10 (the hardest, like diamond), minerals are ranked. Comparing the relative hardness of various materials is made easier by the use of reference minerals. A higher Mohs hardness for ceramics denotes a stronger resistance to scratches.

The Vickers hardness test is a quantitative technique used to determine a material's resistance to indentation. The size of the indentation that results from pressing a diamond-shaped indenter into the ceramic's surface is measured. The dimensions of the indentation are used to determine the Vickers hardness value. Because this test yields an exact numerical value for hardness, it is frequently utilized in the ceramics industry. In practical applications, the hardness of ceramics is critical. High-hardness ceramics, for example, are utilized in wear- resistant parts, grinding wheels, and cutting tools in the manufacturing and machining industries. These ceramics' resistance to wear and deformation guarantees that they will continue to function properly over time, even in harsh conditions.

One important physical characteristic that describes a material's response to stress and deformation is brittleness. Brittleness in the context of ceramics refers to a material's propensity to fracture or shatter under stress with minimal deformation. Brittle materials show little to no plastic deformation and have a tendency to fail abruptly, in contrast to ductile materials, which can experience significant plastic deformation prior to collapse. The propagation of cracks through the material is usually linked to the brittle fracture of ceramics (Venkata Sundeep Seesala et al., 2021). Stress can cause cracks to start and spread quickly throughout the ceramic structure, especially in tension. This process ends abruptly and catastrophically since there is no discernible plastic deformation. Brittle materials are distinguished from ductile materials by their lack of plastic deformation, ductile materials can exhibit visible stretching or distortion prior to breaking. Depending on the use, ceramics' brittleness can be both a benefit and a drawback. Brittleness gives ceramics their high stiffness and hardness, but it can also cause problems like fracture susceptibility (Abdul Hai Alami et al., 2023). This qualifies them for use in specific applications where hardness and sharpness are essential, such as cutting tools and wear-resistant components.

The microstructure of ceramics, which includes elements like porosity, grain size, and flaw presence, frequently affects how brittle they are. Stress concentrators, such as large grains, pores, or other structural abnormalities, can encourage the beginning and spread of cracks. The microstructure of ceramics plays a pivotal role in determining their properties and performance. Various studies have explored the influence of pressure on ceramic microstructures. For instance, Zhang and Li (2015) investigated the impact of pressure forces on the grain size and pore distribution within ceramic layers. They found that higher pressures led to finer grain sizes and more uniform pore distribution, which is crucial for enhancing mechanical properties and overall material homogeneity.

Strength can be divided into tensile strength and compressive strength. The highest stress a material can bear under tension or pulling forces before failing or breaking is known as its tensile strength. Because ceramics are by nature brittle materials, their tensile strength is usually low. Ceramics cannot deform significantly before failing, in contrast to metals. A ceramic material is prone to fracture when a tensile stress is applied because cracks tend to spread quickly. Ceramics are useful in applications where they largely suffer compressive loads due to their remarkable compressive strength, despite their lack of reputation for having strong tensile strength.

The highest stress a material can bear under compression or squeezing forces before failing is known as its compressive strength. Because of their great compressive strength, ceramics are frequently used in situations where loads are compressed. Ceramics' resistance to compression is mostly due to the strong ionic and covalent interactions found in their crystal lattice structure (Abdul Hai Alami et al., 2023). In structural applications where compressive strength is crucial, ceramics are frequently used. High compressive strength ceramics are frequently utilized in building structural elements, tiles, bricks, and some sophisticated ceramics used in engineering.

A material's stiffness is determined by its Young's Modulus (E), which expresses how elastically it may flex in response to an applied force and return to its original shape when the force is released. The ratio of stress to strain in the elastic deformation range is how Young's modulus is described mathematically. In the International System of Units (SI), the unit of Young's modulus is commonly given in Pascals (Pa) or gigapascals (GPa). Ceramics are often stiff materials, as indicated by their high elastic modulus values (Venkata Sundeep Seesala et al., 2021). This high stiffness is a result of the strong ionic and covalent bonding present in the crystal lattice structure.

Ceramics exhibit low elastic deformation despite their stiffness. In contrast to ductile materials like metals, ceramics often behave brittle, which means they don't undergo significant deformation before breaking. When a force is applied, ceramics can experience reversible deformation in the elastic deformation range. The material reverts to its initial shape when the force is released. When choosing materials for certain purposes, engineers and designers take Young's modulus into consideration. High-stiffness materials are favored in applications where the least amount of deformation under load is essential. High elastic modulus ceramics are frequently employed in structural applications where deformation resistance and stiffness are crucial. High-performance ceramic bearings, sophisticated ceramics utilized in precise engineering, and ceramic components in aeronautical structures are a few examples.

Strength is the ability to withstand an applied force without breaking, whereas ductility is the ability to deform plastically, or to withstand a significant amount of deformation before failing. Toughness is the capacity of a material, especially ceramics, to absorb energy and undergo plastic deformation prior to breaking. Tough materials may absorb a large amount of energy before breaking. A material's ductility allows for plastic deformation, which can help absorb energy and prevent an abrupt and catastrophic collapse. Aside from that, a variety of methods are used to achieve toughness, including adding reinforcing phases to the ceramic matrix, like fibers or whiskers, modifying microstructures, or using sophisticated processing methods. These alterations successfully prevent cracks from propagating, enabling ceramics to absorb more energy before failing (Zhang et al., 2024). High-toughness ceramics are used in harsh settings, like biomedical implants, cutting tools, and armor, where toughness and hardness work together to provide maximum performance and longevity. The search for more resilient ceramics broadens the range of possible uses by bridging the gap between the requirements of practical engineering scenarios and the intrinsic brittleness of these materials.

Although they are frequently thought of being brittle, ceramics are generally known for their great strength and rigidity (Chen & Hu, 2024). By definition, brittle materials do not show a great deal of plastic deformation prior to breaking. It is difficult to achieve great toughness in ceramics since conventional ceramics typically don't have the ductility that tough materials do. Scientists and engineers have devised methods to improve ceramics' resilience. To improve the toughness of ceramics, for instance, certain additives or sophisticated processing methods can introduce mechanisms like phase transformation toughening or grain boundary toughening.

In applications where impact resistance is crucial, tough ceramics are preferred. Cutting instruments, ballistic armor, and parts used in industries where materials are subjected to dynamic loads might all fall under this category. Toughness is frequently obtained at the expense of other material qualities. Toughness, hardness, and other mechanical qualities must be balanced while taking the application's unique requirements into account.

In ceramics, fatigue resistance is the material's capacity to bear cyclic stress or repetitive loading without breaking down. In applications where materials are subjected to cyclic or varying loads over time, this feature is essential. Determining how effectively a material can withstand the start and spread of cracks or other types of damage that could result in failure during cyclic loading is the aim of the fatigue resistance assessment process. Because ceramics are naturally fragile materials, their propensity to fracture catastrophically without undergoing considerable plastic deformation affects how they behave under fatigue. Cracks in ceramics usually start at stress concentrations or material flaws, which is where fatigue failure usually starts. After reaching a threshold size, these cracks may then gradually spread under cyclic loading and eventually fracture. The fatigue resistance of the ceramic can be influenced by its composition, which includes the type of ceramic and any reinforcements or additives. The ceramic's fatigue behavior is influenced by its microstructure, which includes elements like grain size and orientation (Gumula et al., 2015). Crack initiation and fatigue resistance can be strongly impacted by surface flaws, imperfections, and stress concentrations. For ceramic components used in engineering applications where cyclic stress is common, fatigue resistance is an important factor to take into account. Turbine blades, bearings, and specific structural elements are a few examples (Chen & Hu, 2024). Evaluating fatigue resistance is crucial to ensuring long-term durability in applications where ceramics are subjected to cyclic loads over a lengthy period of time, including in industrial machinery or aerospace applications. To assess the fatigue resistance of ceramics, engineers employ fatigue testing techniques. In order to measure things like the number of cycles till failure and the degree of damage, these tests entail repeatedly loading specimens and observing how they react.

The practical implications of understanding the effect of pressure forces on ceramics are vast. In the aerospace industry, for instance, pressure-assisted sintering has been applied to manufacture lightweight and high-strength ceramic components for use in aircraft engines (Jones et al., 2020). Similarly, in the field of electronics, pressure-driven compaction has been utilized to enhance the thermal conductivity of ceramics for better performance in electronic devices (Kim and Chang, 2019). In the biomedical sector, ceramic implants with improved mechanical properties have been developed through pressure-assisted processing (Mason et al., 2016). These examples underscore the real-world significance of this research area. While significant progress has been made in understanding the effect of pressure forces on ceramics, several challenges and opportunities for future research exist. One of the challenges is the need for more comprehensive studies on the long-term durability of ceramics subjected to pressure. Additionally, advanced characterization techniques and computational modeling can provide deeper insights into the complex interplay between pressure forces, microstructure, and properties.

In conclusion, the literature reviewed here highlights the critical role of pressure forces in shaping the microstructure, mechanical properties, and applications of ceramics. The findings are of great importance for industries where ceramics are central to performance, as they open avenues for tailoring these materials to specific requirements. Further research and development in this field are expected to yield advanced ceramics with enhanced properties and applications across various sectors. Understanding the intricate relationship between pressure forces and ceramics is essential for pushing the boundaries of material science and engineering.

CHAPTER 3

METHODOLOGY

3.1 Introduction

The technique served as the foundation for this research investigation. This methodology is crucial to carrying out this research investigation in the right way. This chapter provides a detailed explanation of the methodology. The researcher has been able to concentrate on the kind of research methodology that will work best for this study thanks to the literature reviews. Furthermore, the first subtopic in this chapter explained the experimental design, which is represented by the fabrication and preparation process flow chart. The aspects of the study and creation of porous ceramic were covered in the following subtopic, along with an explanation of each phase or operation. Selecting the right kind of powder to utilize is one of the stages in the creation of powder, as there are many different kinds that can be used to make ceramics.

In addition, this chapter examined and analyzed the most effective ceramic production forming process. Because of the equipment available, there must be restrictions on the types of forming agents that can be used in the lab. But use the approach that yielded a good result in order to reach the objective. The three-point flexural strength test, density, porosity, scanning electron microscopy (SEM), and X-ray diffraction analysis (XRD) were among the examinations and tests performed. The goal of all of this testing and research was to determine which parameter or approach would be most useful.

3.2 Raw Materials

Clay + Silica + Feldspar + Polymethyl methacrylate (PMMA)

3.2.1 Clay

Tiny rock and clay mineral particles, with soil particles smaller than 0.005 millimeters in diameter, make up the natural substance known as clay. It takes on several shapes and becomes pliable when combined with water. It is extensively utilized in the construction, ceramics, and pottery sectors. Clay is a versatile material that may be used to create long- lasting items like pottery, bricks, and tiles because it can be hardened through firing. It is also a crucial part of soil since it creates the conditions required for plant growth and water retention. Furthermore, certain kinds of clay, like kaolin, are employed for particular processes, such as the creation of fine china and ceramics.

Figure 3.2.1: Clay

3.2.2 Silica

The compound silica, sometimes referred to as silicon dioxide (SiO2), is made up of silicon and oxygen, the two elements that are most prevalent in the crust of the Earth. It is a prevalent element found in nature as quartz and makes up over 95% of all known rocks.Applications for silica in industry range from construction materials to glass and ceramics manufacture, foundry molds, and moisture removal desiccants. It is also a component of many other goods, including medicines, cosmetics, and food additives. There are two types of silica: crystalline and non-crystalline. Inhaling crystalline silica, like quartz, can be harmful, especially in specific work environments like construction.

Figure 3.2.2:Silica

3.2.3 Feldspar

More than half of the minerals that make up the crust of the Earth are feldspar. Aluminum, silicon, and oxygen are present in this tectosilicate mineral, along with other cations like sodium, calcium, potassium, or barium. The most prevalent mineral group on Earth, feldspar is typically found in igneous, metamorphic, and sedimentary rocks. It makes up over 60% of exposed rocks, as well as soils, clays, and other unconsolidated deposits. Feldspar finds extensive usage in several industrial processes such as glassmaking, ceramics, and metallurgy, where it serves as a flux. Plagioclase (sodium-calcium) feldspars and alkali feldspars are the most prevalent types of feldspars.

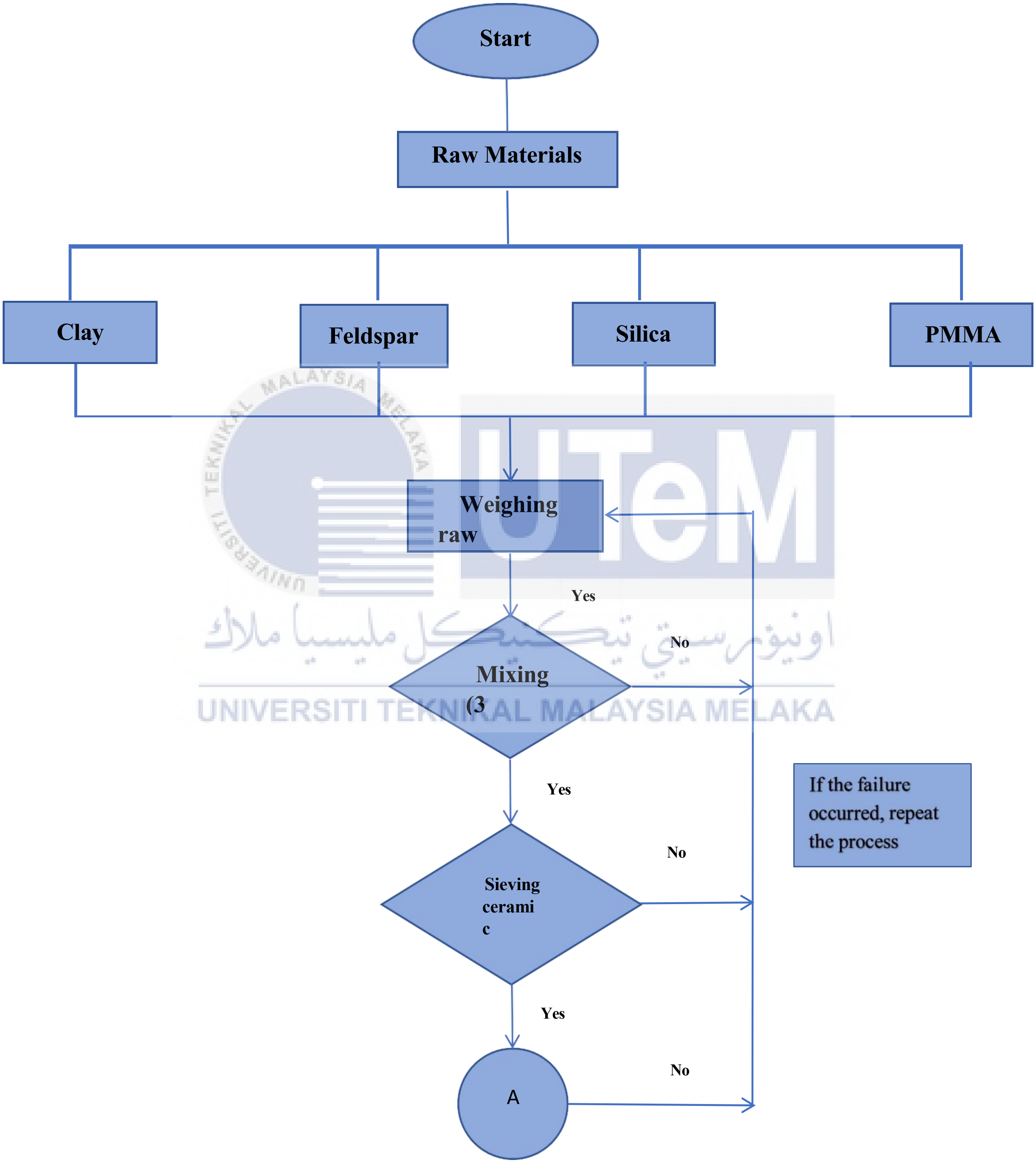
Figure 3.2.3: Feldspar

3.2.4 PMMA

Polymethyl methacrylate, or PMMA for short, is a synthetic resin made by polymerizing methyl methacrylate. It is a clear, stiff plastic that is frequently used in place of glass in items like airplane canopies, illuminated signage, skylights, and shatterproof windows. PMMA is often utilized in the building, automotive, and medical industries. It is often referred to as acrylic or acrylic glass. Compared to other transparent polymers, it offers numerous technical benefits like superior light transmission, an infinite range of color possibilities, and a strong resistance to UV light and weathering. PMMA offers good mechanical, physical, and aesthetic qualities in addition to being inexpensive and simple to work with.

Figure 3.2.4: PMMA

3.3 Process of Fabrication of Dense-Porous Ceramic Layer



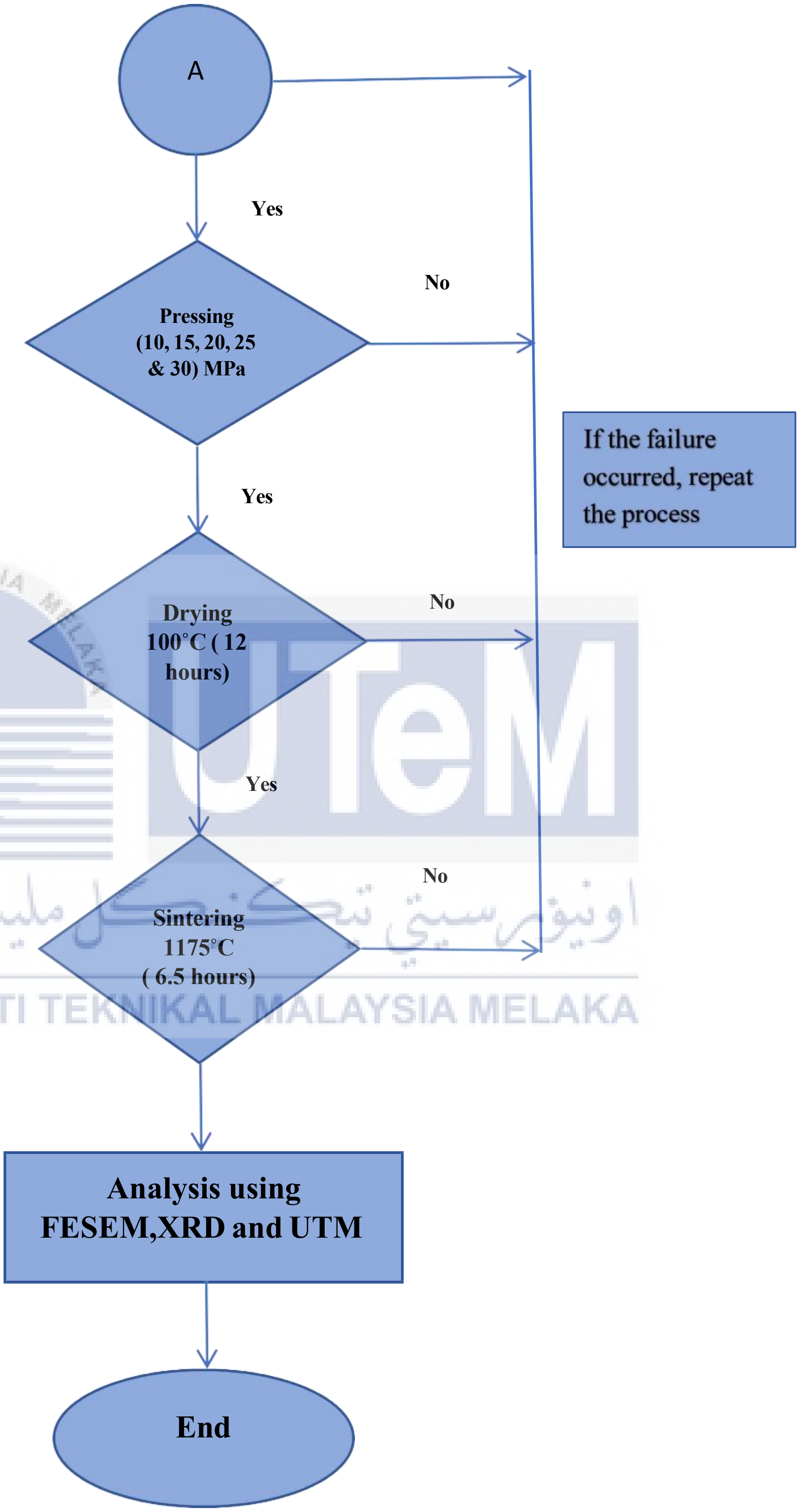


Figure 3.3: Flow Chart of Methodology

3.4 Fabrication of Dense-Porous Ceramic Layers

Four different materials types were employed in this study which are feldspar (46.65g), silica (10.07g), clay (43.27g), and PMMA 5% wt or 5g was weighed using an analytical balance. The first step involved mixing several raw ingredients, including as clays, feldspar, silica, and PMMA, to create ceramic mixes. For three hours, the mixture was ball milled to guarantee a homogeneous blend. As grinding media, alumina balls with different diameters ranging from 5 to 20 mm were used to ensure an efficient blending process. The ceramic slurry was then sieved through mesh to guarantee consistency in particle size. After being sieved, the powders were pressed uniaxially at room temperature at pressures of 10 MPa, 15 MPa, 20 MPa, 25 MPa, and 30 MPa to create bi-layered ceramic. The ceramic disc's lowest layer was porous and of similar thickness, but the upper layer was dense. The resulting discs and bar forms underwent a 12-hour drying procedure at 100˚C in the oven. After that, the samples were sintered for 6.5 hours at 1175˚C in a high-temperature furnace to completely burn the mixture composition. After heating to the profile sintering temperature, the compact porous ceramic was cooled to room temperature in the heat treatment furnace. The samples are prepared for testing and analysis once they have cooled.

3.4.1 Process of Weighing

The weight of each powdered raw ingredient was determined. Each sample has a constant percentage of raw powder in the porous ceramic composition attributable to this weighing process.

Table 3.4.1: The weight of raw materials powder

Type of raw materials	Weight (g)
Clay	43.27
Silica	10.07
Feldspar	46.65
PMMA	5

The weight of each raw material such as clay, silica, feldspar and PMMA is determined by using the analytical balance. An analytical balance is a very accurate weighing device used in labs to measure mass with extreme precision. It is intended to accurately measure minute quantities of chemicals, frequently down to the milligram or microgram level.

Figure 3.4.1: Analytical balance

3.4.2 Process of Mixing

The ball milling machine was being used to blend the raw materials. One technique for turning composite powders into ultra-fine particles is ball milling. To guarantee an effective blending procedure, each porous ceramic powder was combined for three hours at a steady rotating speed in a ball milling machine utilizing varying diameters ranging from five to twenty millimeters.

Figure 3.4.2: Ball Milling Machine

3.4.3 Process of Sieving

Some granulate powder occurs after the mixing process, which calls for the sifting step. Larger particles were extracted from a sample's smaller particle size range with the aid of the sieve procedure. In tap sieve shakers, the sample was shaken either vertically or horizontally.

Figure 3.4.3: Sieving process

3.4.4 Process of Pressing

The ceramic fabrication samples were made on a bar and disc shape, as was previously mentioned. The simplest form and size of bar was found to be effective in compacting the powder in a uniform density under a uniaxial charge. To make a first compact, the process started with the insertion of 1 g of dense ceramic powder to the disc shape mold and 2 g of dense ceramic to the bar shape mold. The plunger was then subjected to low pressure. Next, insert the mold into the Universal Test Machine and press at 10 MPa for 60 seconds. Moreover, add porous ceramic and repeat the process on the dense layer that has been pressed onto the disc and bar shapes. After that, the procedure was repeated with pressures of 15, 20, 25, and 30 MPa. With enough effort, the powder formed a structure like a bar or disc. This procedure is very important to the research.

Figure 3.4.4.1: Disc shape

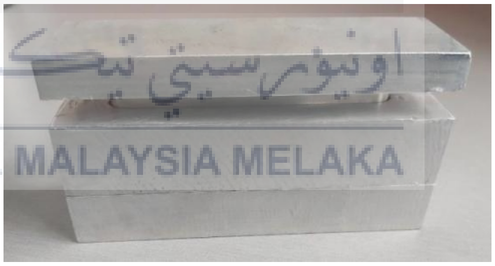


Figure 3.4.4.2: Bar shape

Figure 3.4.4.3: Manual Press

3.4.5 Process of Drying

The resultant dense porous layer of ceramic discs and bar shapes were dried in an oven at a heating rate 0.104˚C/minute for 12 hour until they reached 100˚C. One of the most important steps in the entire ceramic manufacturing or crafting process is the drying process. In order to prepare the produced clay or ceramic material for the ensuing firing process, proper drying is helpful in removing water from it.

Figure 3.4.5: Oven

3.4.6 Process of Sintering

A furnace with a high temperature was used to fire the green bodies. Following the creation of the discs and bars, the correspondingly created discs and bars were sintered for 6.5 hours at 1175˚C in a high-temperature furnace. A front-loading chamber furnace made by Nabertherm is the apparatus used in this experiment.

The ratio sample batch's samples were all heated to 1175°C. At a rate of 5 °C per minute, the equipment in the heat treatment furnace was heated to the 1175°C sintering profile temperature that was previously defined. It took 6.5 hours for the compact ceramic to burn up the entire combined composition at this temperature. After heating to the profile sintering temperature, the compact porous ceramic was cooled to room temperature in the heat treatment furnace. Following sintering, a densified ceramic state was obtained in the compact dense porous ceramic.

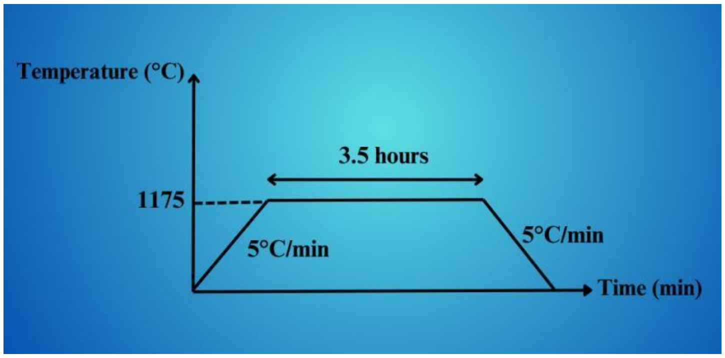


Figure 3.4.6.1: The temperature profile for drying

Figure 3.4.6.2: Furnace

3.4.7 Testing and analysis of dense porous layers of ceramic

The effectiveness of dense porous ceramic layers was assessed using porosity, density, and mechanical characteristics like tensile strength. Scanning electron microscopy (SEM) and tensile strength tests were also used in the investigation. In this investigation, various pressures of 10 MPa, 15 MPa, 20 MPa, 25 MPa, and 30 MPa were utilized to assess the characteristics of porous ceramic.

3.4.7.1 X-ray Diffraction Machine (XRD)

A particularly useful non-destructive technique for characterizing crystalline materials is X-ray diffraction (XRD). X-ray diffraction (XRD) was employed to investigate diffraction peak development. In addition to the bi-layered ceramic's mechanical and physical characteristics, the specimens underwent XRD analysis to identify the phase assemblages both before and after the sintering process. Through this approach, the essential scientific explanations for the observed properties were produced.

Figure 3.4.7.1: XRD

3.4.7.2 Field Emission Scanning Electron Microscopy (FESEM)

A sophisticated microscopy method called field emission scanning electron microscopy offers high-resolution imaging of the surface morphology of materials at the nanoscale. Field emission scanning electron microscopy (FESEM) produces images with greater sharpness and resolution. In this research, the maginifications used are 30K and 100K. The vacuum chamber was vented, and samples were placed on a aluminum stub. The device took pictures of ceramic surface and cross section to observe pores once it had reached the maximum vacuum level.

Figure 3.4.7.2: FESEM

3.4.7.3 Universal Testing Machine (UTM)

The AGS-X universal testing machine (UTM) capable of handling loads at 100K was used to determine the flexural strength of ceramics. The compressive strength of the ceramics was measured using the corresponding machine. The ceramic specimen was subjected to a progressively increasing load by the UTM during the test, executed at a regulated rate of 15 mm per minute until it fractured or reached a predefined degree of distortion. The specimen's displacement or deformation as a result of the applied force was measured by the UTM. These data were used to determine the ceramics' flexural strength, which was reported as stress (force per unit area).

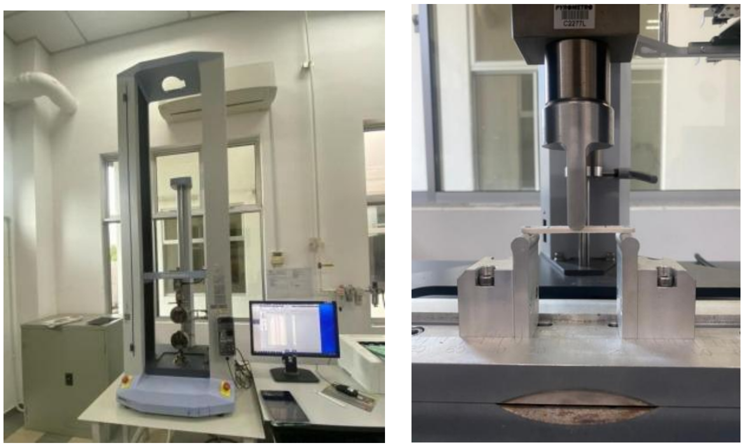


Figure 3.4.7.3: AGS-X (Shimadzu, Japan)

3.4.7.4 Porosity and Density

Archimedes' Principle states that the buoyant force an object exerts when submerged is equal to the weight of the fluid the object displaces. The apparent porosity and density were calculated using the Archimedes buoyancy approach. Wc stands for saturated mass, Wa for dry mass, and Wb for mass suspended in water. After impregnation, the same scale was used to measure the saturated mass (Wc) and the mass suspended in water (Wb). The apparent porosity and density formula were calculated by analyzing the data.

Figure 3.4.7.4: Densimeter

.

CHAPTER 4

RESULT AND DISCUSSION

This chapter included the findings from the density analysis, porosity, X-ray diffraction machine, field emission scanning electron microscopy (FESEM), and flexural test. A flexural test with a 100kN maximum force was also conducted using the Shimadzu AG100kN-X plus. The apparent porosity of the samples was determined using Archimedes' Principles, the bilayer's top surface and cross-section were observed using a FESEM, and the phase and structural properties of the ceramic materials were investigated using XRD analysis. Data from the microstructure, density, XRD, and flexural strength test were analyzed in this chapter.

4.1 The Sintering Temperature's Effect

An essential step in the production of ceramics, sintering is crucial in determining the final characteristics of ceramic materials. Of all the variables affecting the results of sintering, temperature matters a lot. Sintering causes significant changes to the microstructure and characteristics of bilayer ceramic materials at 1175 degrees Celsius. Because of its layered composition, bilayer ceramics offer a novel platform for studying the complex relationship between sintering temperature and material behavior. In this context, it becomes critical to comprehend how bilayer ceramic is affected by the 1175°C sintering temperature to optimize material performance and qualities for a variety of applications. This critical temperature acts as a crucible where grain growth, densification, phase evolution, and structural alterations come together to form the final ceramic product. Through rigorous research, the subtle effects of sintering at 1175°C are clarified, revealing avenues for improving the mechanical strength, thermal stability, and functional diversity of bilayer ceramics (Zhao et al., 2016).

Table 4.1.1: Physical changes of the bilayer disc samples before and after sintering

Pressure (MPa)	Types of samples	Original size (mm)		Sintered size (mm)	
		Diameter	Thickness	Diameter	Thickness
10	Sample 1	13	10	11.4	7.7
	Sample 2	13	10	11.3	8.2
	Sample 3	13	10	11.5	7.3
15	Sample 1	13	10	11.6	7.7
	Sample 2	13	10	11.6	7.7
	Sample 3	13	10	11.5	7.6
20	Sample 1	13	10	11.7	7.6
	Sample 2	13	10	11.6	7.4
	Sample 3	13	10	11.6	7.4
25	Sample 1	13	10	11.7	7.3
	Sample 2	13	10	11.8	7.2
	Sample 3	13	10	11.7	7.1
30	Sample 1	13	10	11.8	7.3
	Sample 2	13	10	11.6	7.1
	Sample 3	13	10	11.4	7.2

Densification, shrinkage, phase transitions, temperature gradients, and the sintering environment are some of the variables that might affect a bilayer disc's parameters, including thickness and diameter, after sintering at 1175 °C. Ceramic particles go through a consolidation process during sintering, where they join forces to form a solid mass. The material's total porosity decreases as a result of this densification. As a result of the removal of vacant spaces between particles, the thickness of the bilayer disc may decrease. Materials frequently shrink during sintering as a result of the particles rearranging and packing closer together (German, 2010; Manière et al., 2022). The bilayer disc shrinks in both the vertical (thickness) and lateral (diameter) directions. The amount of shrinkage that occurs depends on a number of factors, such as the composition of the ceramic, the initial porosity, and the sintering temperature. However, in this study, the pressure variations of 10, 15, 20, 25, and 30 MPa that are applied to the samples during the pressing process are the main cause of the different sizes of sintered samples (Fátima Ternero et al., 2020).

During the sintering process, certain ceramic materials have phase transitions that modify their crystal structure or volume. The bilayer disc may undergo dimensional changes as a result of these phase shifts. Certain phase transitions may take place at 1175 °C, which could lead to alterations in dimension (Mączka & Ptak, 2022). Temperature gradients across the bilayer disc may result from an uneven temperature distribution within the sintering furnace. Differential sintering rates due to temperature variations can lead to non-uniform shrinkage and dimensional changes. Minimizing dimensional deviations during sintering requires careful control of temperature gradients. Table above show that there are different diameter and thickness between original size and sintered size of the disc bilayer shape.

Table 4.1.2: Physical changes of the bilayer bar samples before and after sintering

Pressure (MPa)	Types of samples	Original size (mm) l x w x h	Sintered size (mm) l x w x h
10	Sample 1	75 x 10 x 5	64.9 x 8.3 x 2.9
	Sample 2	75 x 10 x 5	64.8 x 8.4 x 3.0
	Sample 3	75 x 10 x 5	64.7 x 8.4 x 2.9
15	Sample 1	75 x 10 x 5	65.7 x 8.5 x 2.9
	Sample 2	75 x 10 x 5	65.2 x 8.7 x 2.8
	Sample 3	75 x 10 x 5	65.4 x 8.5 x 2.9
20	Sample 1	75 x 10 x 5	65.6 x 8.6 x 2.8
	Sample 2	75 x 10 x 5	65.7 x 8.6 x 2.9
	Sample 3	75 x 10 x 5	65.7 x 8.8 x 2.9
25	Sample 1	75 x 10 x 5	65.9 x 8.6 x 2.8
	Sample 2	75 x 10 x 5	66.4 x 8.7 x 2.7
	Sample 3	75 x 10 x 5	65.7 x 8.7 x 2.9
30	Sample 1	75 x 10 x 5	66.5 x 8.8 x 2.9
	Sample 2	75 x 10 x 5	66.6 x 8.7 x 2.8
	Sample 3	75 x 10 x 5	66.6 x 8.7 x 2.9

High temperatures are applied to the ceramic material during sintering, which causes the particles to fuse together. The material becomes denser as a result of this bonding, which lowers the porosity the amount of empty space between particles. The empty spaces between the particles are filled as they bind together during sintering, which reduces the volume of the ceramic substance. This reduction in volume aids in the material's densification. The length, width, and height of the bilayer bar shrink as a result of the material getting denser and having less empty space inside of it (Hartwell et al., 2022). The table above demonstrates that the original and sintered sizes of the bilayer bar samples differ in size, with each dimension of the original size having shrunk to a range of distinct sizes. Materials frequently shrink during sintering as a result of the particles rearranging and packing closer together. During the sintering process, the material experiences structural changes that cause this shrinkage. The bilayer bar shrinks consistently in length, width, and height, causing proportionate dimensional changes across the structure.

A number of variables, including the ceramic material's composition, the green (unfired) compact's initial porosity, and the sintering temperature, can affect how much the compact shrinks during the process. Because 5g of PMMA was utilized in each sample, the composition of the ceramic employed in this investigation is the same, as is the initial porosity of the green compact. During the sintering process, all samples are subjected to the same temperature of 1175 °C. As a result, the dimension may vary significantly due to the aforementioned reasons. However, based on the outcome, the sintered samples' dimensions differ due to the fact that varied pressing pressures 10, 15, 20, 25, and 30 MPa are used during the process, which causes more shrinkage. The material tends to compact and lose volume when sintering at 1175 °C under varying pressures throughout the pressing process, which reduces the bilayer bar's dimensions in all directions (Bai et al., 2019; Xu et al., 2021).

4.2 Apparent Porosity and Relative Density

By using Archimedes' Principle, the porosity of the samples was ascertained. Using a densimeter, two independent analyses were carried out as Wa, Wb, and Wc, covering pressure values of 10, 15, 20, 25, and 30 MPa. After these analyses, the gathered data was carefully examined using the appropriate formulas to determine the required parameters, including density and more especially the apparent porosity.

Then, each sample's apparent porosity and relative density were determined by multiplying the result by the fundamental formula of Archimedes:

$$P = \frac{Wc - Wa}{Wc - Wb} \times 100$$

Where Wa is the dry mass, Wb is the mass suspended in water, and Wc is the saturated mass. P stands for apparent porosity.

Table 4.2: Results of relative density and apparent porosity with different pressure for bilayer

Pressure (MPa)	Type of sample	Dry Mass (Wa)	Mass Suspended In Water (Wb)	Saturated Mass (Wc)	Relative Density	Apparent Porosity
10	Sample 1	1.96	1.04	1.99	2.230	3.158
	Sample 2	1.93	1.08	1.98	2.248	5.556
	Sample 3	2.05	1.14	2.09	2.247	4.211
Average		1.98	1.09	2.02	2.242	4.301
15	Sample 1	1.97	1.09	2.07	2.246	10.204
	Sample 2	1.91	1.06	1.96	2.244	5.556
	Sample 3	1.97	1.09	2.05	2.251	8.333
Average		1.95	1.08	2.03	2.247	8.421
20	Sample 1	1.93	1.08	2.04	2.267	11.458
	Sample 2	1.89	1.05	1.94	2.244	5.618
	Sample 3	1.88	1.05	2.00	2.244	12.632
Average		1.90	1.06	1.99	2.252	9.677
25	Sample 1	1.91	1.06	2.00	2.244	9.574
	Sample 2	1.93	1.07	2.00	2.239	7.527
	Sample 3	1.91	1.06	1.97	2.259	6.593
Average		1.92	1.06	1.99	2.247	7.527
30	Sample 1	1.92	1.07	1.98	2.253	6.593
	Sample 2	1.89	1.06	1.93	2.242	4.598
	Sample 3	1.90	1.06	1.96	2.230	6.667
Average		1.90	1.06	1.96	2.241	6.667

As the pressing pressure is increased, the ceramic particles get more compacted. The volume of empty spaces decreases, the overall apparent porosity decreases, and the density increases as a result of the particles in the porous and dense layers packing more densely under increased pressure (Xu et al., 2021; Raju et al., 2022). The results demonstrate that as density rises, apparent porosity falls and vice versa. Nevertheless, because of increasing apparent porosity at 15 and 20 MPa and decreasing density at 25 MPa, the results are contradictory. Excessive compaction or particle crushing is blamed for this discrepancy. When applying too much pressure, especially to brittle materials, the particles may get overcompacted or even crushed, which may reduce the material's density and effective volume (Pan et al., 2022). Crushed particles can also produce additional empty areas, increasing the apparent porosity.

The development of agglomerates or clusters is another element that increases porosity. Agglomerates, or clusters of particles, may form as a result of excessive pressure, which could create vacuum spaces between the particles and increase apparent porosity without effectively adding to higher density (Vivacqua & Ghadiri, 2018). High pressures can also cause a material to become trapped in air or other gasses, particularly if the material is porous or includes volatile components. Trapped gas can produce an apparent increase in porosity even when the material's real density increases.

Pressing pressure can have distinct effects on the initial porosity and particle arrangement of the porous and dense layers. A higher pressure may cause the porous layer to compress more forcefully and solidify the dense layer even more, reducing the porosity of the bilayer ceramic and producing a more uniform microstructure (Jin & Cramer, 2021). Furthermore, applying more pressure when pressing can fortify the bond between the dense and porous layers, reducing the likelihood of interfacial voids or gaps. Improved interlayer bonding reduces the apparent porosity of the bilayer ceramic by producing a more homogenous structure and by blocking the channels via which porosity spreads.

The distinct composition and design of the bilayer ceramic, along with the thickness and porosity gradient between the layers, influence the material's response to pressure during the pressing process. Porosity across the bilayer structure can be decreased and densification can be maximized with optimal design considerations. In conclusion, apparent porosity is often decreased by pressing a bilayer ceramic at different pressures (10 MPa, 15 MPa, 20 MPa, 25 MPa, and 30 MPa). This is because to the improved interlayer bonding, compaction, and densification of both layers, as well as the microstructural design of the bilayer ceramic. The characteristics of the dense and porous layers as well as the pressing pressure used during production affect the bilayer ceramic's density and apparent porosity. Higher pressures normally cause both layers to appear less porous and more dense, although the porous layer usually stays less dense and more porosity than the dense layer.

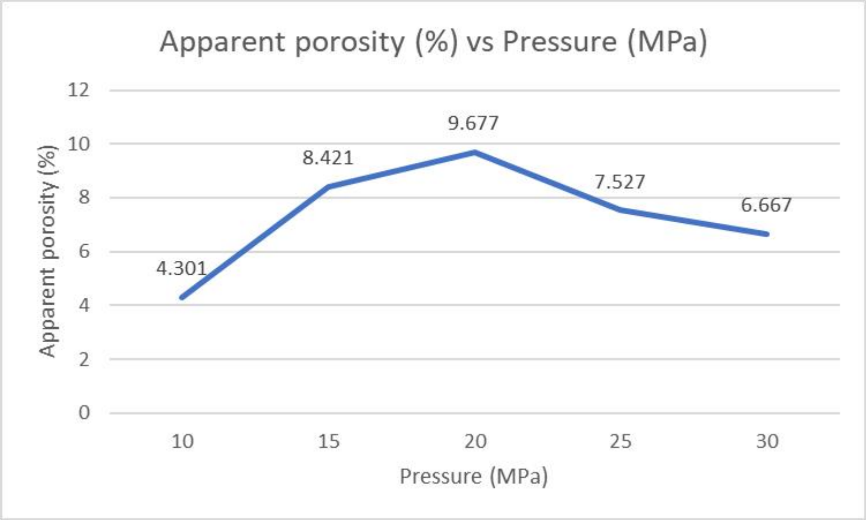


Figure 4.2.1: Percentage of apparent porosity at different pressure

The graph above illustrates a general tendency of rising apparent porosity up to 20 MPa of pressure, then decreasing apparent porosity at 25 and 30 MPa of pressure. There is a noticeable rise in apparent porosity as pressure increases in the first part of the graph, which shows a pressure increase from 10 MPa to 20 MPa. This implies that the material experiences changes within this pressure range that result in the pore space expanding or in the formation of new pores. The material's particles rearranging themselves, pore spaces opening up, or stress-induced microcracks starting could all be contributing factors to this increase (Balima et al., 2019). The dataset's apparent porosity, which is 9.677, reaches its maximum value at about 20 MPa. This peak indicates the ideal pressure situation at which the material displays its maximum porosity in response to an external pressure application. The apparent porosity starts to decrease above 20 MPa. This decrease suggests that the material begins to compress or experiences structural alterations that lower its porosity overall. The material's matrix probably gets denser as pressure rises, which leads to pores collapsing or closing. The rate of porosity decline seems to stabilize between 25 and 30 MPa. Even while porosity is still decreasing, the pace of change may be slowing down, which would suggest that the material is getting closer to a more stable state given the applied pressure settings. This stabilization may indicate that a new equilibrium state is being reached by the material after considerable compaction or pore closure.

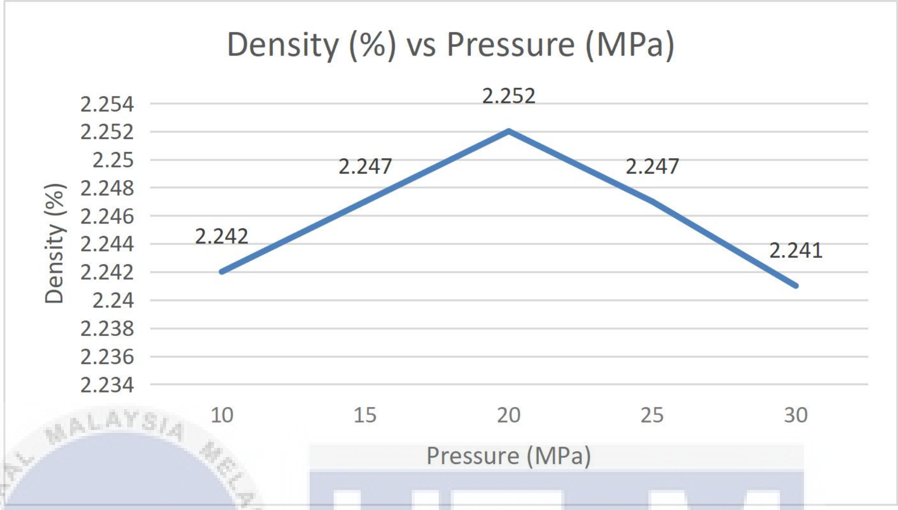


Figure 4.2.2: Percentage of density at different pressure

The density increases steadily from 2.242 to 2.252, or from 10 MPa to 20 MPa, as seen in the graph above. This implies that the material gets denser or more compact when pressure rises within this range. When pressure is applied, the material's particles compress and the pore volume decreases, increasing the density. The density in the dataset reaches its maximum value of 2.252 at around 20 MPa. This peak density, like the peak apparent porosity previously noted, might indicate an ideal pressure situation at which the material attains its maximum density while applying pressure. After this, applying further pressure might not have a substantial impact on the material's density or might have decreasing returns in terms of improving density. There are variations in density above 20 MPa. The density marginally drops to 2.247 at 25 MPa and then drops to 2.241 at 30 MPa. Variations in the material's reactivity to rising pressure, alterations to its microstructure, or experimental variability are a few possible explanations for these oscillations

(Park et al., 2021). It is clear that there are inverse correlations between the trends of perceived porosity and density. Aesthetic porosity decreases with increasing density and vice versa, demonstrating how these two characteristics work in synchrony to describe how a material responds to pressure.

4.3 Peak Formation of Ceramics by X-ray Diffraction Analysis (XRD)

The phase and structural properties of the ceramic materials under examination were carefully examined using X-ray diffraction (XRD) analysis. For porous ceramics exposed to different pressures of 10 MPa, 15 MPa, 20 MPa, 25 MPa, and 30 MPa, specifically, XRD patterns were produced. The ceramic mixture showed clear and distinct peaks, consisting of feldspar ($KAlSi3O_8$), and silica (SiO_2). This suggests that the sintering process, which is essential for improving the material's characteristics, was successful in forming the main ceramic structure and phases. Improved crystallite formation and fewer flaws in the material's crystal lattice are responsible for the peaks' increasing intensity at higher sintering temperatures.

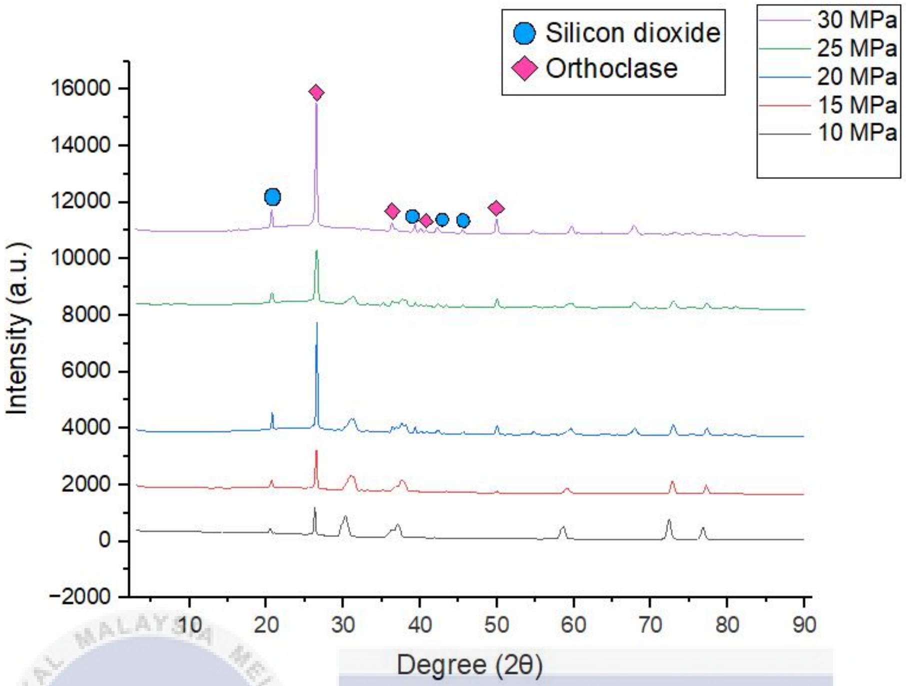


Figure 4.3: XRD patterns of ceramic at different pressure

The cross-sectional reflectance patterns (XRD patterns) of porous ceramics exposed to different pressures of 10 MPa, 15 MPa, 20 MPa, 25 MPa, and 30 MPa provide significant information about the phase and structural properties of the materials. The two main phases that have been identified are orthoclase ($KAlSi3O_8$), denoted by pink diamonds, and silicon dioxide (SiO_2), denoted by blue circles. A higher proportion of amorphous content and a lesser degree of crystallinity are indicated by the comparatively low intensity peaks in the XRD pattern at 10 MPa. Peak intensity increases noticeably when the pressure rises to 15 MPa, indicating enhanced crystallinity.

The peak intensities increase further at 20 MPa, suggesting decreased lattice defects and improved crystallite production. This pattern is maintained at 25 MPa, where notable peaks with greater intensities are seen, suggesting ideal crystallite production and a reduced number of crystal structural flaws. Among the investigated pressures, the pattern at 30 MPa displays the highest peak intensities, especially at 26° (2θ) for silicon dioxide and 30° (2θ) for orthoclase. This indicates the highest degree of crystallinity.

The silicon dioxide analysis exhibits rising intensities with pressure, peaking at 30 MPa, and peaks at around 20°, 26°, and 50° (2θ). This suggests enhanced crystalline quality and decreased amorphous content at higher pressures. Similar to this, orthoclase peaks at around 16°, 20°, 26°, 30°, and 33° (2θ) likewise exhibit intensities that increase with pressure, peaking at 30 MPa, indicating improved crystallization and fewer flaws.

To sum up, the XRD study shows that a significant improvement in crystallinity occurs when the pressure is increased during the creation of porous ceramics. The peaks become more noticeable at greater pressures, suggesting better crystal quality and fewer flaws (Li et al., 2020). This study demonstrates that 30 MPa is the ideal pressure to attain the maximum level of crystallinity in the ceramic material, offering important information for maximizing pressure settings during the production of premium ceramic materials.

4.4 Flexural Strength Test

Table 4.4: Maximum stress of bilayer ceramic with different pressure

Pressure (MPa)	Type of Sample	Width (mm)	Thickness (mm)	Lower Support (mm)	Maximum Stress (N/mm^2)
10	Sample 1	8.3	2.9	32.5	31.5237
	Sample 2	8.4	3.0	32.4	10.8923
	Sample 3	8.4	2.9	32.4	26.4053
Average		8.4	2.9	32.4	22.9404
15	Sample 1	8.5	2.9	32.9	22.5102
	Sample 2	8.7	2.8	32.6	27.4148
	Sample 3	8.5	2.9	32.7	21.1340
Average		8.6	2.9	32.7	23.6863
20	Sample 1	8.6	2.8	32.8	30.1601
	Sample 2	8.6	2.9	32.9	30.0127
	Sample 3	8.8	2.9	32.9	28.4368
Average		8.7	2.9	32.9	29.5365
25	Sample 1	8.6	2.8	33.0	31.9782
	Sample 2	8.7	2.7	33.2	29.9332
	Sample 3	8.7	2.9	32.9	24.7475
Average		8.7	2.8	33.0	28.8863
30	Sample 1	8.8	2.9	33.3	10.8006
	Sample 2	8.7	2.8	33.3	29.3907
	Sample 3	8.7	2.9	33.3	26.0424
Average		8.7	2.9	33.3	22.0779

Changing the pressing pressure during the development of a dense porous layer in ceramics has a big impact on the mechanical properties and microstructure of the material. Because the ceramic particles are packed closer together under increased pressure, the porosity and density decrease, leaving fewer voids and flaws that can serve as stress concentrators. Greater pressures frequently result in microstructures that are finer and more uniform, with grain boundaries that effectively stop cracks from spreading and enhance mechanical properties (Das et al., 2019). Stronger interparticle connections are a result of improved particle bonding and interaction, which raises mechanical strength, especially flexural strength.

In ceramics, altering the pressing pressure during the formation of a dense porous layer has a significant effect on the material's mechanical characteristics and microstructure. Porosity and density drop as a result of the ceramic particles being pressed closer together under higher pressure, resulting in fewer voids and imperfections that can act as stress concentrators (T. Norfauzi et al., 2021). Higher pressures usually produce more homogeneous and finer microstructures with grain boundaries that effectively prevent cracks from propagating and improve mechanical characteristics. Improved particle bonding and interaction lead to stronger interparticle connections, which increase mechanical strength, particularly flexural strength.

For example, the maximum stress rises dramatically from 10 MPa to 15 MPa, suggesting better mechanical properties brought about by decreased porosity and increased particle bonding. The maximum stress increases with subsequent pressure increases from 15 MPa to 20 MPa, indicating that the material benefits from additional compaction. But there is a discernible drop in maximum stress from 20 MPa to 25 MPa, which could be brought on by microcracking or residual strains from pressing or by an overabundance of density (Kabir et al., 2016). Nevertheless, the maximum stress drops once more from 25 MPa to 30 MPa, most likely as a result of negative consequences such microcracking brought on by high pressure.

The significance of balancing density, porosity, and internal stresses during the pressing process is highlighted by these variations in maximum stress (Fedor Panteleyenko et al., 2019). At pressures 20 MPa, the ceramic exhibits its maximum mechanical properties. The material's structural integrity is jeopardized beyond this point, making the advantages of increased pressure negligible. Therefore, to achieve the necessary mechanical properties in ceramics, pressing parameters must be carefully considered.

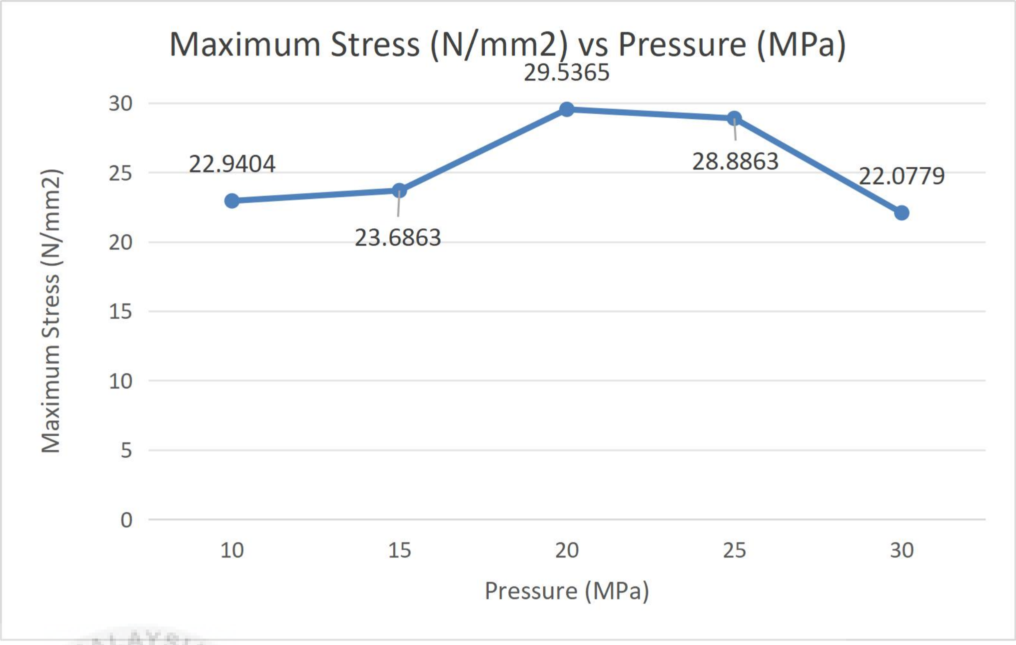


Figure 4.4: Maximum stress for bilayer ceramic at different pressure

The graph highlights how stress changes with different pressure levels by showing the link between applied pressure (measured in MPa) and maximum stress (measured in N/mm²). The data points show a clear trend the maximum stress first marginally reduces, then climbs dramatically, and eventually drops down after peaking as pressure increases from 10 MPa to 30 MPa. The stress is approximately 22.9404 N/mm² at 10 MPa, rises to 23.6863 N/mm² at 15 MPa, and then rises quickly to a high of 29.5365 N/mm² at 20 MPa. The stress then falls to 28.8863 N/mm² at 25 MPa and then to 22.0779 N/mm² at 30 MPa after reaching its peak. The strength of the material may be decreased by overcompaction due to microcracking or residual stresses. Furthermore, non-uniform compaction may result in weak spots, which would reduce the maximum stress even more (Bolzon & Pitchai, 2021). The graph clearly shows that the optimum pressure of 20 MPa is the highest maximum stress value at 29.5365 N/mm². This peak shows the maximum amount of stress that the material or system under study can tolerate at this pressure level. The capacity of 20 MPa to push a material to its maximum performance capacity without producing an instantaneous decrease or failure makes it the ideal pressure. After this point, the stress starts to drop, which could indicate that structural alterations, yielding, or other processes resulting in a lower stress tolerance are occurring in the material or system.The most effective pressure threshold, then, at which the material reaches its maximum stress potential is 20 MPa. This guarantees optimal performance and structural integrity before adverse consequences occur at higher pressures.

4.5 Field Emission Scanning Electron Microscopy (FESEM)

A field emission gun serves as the electron source in a sort of scanning electron microscopy (SEM) known as field emission scanning electron microscopy (FESEM). Imaging at far greater resolutions is made possible by the narrow and intensely concentrated electron beam produced by this cannon. High-resolution photographs of a sample's surface morphology are produced by FESEM, which provides comprehensive details about the topography, texture, and structure at the nanoscale. Fine surface characteristics like pores, cracks, grains, and particles can be captured by it. When used in conjunction with FESEM, EDX maps the surface of the sample and performs elemental analysis to determine the distribution and composition of its constituent elements. Researchers are able to associate morphological traits with chemical composition because of this combination.

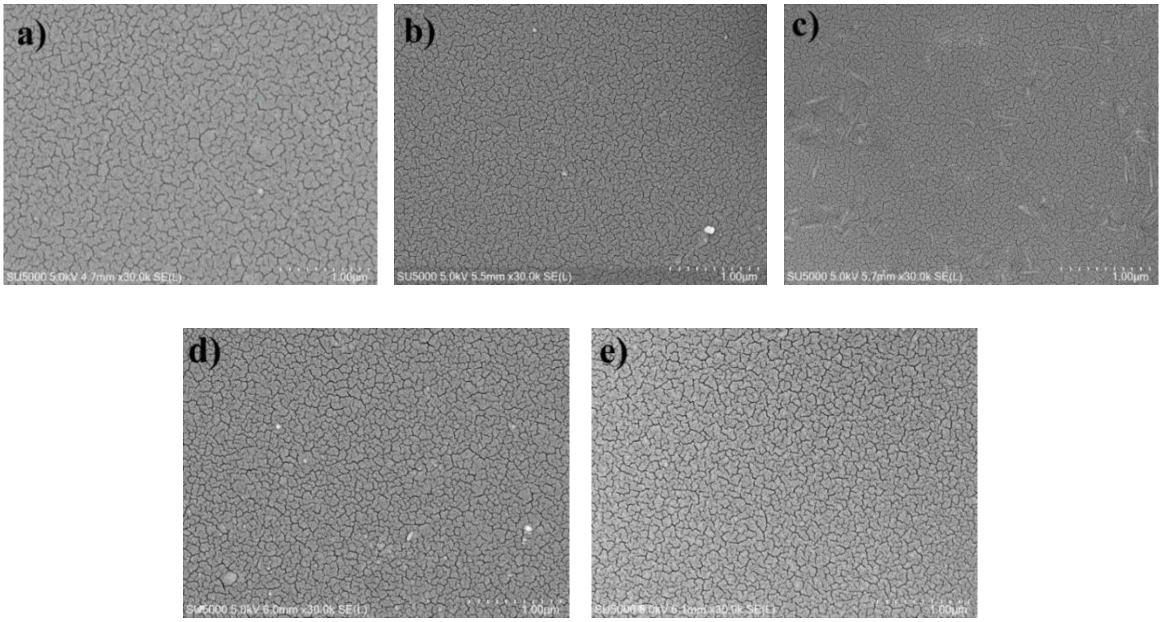


Figure 4.5.1: FESEM image of sintered sample at top surface with varying pressure at 30K magnification a) 10 MPa, b) 15 MPa, c) 20 MPa, d) 25 MPa and e) 30 MPa

The accompanying FESEM micrograph shows the grain boundaries of a ceramic material pressed at 10 MPa. This image shows a network of grain boundaries delineating individual grains within the ceramic. Each of these boundaries, which show up as dark lines dividing lighter areas, represents a distinct grain. The sample exhibits bigger and more asymmetrical grains because to the decreased densification and compaction at this pressure. The irregular shapes point to limited deformation, suggesting that more of the original morphology of the grains has been kept.

In contrast, more uniform and densely packed grains can be seen in the FESEM micrograph of materials that were compressed at 15 MPa. Better intergranular contact is shown by the more prominent and continuous grain boundaries, which are represented by black lines. Smaller and more uniform grains are the result of increased compaction combined with a higher degree of deformation and rearrangement. Less tiny spaces than in the 10 MPa sample are the result of improved particle packing, which lowers the sample's total porosity. Because there are less voids between the grains and greater particle organization, the surface seems smoother due to the increased pressure.

Compared to ceramic materials pressed at 10 and 15 MPa, the FESEM micrograph of a material pressed at 20 MPa reveals more uniformly formed and densely packed grains. Grain boundaries are strongly defined and intricately woven, these are illustrated by black lines, which represent effective intergranular bonding. Grain equiaxes and size decrease with increased pressure, suggesting a higher degree of deformation. Better uniformity and compaction result from this. When compared to samples that are pressed at lesser pressures, the higher pressure effectively closes more gaps, leaving even less porosity (Raju et al., 2022). The texture becomes smoother and more continuous as surface roughness reduces and particle organization gets better.

The FESEM micrograph of materials pressed at 25 MPa shows strong intergranular bonding and represent well-defined, linked grain boundaries. The smaller and more equiaxed grains, which have better compaction and homogeneity, suggest that the increased pressure appears to have caused considerable deformation and rearrangement. Effective sealing of more holes results in a significant reduction in porosity. The smoother and more consistent surface texture suggests better particle organization and decreased surface roughness.

Compared to materials pressed at lower pressure, the FESEM micrograph of materials pressed at 30 MPa reveals grains that are evenly formed and densely packed. There are minimal gaps and excellent intergranular bonding inside the dense, interconnected network created by the sharply defined, black grain boundaries. The high levels of homogeneity and compaction are achieved through significant distortion and rearrangement of equiaxed, minuscule grains caused by the severe pressure. Tight packing and almost no visible voids point to a nearly compact structure with much reduced porosity. Nevertheless, even though the surface texture is incredibly continuous and smooth, pressing at 20 MPa still produces the smoothest surface as opposed to the marginally rougher surface seen at 30 MPa (Edwin Spartakovych Gevorkyan et al.,2022). In conclusion, among the pressures examined, the material pressed at 20 MPa has the smoothest and most uniform microstructure, offering the best possible balance between compaction, deformation, and intergranular bonding. Accordingly, the best pressure to get the smoothest surface in ceramic materials is 20 MPa.

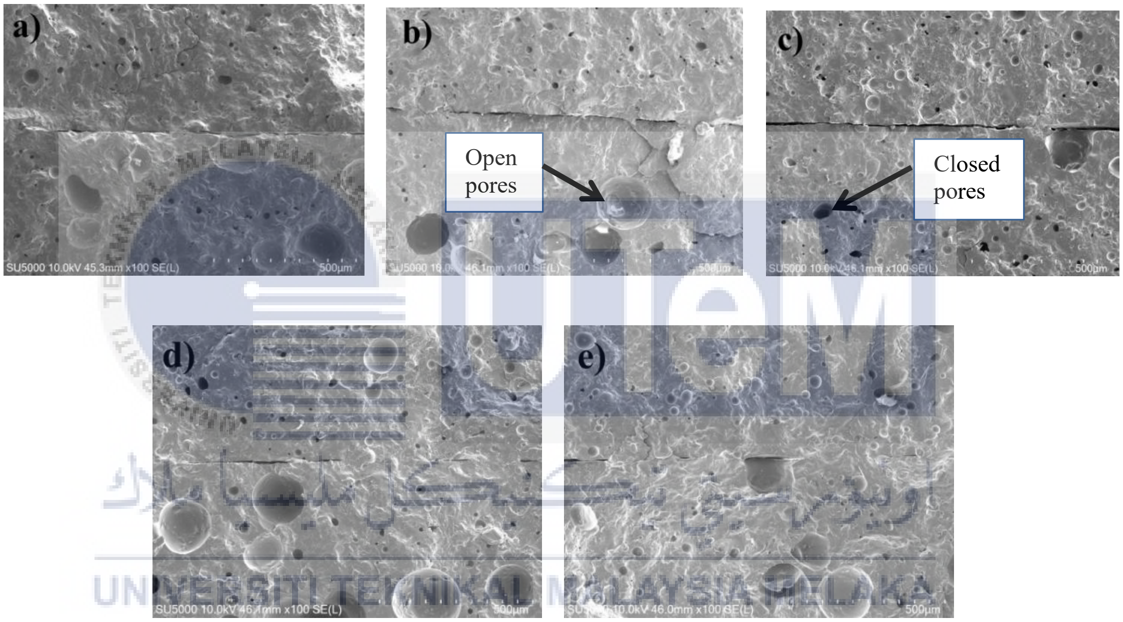


Figure 4.5.2: FESEM image of sintered bilayer sample at cross section with varying pressure at 100K magnification a) 10 MPa, b) 15 MPa, c) 20 MPa, d) 25 MPa and e) 30 MPa

The cross-sections of bilayer ceramic materials pressed at various pressures which are 10, 15, 20, 25, and 30 MPa are shown in the FESEM micrographs. Every micrograph exhibits an upper layer that is dense and a lower layer that is porous, indicating the impact of pressing pressure on the microstructure.With closely spaced grains and few gaps, the thick top layer at

10 MPa appears smooth and compact, suggesting better consolidation, reduced porosity, and increased particle packing density. Strong interparticle bonding is probably the cause of this layer's higher mechanical strength and toughness. On the other hand, there is less compaction and a lower particle packing density in the porous lower layer, which has a coarser structure and many visible voids. The lower layer's high porosity, in spite of its decreased mechanical strength, making it appropriate for applications needing particular thermal or acoustic insulation qualities or lightweight materials (Dolores et al., 2022). The clear demarcation separating the layers points to notable variations in microstructure and density, which may compromise the mechanical integrity of the bilayer material as a whole.

When compared to the 10 MPa sample, the dense top layer at 15 MPa exhibits a smoother, more compact microstructure with fewer apparent voids, indicating improved particle packing and less porosity as a result of the greater pressing pressure (T. Norfauzi et al., 2021). This suggests greater mechanical strength and toughness. The porous lower layer shows a moderate reduction in pore size and number, indicating an intermediate degree of compaction and porosity, even if it is still rough and irregular. The separation of the layers is still evident, but it might transition more smoothly than it did at 10 MPa, indicating better integration and possibly improving the mechanical integrity of the material as a whole.

The dense layer shows a very smooth, compact structure with little porosity at 20 MPa, suggesting increased mechanical strength and shock resistance. Better compaction is demonstrated by the porous lower layer, which retains its distinctive roughness and voids. The distinct border between the layers points to a significant separation, which may concentrate stress at the contact and affect the mechanical properties of the material (Peyman Khajavi et al., 2020). The ceramic material has a smooth surface in the upper dense layer and a high particle packing density at 25 MPa. Few cavities are visible in this tight layer, indicating increased mechanical strength and longevity. The porous lower layer at 25 MPa shows less porosity than samples pressed at lower pressures, even though it still has gaps and pores, indicating better particle consolidation. A distinct change in microstructure and density is shown by a discernible horizontal line at the interface. The mechanical performance could be affected by this significant separation, especially when under stress.

The dense top layer of the ceramic material at 30 MPa has a high particle packing density and very few vacancies, which help to create a smooth, compact surface with less porosity and more mechanical strength. The lower porous layer at 30 MPa has fewer and smaller pores than samples pressed at lower pressures, indicating increased compaction and decreased porosity. A strong separation is indicated by the prominent horizontal line at the interface, which is essential for maintaining structural integrity and performance under stress. It also suggests a sudden shift in density and microstructure. While the porous layer might have advantages like reduced weight or particular insulating qualities, the dense layer's great compaction suggests superior mechanical support (Chen et al., 2021).

In contrast to materials pressed at 10, 15, 25, and 30 MPa, the material pressed at 20 MPa has the smoothest surface, according to the FESEM micrograph. Grain boundaries are well defined and intricately braided at 20 MPa, indicating efficient intergranular bonding. The grains show ideal particle packing density because they are more uniformly produced, tightly packed, and have few voids. The end product is a very homogeneous microstructure with improved particle organization and less surface roughness. 20 MPa is the most suitable pressure for obtaining the smoothest surface and perfect compaction in ceramic materials because it achieves a higher level of smoothness than 10, 15, 25, and 30 MPa. In addition to increasing mechanical strength, the increased surface texture at 20 MPa also helps to improve durability and performance under stress.

Table 4.5: The elements of EDX with varying pressure

Pressure (MPa)	O (%)	Na (%)	Mg (%)	Al (%)	Si (%)	K (%)
10	64.8	2.1	0.1	6.8	23.2	2.9
15	64.7	1.9	0.1	11.1	19.3	3.0
20	66.1	2.4	0.2	7.2	20.6	3.5
25	61.2	2.3	0.2	8.4	23.8	4.1
30	62.5	2.2	0.3	7.9	23.4	3.8

The table presents the constituent composition of a ceramic material at different pressing pressures (MPa) based on an investigation conducted using Energy Dispersive X-ray Spectroscopy (EDX). The major component of ceramics, oxygen, remains present in percentages ranging from 61.2% to 66.1% across the pressure range. The levels of magnesium and sodium are negligible, varying just slightly between 1.9% and 2.4% and less than 0.3%, respectively. Aluminum, which is important for structural stability, notably varies a lot it ranges from 6.8% to 11.1%. Another important component that affects mechanical characteristics, silicon, shows a significant degree of variability, ranging from 19.3% to 23.8%. Although quite low, the potassium level varies slightly, usually being less than 4.1%. These variations most likely result from modifications to the packing and composition of particles under various pressure settings, which affect how elements are distributed inside the ceramic material (Lin et al., 2022).

CHAPTER 5

CONCLUSION AND RECOMMEMNDATIONS

5.1 Conclusion

This experiment successfully built a bi-layered ceramic structure with a dense layer on top and a porous layer at the bottom using different pressures of 10, 15, 20, 25, and 30 MPa. A detailed analysis of the porosity, mechanical characteristics, and physical characteristics of the ceramics was conducted, with a focus on the effects of varying pressures on these characteristics as the objectives of this study. The study examined the effects of a 1175°C sintering temperature in detail on bilayer ceramic materials and showed that this temperature has a significant impact on the ceramics' microstructure and physical properties. The ceramic samples showed significant densification and shrinkage throughout the sintering process, as shown by the decrease in both thickness and diameter. The porosity study confirmed that the ideal pressure of 20 MPa resulted in the maximum value of apparent porosity measured at 9.677% using Archimedes' principle, indicating a successful densification process. Better phase transitions and grain growth were shown by microstructural analysis using a FESEM, which was crucial for enhancing the material's mechanical properties. Flexural test results, which showed maximum performance capacity which is 29.5365 N/mm^2 at 20 MPa in the sintered samples and were compatible with the densification and grain development observed, supported these conclusions. Moreover, XRD examination verified the sintering-induced structural changes by indicating significant phase evolution. By assessing the ceramic material's porosity, density, mechanical strength, and structural integrity at various pressures, the ideal pressure is found.

As a result, for the ceramic material to have the optimal balance of mechanical characteristics, density, and smoothness under the tested conditions, a pressure of 20 MPa is the best.

5.2 Recommendations

In order to maximize the properties of bilayer ceramics, further research should examine sintering procedures at various pressures and temperatures, with a focus on temperature gradient management for uniform shrinkage. Examining various ceramic compositions and initial porosities can provide information about how to get the required qualities of the material. In order to optimize mechanical and thermal properties during sintering, a thorough understanding of phase transitions and microstructural changes is essential. By investigating different pore-forming agents, like incorporating glass fiber, and assessing both cold isostatic pressing (CIP) and hot isostatic pressing (HIP) techniques for improving sample pressing procedures, researchers might increase rigor. Cost-effective density gains are provided by CIP, and mechanical characteristics and corrosion and fatigue resistance are improved by HIP. Utilizing these results which include information from the ideal pressure of 20 MPa will direct future developments in bilayer ceramics. Extensive studies of their industrial applications can improve study results even more.

REFERENCES

Venkata Sundeep Seesala, Rajasekaran, R., Dutta, A., Pravin Vasudeo Vaidya, & Santanu Dhara. (2021). Dense-porous multilayer ceramics by green shaping and salt leaching. *Open Ceramics*, *5*, 100084–100084. https://doi.org/10.1016/j.oceram.2021.100084

Handbook of Advanced Ceramics: Materials, Applications, Processing, and Properties. (2013). In Google Books. Academic Press. https://books.google.com.my/books?hl=en&lr=&id=tdx7lS4fO9wC&oi=fnd&pg=PP1&d q=ceramic+materials+and+properties&ots=O-r6_cJQ4P&sig=ha_KgOvAR8TPgYfXvq9DRrPXZLM&redir_esc=y#v=onepage&q=cer a mic%20materials%20and%20properties&f=false

Kingery, W. D., Bowen, H. K., & Uhlmann, D. R. (1976). Introduction to Ceramics. In Google Books. John Wiley & Sons. https://books.google.com.my/books?id=nGjjDwAAQBAJ&lpg=PR1&ots=On4BaOJ2jd&dq=introduction%20of%20ceramics%20materials&lr&pg=PR12#v=onep age&q=introd uc tion%20of%20ceramics%20materials&f=false

Barsoum, M. (2019). Fundamentals of Ceramics. In Google Books. CRC Press. https://books.google.com.my/books?id=n_vDDwAAQBAJ&lpg=PT10&ots=E2WEG74p kH&dq=introduction%20of%20ceramics%20materials&lr&pg=PT25#v=onepage&q=int r oduction%20of%20ceramics%20materials&f=false

Toozandehjani, M., Matori, K. A., Ostovan, F., Abdul Aziz, S., & Mamat, M. S. (2017). Effect of Milling Time on the Microstructure, Physical and Mechanical Properties of Al- Al2O3 Nanocomposite Synthesized by Ball Milling and Powder Metallurgy. Materials (Basel,Switzerland), 10(11), E1232. https://doi.org/10.3390/ma10111232

Li, M., Gehre, P., & Aneziris, C. G. (2013). Investigation of calcium zirconate ceramic synthesized by slip casting and calcination. Journal of the European Ceramic Society, 33(10), 2007–2012. https://doi.org/10.1016/j.jeurceramsoc.2013.02.010

Yin, J., Li, X., Lai, Y., Zhang, X., Yu, S., & Luo, Y. (2023). Ultra-high quality factor of transparent Al2O3 ceramics fabricated by vacuum sintering and post hot isostatic pressing. Ceramics International, 49(22, Part B), 36879–36884. https://doi.org/10.1016/j.ceramint.2023.09.018

Dreier, T., Riaz, A., Ahrend, A., Polley, C., Bode, S., Milkereit, B., & Seitz, H. (2023). 3D printing of aluminum oxide via composite extrusion modeling using a ceramic injection molding feedstock. Materials & Design, 227, 111806. https://doi.org/10.1016/j.matdes.2023.111806

Rezania, M., Panahandeh, M., Razavi, S. M. J., & Berto, F. (2019). Experimental study of the simultaneous effect of nano-silica and nano-carbon black on permeability and mechanical properties of the concrete. Theoretical and Applied Fracture Mechanics, 104, 102391. https://doi.org/10.1016/j.tafmec.2019.102391

Kłosek-Wawrzyn, E., Frąc, M., & Pichór, W. (2023). Influence of pregranulation and low- pressure compaction on the properties of ceramic materials incorporating clay and spent coffee grounds. Applied Clay

Science, 245, 107154. https://doi.org/10.1016/j.clay.2023.107154

Ozkan, B., Sameni, F., Goulas, A., Karmel, S., Engstrøm, D. S., & Sabet, E. (2022). Hot ceramic lithography of silica-based ceramic cores: The effect of process temperature on vat-photopolymierisation. Additive Manufacturing, 58, 103033. https://doi.org/10.1016/j.addma.2022.103033

Abdul Hai Alami, Abdul Ghani Olabi, Adnan Alashkar, Shamma Alasad, Haya Aljaghoub, Rezk, H., & Mohammad Ali Abdelkareem. (2023). Additive manufacturing in the aerospace and automotive industries: Recent trends and role in achieving sustainable development goals. Ain Shams Engineering Journal, 14(11), 102516–102516. https://doi.org/10.1016/j.asej.2023.102516

Rumi, M. Kh., Urazaeva, E. M., Irmatova, Sh. K., Nurmatov, Sh. R., Zufarov, M. A., Mansurova, E. P., & Ziyovaddinov, Zh. K. (2023). Influence of heat treatment on the structure and properties of ceramic heat-insulating composites based on phosphate bound expanded perlite-expanded clay. Open Ceramics, 14, 100344. https://doi.org/10.1016/j.oceram.2023.100344

Wu, J., Wang, H., Zhang, Z., Wang, C., Hou, Z., Wan, S., Wu, D., & Ouyang, X. (2023). High-pressure synthesis and performance analysis of WC-cBN-MoS2 self-lubricating ceramic composites. International Journal of Refractory Metals and Hard Materials, 110, 105989. https://doi.org/10.1016/j.ijrmhm.2022.105989

Lou, J., He, C., Shui, A., & Yu, H. (2023). Enhanced sound absorption performance of porous ceramics with closed-pore structure. Ceramics

International, 49(23, Part A), 38103– 38114. https://doi.org/10.1016/j.ceramint.2023.09.140

Sylvain Meille, Lombardi, M., Chevalier, J., & Montanaro, L. (2012). Mechanical properties of porous ceramics in compression: On the transition between elastic, brittle, and cellular behavior. 32(15), 3959–3967. https://doi.org/10.1016/j.jeurceramsoc.2012.05.006

Huang, K., Wang, L., Li, M., Mi, T., Zhang, J., Liu, J., & Yi, X. (2023). Mechanism of porous ceramic fabrication using Second Aluminum Dross assisted by corn stalk as pore- forming agent. Environmental Technology & Innovation, 31, 103195. https://doi.org/10.1016/j.eti.2023.103195

Cha, H.-A., Jo, M.-G., Moon, Y. K., Hahn, B.-D., Ahn, C.-W., Choi, J.-J., & Kim, D. K.(2023). Highly porous YSZ ceramic foams using hollow spheres with holes in their shell for high-performance thermal insulation. Journal of the European Ceramic Society, 43(15), 7041–7052. https://doi.org/10.1016/j.jeurceramsoc.2023.07.029

Chen, B., Xiao, G., Yi, M., Zhang, J., Zhou, T., Chen, Z., & Xu, C. (2021). Mechanical properties and microstructure of Al2O3/TiB2 and Al2O3/TiB2/GNPs ceramic tool materials prepared by spark plasma sintering. Ceramics International, 47(8), 11748–11755. https://doi.org/10.1016/j.ceramint.2021.01.015

Guo, F., Wu, F., Li, J., Liu, L., & Huang, Y. (2023). A facile approach for preparing Al2O3 reticulated porous ceramics with optimized closed-cell struts and excellent mechanical properties. Ceramics International, 49(13), 22054–22061. https://doi.org/10.1016/j.ceramint.2023.04.031

Wenjing, S., Zhang, J., Ge, S., Shi, P., Li, L., Zhang, Y., Yuan, H., Gui, D., & Shi, Z. (2023). Effect of solid content on the piezoelectric properties of porous (Ba0.85Ca0.15)(Zr0.1Ti0.9)O3 ceramics. Ceramics International, 49(22, Part B), 36691– 36699. https://doi.org/10.1016/j.ceramint.2023.08.352

Zhao, X., Zuo, D., Zhang, M., Xu, F., Wang, J., & Feng, S. (2016). Effect of Sintering Temperature on the Microstructure and Properties of Ultra-Fine Ti(C,N)-Based Cermets. Materials Transactions, 57(9), 1615–1619. https://doi.org/10.2320/matertrans.m2016116

Xu, Z., Wu, F., Pan, K., Liao, Y., Wang, F., Cheng, L., Yu, J., Liu, Y.-T., & Ding, B. (2023). Ceramic aerogels constructed from dense, non-porous ceramic nanofibers with robust and elastic properties up to 1300 °C. Ceramics International. https://doi.org/10.1016/j.ceramint.2023.11.373

Zhao, K., Ye, F., Cheng, L., Yang, J., & Chen, X. (2023). An overview of ultra-high temperature ceramic for thermal insulation: Structure and composition design with thermal conductivity regulation. Journal of the European Ceramic Society, 43(16), 7241– 7262. https://doi.org/10.1016/j.jeurceramsoc.2023.07.046

Youness, R. A., Al-Ashkar, E., & Taha, M. A. (2023). Role of porosity in the strength, dielectric properties, and bioactivity of hardystonite ceramic material for use in bone tissue engineering applications. Ceramics International, 49(24, Part A), 40520–40531. https://doi.org/10.1016/j.ceramint.2023.10.029

Gharibi, H., Mostofinejad, D., Bahmani, H., & Hadadzadeh, H. (2022). Improving thermal and mechanical properties of concrete by using ceramic electrical insulator waste as aggregates. Construction and Building Materials, 338, 127647. https://doi.org/10.1016/j.conbuildmat.2022.127647

Shanmugam, M., Sivakumar, G., Arunkumar, A., Rajaraman, D., & Indhira, M. (2020). Fabrication and assessment of reinforced ceramic electrical insulator from bamboo leaf ash waste. Journal of Alloys and Compounds, 824, 153703. https://doi.org/10.1016/j.jallcom.2020.153703

German, R. M. (2010). Coarsening in Sintering: Grain Shape Distribution, Grain Size Distribution, and Grain Growth Kinetics in Solid-Pore Systems. Critical Reviews in Solid State and Materials Sciences, 35(4), 263–305. https://doi.org/10.1080/10408436.2010.525197

Manière, C., Grippi, T., & Sylvain Marinel. (2022). Estimate microstructure development from sintering shrinkage: A kinetic field approach. Materials Today Communications, 31, 103269–103269. https://doi.org/10.1016/j.mtcomm.2022.103269

Kim, Y.-S., Kim, Y.-R., Kang, J.-H., Yun, Y.-N., Park, S.-W., Lim, H.-P., Yun, K.-D., Jang, W.-H., Lee, D.-J., & Park, C. (2023). Ceramic 3D printing using lithium silicate prepared by sol-gel method for customizing dental prosthesis with optimal translucency. Ceramics International, 49(24, Part A), 39788–39799. https://doi.org/10.1016/j.ceramint.2023.08.220

Wang, Y., Wang, J., Zhang, X., Li, N., Wang, J., & Liang, X. (2022). Order–disorder structural tailoring and its effects on the chemical stability of (Gd, Nd)2(Zr, Ce)2O7 pyrochlore ceramic for nuclear waste forms. Nuclear Engineering and Technology. https://doi.org/10.1016/j.net.2022.02.001

Chen, K.-W., & Hu, L.-H. (2024). The mechanical properties of ceramic matrix composite composed of polysilazane-derived silicon oxycarbonitride ceramic with nano alumina. Journal of Alloys and Compounds, 976, 173136. https://doi.org/10.1016/j.jallcom.2023.173136

Zhang, B., Yang, Y., & Fan, X. (2024). Processing, microstructure, and properties of porous ceramic composites with directional channels. Journal of Materials Science & Technology,168,1–15. https://doi.org/10.1016/j.jmst.2023.04.039

Gumula, T., Rudawski, A., Michalowski, J., & Blazewicz, S. (2015). Fatigue behavior and oxidation resistance of carbon/ceramic composites reinforced with continuous carbon fibers. Ceramics International, 41(6), 7381–7386. https://doi.org/10.1016/j.ceramint.2015.02.046

Chen, Y., Wang, N., Ola, O., Xia, Y., & Zhu, Y. (2021). Porous ceramics: Light in weight but heavy in energy and environment technologies. Materials Science and Engineering: R:Reports, 143, 100589. https://doi.org/10.1016/j.mser.2020.100589

Fátima Ternero, Astacio, R., Caballero, E. S., Cuevas, F. G., & Montes, J. M. (2020). Influence of Processing Parameters on the Conduct of Electrical Resistance Sintering of Iron Powders. Metals, 10(4), 540–540. https://doi.org/10.3390/met10040540

Mączka, M., & Ptak, M. (2022). Temperature-Dependent Raman Studies of FAPbBr3 and MAPbBr3 Perovskites: Effect of Phase Transitions on Molecular Dynamics and Lattice Distortion. Solids, 3(1), 111–121. https://doi.org/10.3390/solids3010008

Hartwell, A. R., Slabaugh, N., & Ahn, J. (2022). Utilizing Bilayer Shrinkage to Assemble Complex Ceramic Shapes. Volume 9: Mechanics of Solids, Structures, and Fluids; Micro- and Nano-Systems Engineering and Packaging; Safety Engineering, Risk, and Reliability Analysis; Research Posters. https://doi.org/10.1115/imece2022-95531

Xu, H., Zou, J., Wang, W., Wang, H., Ji, W., & Fu, Z. (2021). Densification mechanism and microstructure characteristics of nano- and micro-crystalline alumina by high-pressure and low temperature sintering. Journal of the European Ceramic Society, 41(1), 635–645. https://doi.org/10.1016/j.jeurceramsoc.2020.08.018

Bai, Y., Ma, Y., Sun, M., Cheng, L., & Fan, S. (2019). Sintering temperature effect on microstructure, mechanical and electrical properties of multi-layered ZrB2-based ceramics with thin Ti interlayer. Journal of the European Ceramic Society, 39(14), 3938–3948. https://doi.org/10.1016/j.jeurceramsoc.2019.06.005

Raju, P., Biswas, P., Asit Khanra, Rao, Y., & Johnson, R. (2022). Investigations on colloidal and dry formed alumina parts under pressure and pressure-less conditions. Processing and Application of Ceramics, 16(2), 160–166. https://doi.org/10.2298/pac2202160r

Pan, Z., Zhang, C., Guo, X., Ma, C., Ma, L., & Gan, S. (2022). Influence of particle size scale on mechanical properties of tailings under high pressure. Proceedings of the Institution of Civil Engineers. Geotechnical Engineering/Proceedings of ICE. Geotechnical Engineering, 175(2), 200–213. https://doi.org/10.1680/jgeen.20.00216

Vivacqua, V., & Ghadiri, M. (2018). Modelling of auto-agglomeration of cohesive powders. Chemical Engineering Research and Design, 133, 137–141. https://doi.org/10.1016/j.cherd.2018.03.018

Jin, Z.-H., & Cramer, C. L. (2021). A Lamination Model for Pressure-Assisted Sintering of Multilayered Porous Structures. Journal of Composites Science, 5(2), 53–53. https://doi.org/10.3390/jcs5020053

Balima, F., Le Floch, S., San-Miguel, A., Reinert, L., Duclaux, L., Nguyen, A. N., Daniel, I., Brûlet, A., Gremillard, L., & Pischedda, V. (2019). Porosity evolution of expanded vermiculite under pressure: the effect of pre-compaction. SN Applied Sciences, 1(6). https://doi.org/10.1007/s42452-019-0627-9

Park, H.-S., Ali, Celliers, P. M., F. Coppari, Eggert, J., Krygier, A., Lazicki, A. E., Mcnaney, J. M., M. Millot, Ping, Y., Rudd, R. E., Remington, B. A., Sio, H., Smith, R. F., Knudson, M. D., & McBride, E. E. (2021). Techniques for studying materials under extreme states of high energy density compression. Physics of Plasmas, 28(6). https://doi.org/10.1063/5.0046199

Li, J., Ren, X., Zhang, Y., & Hou, H. (2020). Porous process and its effects on the microstructure and properties of SiC ceramics sintered with Mg additive. Journal of Materials Research and Technology, 9(1), 33–41. https://doi.org/10.1016/j.jmrt.2019.10.026

Fedor Panteleyenko, Andrzej Kuczumow, Sieniawski, J., Katerina Panteleyenko, Shmuradko, V., & Vladimir Korotin. (2019). Mechanisms of technical ceramic density adjusting. MATEC Web of Conferences, 297, 0400704007.

https://doi.org/10.1051/matecconf/201929704007

Das, J., Patel, P., J. Janardhana Reddy, & V.V. Bhanu Prasad. (2019). Microstructure and mechanical properties of a SiC containing advanced structural ceramics. International Journal of Refractory & Hard Metals, 84, 105030–105030. https://doi.org/10.1016/j.ijrmhm.2019.105030

T. Norfauzi, A.B. Hadzley, U.A.A. Azlan, Azhar, A. A., & S. Noorazizi. (2021). Effect Of Pressure On Density, Porosity And Flexural Strength During Cold Isostatic Press Of Alumina-Ysz-Chromia Cutting Tool. Journal of Physics. Conference Series, 1793(1), 012073–012073. https://doi.org/10.1088/1742-6596/1793/1/012073

Kabir, K., Chavara, D. T., Toppler, K., Saleh, M., Ruys, A. J., & Vladimir Luzin. (2016). Neutron Diffraction Measurements of Residual Stress and Mechanical Testing of Pressure Sintered Metal-Ceramic Composite Systems. Materials Research Proceedings. https://doi.org/10.21741/9781945291173-92

Bolzon, G., & Pitchai, P. (2021). The influence of imperfect interfaces on the measurable effective properties of ceramic composites. Composite Interfaces, 1–20. https://doi.org/10.1080/09276440.2021.1942716

Kini, M. K. (2018). Grain boundary crystallography in polycrystalline yttria-stabilised cubic zirconia. The Philosophical Magazine a Journal of Theoretical Experimental and Applied Physics, 98(20), 1865–1883. https://doi.org/10.1080/14786435.2018.1464677

Edwin Spartakovych Gevorkyan, Volodymyr Pavlovych Nerubatskyi, Oksana

Mykolaivna Morozova, Dmytro Semenovych Sofronov, Volodymyr Oleksiyovych Chyshkala, & Liudmyla Volodymyrivna Voloshyna. (2022). DEVELOPMENT of CERAMIC MATERIALS ZrO2–CeO2 of BIOENGINEERING APPLICATIONS. Zbìrnik Naukovih Prac′ Ukraïns′koï Deržavnoï Akademìï Zalìzničnogo Transportu/Zbìrnik Naukovih Prac′, 199,6–16. https://doi.org/10.18664/19947852.199.2022.258543

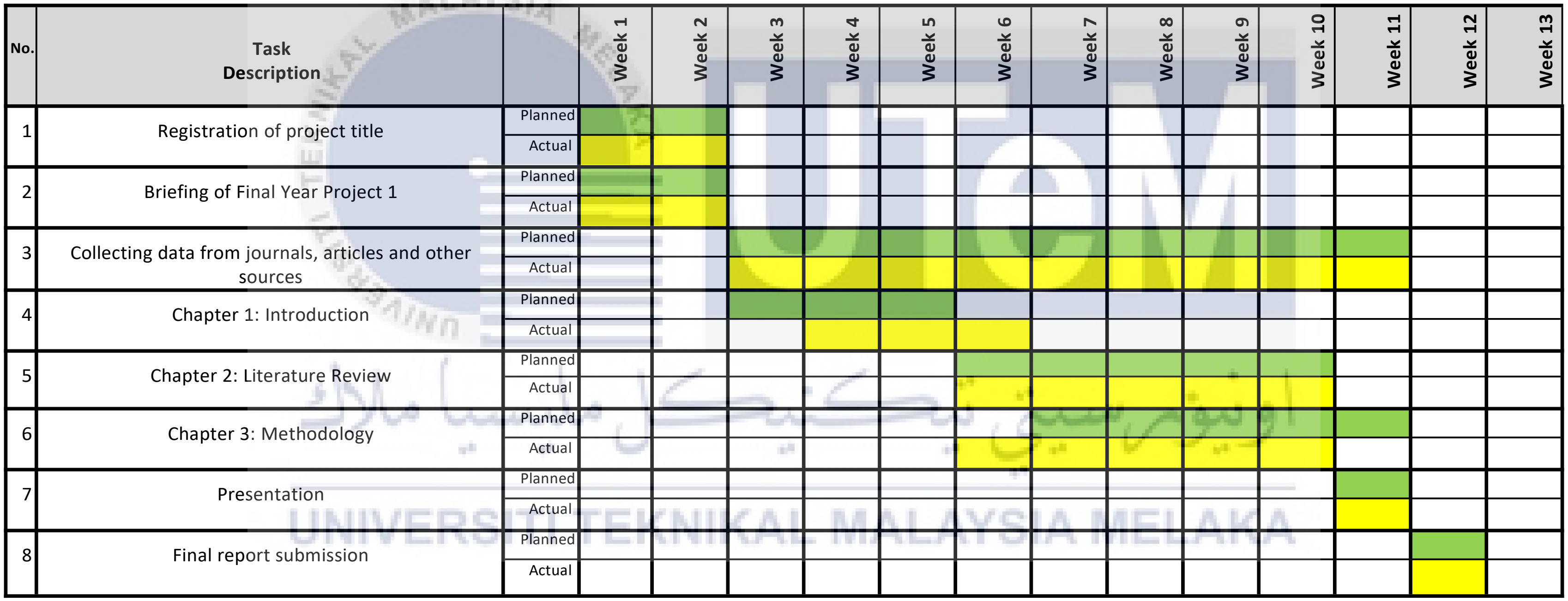
Dolores, M., Shynar Kultayeva, & Kim, Y.-W. (2022). Improved mechanical strength and thermal resistance of porous SiC ceramics with gradient pore sizes. Journal of the European Ceramic Society, 42(15), 6785–6794. https://doi.org/10.1016/j.jeurceramsoc.2022.09.001

Peyman Khajavi, Chevalier, J., Peter Vang Hendriksen, Tavacoli, J. W., Laurent Gremillard, & Henrik Lund Frandsen. (2020). Double Torsion testing of thin porous zirconia supports for energy applications: Toughness and slow crack growth assessment. Journal of the European Ceramic Society, 40(8),3191–3199. https://doi.org/10.1016/j.jeurceramsoc.2020.02.019

Lin, Y., Zhao, D., Yu, Z., Wang, J., Cao, M., Jiang, D., Zhang, X., Song, Y., Liu, H., Gao, C., & Han, Y. (2022). Pressure-Induced Abnormal Electrical Transport Transition from Pure Electronic to Mixed Ionic–Electronic in Multiferroic BiFeO3 Ceramics. Journal of Physical Chemistry. C./Journal of Physical Chemistry. C, 126(51), 21833–21838. https://doi.org/10.1021/acs.jpcc.2c07107

APPENDICES

APPENDIX A



Final Year Project 1 Gantt Chart

Name: Nur Asyilah Binti Awang Ngah
Project: Effect of Different Pressure Forces On The Dense-Porous Layers of Ceramics

No.	Task Description		Week 1	Week 2	Week 3	Week 4	Week 5	Week 6	Week 7	Week 8	Week 9	Week 10	Week 11	Week 12	Week 13
1	Registration of project title	Planned	🟩	🟩											
		Actual	🟨	🟨											
2	Briefing of Final Year Project 1	Planned	🟩	🟩											
		Actual	🟨	🟨											
3	Collecting data from journals, articles and other sources	Planned			🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩		
		Actual			🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨		
4	Chapter 1: Introduction	Planned			🟩	🟩	🟩								
		Actual				🟨	🟨	🟨							
5	Chapter 2: Literature Review	Planned						🟩	🟩	🟩	🟩	🟩			
		Actual						🟨	🟨	🟨	🟨	🟨			
6	Chapter 3: Methodology	Planned							🟩	🟩	🟩	🟩	🟩		
		Actual						🟨	🟨	🟨	🟨	🟨			
7	Presentation	Planned											🟩		
		Actual											🟨		
8	Final report submission	Planned												🟩	
		Actual												🟨	

APPENDIX B

Final Year Project 2 Gantt Chart

Name: Nur Asyilah Binti Awang Ngah
Project: Effect of Different Pressure Forces On The Dense-Porous Layers of Ceramics

No.	Task Description		Week 1	Week 2	Week 3	Week 4	Week 5	Week 6	Week 7	Week 8	Week 9	Week 10	Week 11	Week 12	Week 13	Week 14	Week 15
1	Project's Title Exchange Registration	Planned	🟩														
		Actual	🟨														
2	Briefing of Final Year Project 2	Planned	🟩	🟩													
		Actual	🟨	🟨													
3	Carrying Out An Experiment	Planned	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩						
		Actual	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨							
4	Chapter 4: Result And Discussion	Planned								🟩	🟩	🟩	🟩	🟩			
		Actual							🟨	🟨	🟨	🟨	🟨	🟨			
5	Chapter 5: Conclusion And Recommendation	Planned												🟩	🟩		
		Actual													🟨		
6	Presentation	Planned														🟩	
		Actual														🟨	
7	Technical Report	Planned															🟩
		Actual															🟨
8	Final report submission	Planned															🟩
		Actual															🟨