



REPUBLIC OF TÜRKİYE

ALTINBAŞ UNIVERSITY

Institute of Graduate Studies

Mechanical Engineering

**INVESTIGATION ON THE MECHANICAL  
PROPERTIES OF COMPOSITE MATERIALS  
(PMMA AND SiO<sub>2</sub>) IN PROSTHESIS COMPLETE  
DENTURE**

**Veian Asgher Acbbar ACBBAR**

Master's Thesis

Supervisor

Assoc. Prof. Dr. Süleyman BAŞTÜRK

İstanbul, 2024

**INVESTIGATION ON THE MECHANICAL PROPERTIES OF  
COMPOSITE MATERIALS (PMMA AND SiO<sub>2</sub>) IN PROSTHESIS  
COMPLETE DENTURE**

**Veian Asgher Acbbbar ACBBAR**

Mechanical Engineering

Master's Thesis

ALTINBAŞ UNIVERSITY

2024

The thesis titled INVESTIGATION ON THE MECHANICAL PROPERTIES OF COMPOSITE MATERIALS (PMMA AND  $\text{SiO}_2$ ) IN PROSTHESIS COMPLETE DENTURE prepared by VEIAN ASGHER ACBBAR and submitted on 19/01/2024 has been **accepted unanimously** for the degree of Master of Science in Mechanical Engineering.

---

Assoc. Prof. Dr. Süleyman BAŞTÜRK

Supervisor

Thesis Defense Jury Members:

Assoc. Prof. Dr. Süleyman  
BAŞTÜRK.

Department of Mechanical  
Engineering,  
Altınbaş University

Asst. Prof. Dr. İbrahim KOÇ

Department of Mechanical  
Engineering ,  
Altınbaş University

Asst. Prof. Dr. Haydar UYANIK

School of Applied Science  
Pilotage,  
KTO Karatay University

I hereby declare that this thesis meets all format and submission requirements of a Master's thesis.

I hereby declare that all information/data presented in this graduation project has been obtained in full accordance with academic rules and ethical conduct. I also declare all unoriginal materials and conclusions have been cited in the text and all references mentioned in the Reference List have been cited in the text, and vice versa as required by the abovementioned rules and conduct.

Veian Asgher Acbbbar ACBBAR

Signature

## **PREFACE**

I would like to express my deep gratitude to my supervisor. Assoc. Professor Dr. Süleyman BAŞTÜRK a faculty member at Altınbaş University and head of the Department of Mechanical Engineering. For providing constant support during this research and invaluable guidance through many tips, instructions, and accurate information. I would also like to express my gratitude to the remaining teachers who carried out their academic responsibilities flawlessly. I also thank all the people who supported me, encouraged me, and gave me great advice and information.



## ABSTRACT

# INVESTIGATION ON THE MECHANICAL PROPERTIES OF COMPOSITE MATERIALS (PMMA AND SiO<sub>2</sub>) IN PROSTHESIS COMPLETE DENTURE

ACBBAR, Veian Asgher Acbbbar

M.Sc., Mechanical Engineering, Altınbaş University,

Supervisor: Assoc. Prof. Dr. Süleyman BAŞTÜRK

Date: 01/2024

Pages: 123

Dental materials are an academic discipline that pertains to the study of materials employed in dentistry, encompassing their physical, chemical, and mechanical properties as well as their manipulation. These properties are closely tied to dental practitioners' appropriate selection and utilization of these materials. The field of dental materials facilitates the comprehension of the properties and characteristics of these substances, the appropriate selection for utilization in patients, and the optimal methods for their application. This research aimed to produce and characterize polymer matrix composites PMC for prosthesis. A complete denture polymer matrix was synthesized through nanoparticles added to poly (methyl methacrylate) PMMA. The current study aims to investigate the effect of particle size (nano and micro size) of reinforcement material for composite samples consisting of PMMA with different percentages such as 1, 2, 3, and 4% on the mechanical properties of samples in dental applications. The mechanical properties were investigated by fracture toughness, impact test, and microhardness test for samples prepared by PMMA with different nano and microparticle sizes. The obtained results demonstrate that the hardness increased with increasing percentages for both particle sizes, micro and nano, while the impact strength and fracture toughness were reduced.

**Keywords:** Prosthesis Complete Denture, Nano Particles, Micro Particle, PMMA, Aluminum.

# TABLE OF CONTENTS

|                                                             | <u>Pages</u> |
|-------------------------------------------------------------|--------------|
| <b>ABSTRACT .....</b>                                       | <b>vi</b>    |
| <b>LIST OF TABLES.....</b>                                  | <b>xi</b>    |
| <b>LIST OF FIGURES.....</b>                                 | <b>xii</b>   |
| <b>LIST OF SYMBOLS.....</b>                                 | <b>xvii</b>  |
| <b>1. INTRODUCTION .....</b>                                | <b>1</b>     |
| 1.1 TYPES OF COMPOSITE MATERIALS .....                      | 2            |
| 1.2 POLYMER .....                                           | 3            |
| 1.3 PROBLEM STATEMENT.....                                  | 5            |
| 1.4 AIMS & OBJECTS .....                                    | 5            |
| 1.5 THESIS LAYOUT .....                                     | 6            |
| <b>2. LITERATURE REVIEW .....</b>                           | <b>7</b>     |
| 2.1 INTRODUCTION .....                                      | 7            |
| 2.2 FIBER-REINFORCED COMPOSITE MATERIALS .....              | 8            |
| 2.3 IMPACT FACTOR OF MECHANICS OF COMPOSITE MATERIALS ..... | 10           |
| 2.4 PHASES IN COMPOSITES .....                              | 11           |
| 2.5 COMPOSITE MANUFACTURING METHODS .....                   | 12           |
| 2.5.1 Open Contact Molding.....                             | 12           |
| 2.5.2 Resin Infusion Processes.....                         | 14           |
| 2.5.3 Compression Molding.....                              | 16           |
| 2.5.4 Injection Moulding.....                               | 17           |
| 2.5.5 Filament Winding .....                                | 18           |
| 2.5.6 Pultrusion Process .....                              | 18           |
| 2.5.7 Automated Fibre Placement.....                        | 19           |
| 2.5.8 Additive Manufacturing.....                           | 20           |

|                                                         |           |
|---------------------------------------------------------|-----------|
| 2.6 BIOMEDICAL MATERIALS .....                          | 21        |
| 2.6.1 Metallic Biomaterials .....                       | 23        |
| 2.6.2 Ceramic Materials .....                           | 24        |
| 2.6.3 Polymeric Biomaterials .....                      | 26        |
| 2.7 DENTAL APPLICATIONS .....                           | 27        |
| 2.7.1 Recent Development in The Polymer Blend.....      | 29        |
| 2.7.2 Characterization Technique of Polymer Blend ..... | 31        |
| 2.8 PMMA .....                                          | 32        |
| 2.8.1 Properties .....                                  | 34        |
| 2.8.2 Modification of Properties.....                   | 35        |
| 2.8.3 Applying PMMA Dentistry.....                      | 36        |
| 2.8.4 PMMA Popularity .....                             | 37        |
| 2.8.5 Multilayer Dental PMMA .....                      | 37        |
| 2.9 FRACTURE OF DENTURES .....                          | 38        |
| 2.9.1 Causes of Fracture.....                           | 39        |
| 2.9.2 Modes of Fracture .....                           | 39        |
| 2.9.2.1 Impact fracture .....                           | 40        |
| 2.9.2.2 Fatigue fracture .....                          | 41        |
| 2.10 TYPES OF DENTURE BASE MATERIALS DEFECTS .....      | 42        |
| 2.10.1 Porosity .....                                   | 42        |
| 2.10.2 Crazeing .....                                   | 43        |
| 2.10.3 Warpage in Denture .....                         | 44        |
| <b>3. EXPERIMENTAL STUDIES.....</b>                     | <b>45</b> |
| 3.1 INTRODUCTION .....                                  | 45        |
| 3.2 CLASSIFICATION OF DENTURE BASE MATERIALS .....      | 45        |
| 3.2.1 Composition of Acrylic Denture Base .....         | 46        |
| 3.2.2 Powder .....                                      | 46        |

|                                                                     |    |
|---------------------------------------------------------------------|----|
| 3.2.3 Liquid .....                                                  | 48 |
| 3.2.4 Pour Acrylic Resins (Fluid Acrylic Resins) Denture Base ..... | 49 |
| 3.2.5 Techniques of Acrylic Resin Polymerization.....               | 50 |
| 3.2.6 Heat-Activated Acrylic Denture Base.....                      | 50 |
| 3.2.7 Chemically (Self) Activated Acrylic Denture Base .....        | 52 |
| 3.2.8 Rapid Heat Polymerized Acrylic Resin .....                    | 52 |
| 3.2.9 Visible Light Activated Acrylic Denture Base .....            | 52 |
| 3.3 MATERIALS AND SAMPLE PREPARATION .....                          | 54 |
| 3.3.1 Matrix material (PMMA denture base resin) .....               | 54 |
| 3.3.2 Reinforcing Materials.....                                    | 55 |
| 3.3.2.1 Particles reinforcement.....                                | 56 |
| 3.4 SPECIMENS GROUPING.....                                         | 56 |
| 3.5 GENERAL PREPARATION OF TEST SPECIMENS .....                     | 57 |
| 3.5.1 Mould Preparation.....                                        | 57 |
| 3.5.2 Proportioning and Mixing of Acrylic.....                      | 57 |
| 3.5.3 Curing Cycle Employed.....                                    | 58 |
| 3.5.4 Cooling Process.....                                          | 58 |
| 3.5.5 Finishing and Polishing.....                                  | 59 |
| 3.6 CONDITIONING OF THE ACRYLIC SPECIMENS.....                      | 59 |
| 3.6.1 Preparation of Hybrid Laminated Composites Specimens .....    | 60 |
| 3.7 MECHANICAL PROPERTIES .....                                     | 60 |
| 3.7.1 Tensile Test .....                                            | 61 |
| 3.7.2 Compression Test.....                                         | 62 |
| 3.7.3 Flexural Test.....                                            | 63 |
| 3.7.4 Impact Test.....                                              | 65 |
| 3.7.5 Hardness Test .....                                           | 67 |
| 3.7.6 Corrosion Test.....                                           | 69 |

|                                                 |           |
|-------------------------------------------------|-----------|
| 3.8 MORPHOLOGY TESTS .....                      | 71        |
| 3.8.1 Light Optical Microscope (LOM) Test ..... | 71        |
| <b>4. RESULTS AND DISCUSSIONS.....</b>          | <b>72</b> |
| 4.1 INTRODUCTION .....                          | 72        |
| 4.2 MECHANICAL TESTS .....                      | 72        |
| 4.2.1 Hardness Test Results .....               | 72        |
| 4.2.2 Impact Test Results .....                 | 75        |
| 4.2.3 Modulus of Elasticity .....               | 80        |
| 4.2.4 Compressive Strength .....                | 82        |
| 4.2.5 Tensile Strength .....                    | 85        |
| 4.3 ANTIBACTERIAL TEST RESULTS .....            | 89        |
| 4.4 MORPHOLOGY TESTS .....                      | 91        |
| <b>5. CONCLUSION AND RECOMMENDATION.....</b>    | <b>96</b> |
| 5.1 INTRODUCTION .....                          | 96        |
| 5.2 RECOMMENDATIONS.....                        | 97        |
| <b>REFERENCES .....</b>                         | <b>98</b> |

## LIST OF TABLES

|                                                                                                                                  | <u>Pages</u> |
|----------------------------------------------------------------------------------------------------------------------------------|--------------|
| Table 2.1: Biomaterials Uses .....                                                                                               | 23           |
| Table 2.2: Ceramic Utilized for Biomedical Purposes .....                                                                        | 26           |
| Table 2.3: Polymeric Biomaterials Usage .....                                                                                    | 27           |
| Table 3.1: Classification and Polymerization Temperature of Denture Base Materials According to EN ISO 20795-1:2008 .....        | 46           |
| Table 3.2: Comparing Compositions of Heat Activated and Chemically (Self) Activated PMMA Resins .....                            | 53           |
| Table 3.3: Comparison of Properties of Heat and Chemically (Self) Cured PMMA Resin .....                                         | 54           |
| Table 3.4: Various Mechanical Features of Pour PMMA Polymer Utilized in this Investigation Based on (Vertex–Dental Company)..... | 55           |
| Table 3.5: Sets of PMMA Composite Materials and Hybrid Laminated Composite Materials That Produced in This Investigation .....   | 56           |
| Table 3.6: Chemical of Saliva Solution.....                                                                                      | 69           |
| Table 4.1: Summary of the Obtained Results.....                                                                                  | 88           |
| Table 4.2: Isolated Bacteria Kinds from the Specimens .....                                                                      | 90           |

## LIST OF FIGURES

|                                                                                                | <u>Pages</u> |
|------------------------------------------------------------------------------------------------|--------------|
| Figure 1.1: Components Of Composite Materials.....                                             | 1            |
| Figure 2.1: Composite Materials Matrices Organization .....                                    | 8            |
| Figure 2.2: Clarifying The Composite Composite Phases .....                                    | 11           |
| Figure 2.3: Process Of Hand Lay-Up .....                                                       | 13           |
| Figure 2.4: The Graphic Process Of The Spray Lay-Up .....                                      | 14           |
| Figure 2.5: The Representation Of The RTM Process .....                                        | 15           |
| Figure 2.6: The Representation Of The VARTM Process .....                                      | 15           |
| Figure 2.7: The Representation Of The Resin Film Infusion Process.....                         | 16           |
| Figure 2.8: The Representation Of The Compression Molding Process.....                         | 17           |
| Figure 2.9: Simplified Diagram Of The Moulding Process .....                                   | 17           |
| Figure 2.10: The Representation Of The Filament Winding Process.....                           | 18           |
| Figure 2.11: The Representation Of The Pultrusion Process .....                                | 19           |
| Figure 2.12: The Representation Of The Automated Fibre-Placement Process.....                  | 20           |
| Figure 2.13: The Representation Of The 3D Printing Process For Polymer Composites..            | 21           |
| Figure 2.14: Chemical Composition Polymethyl Methacrylate .....                                | 33           |
| Figure 2.15: Using Of PMMA Teeth .....                                                         | 36           |
| Figure 2.16: Applying PMMA In The Dental Field.....                                            | 38           |
| Figure 2.17: Images For Various Locations Of Fracture For The Prosthetic Denture.....          | 39           |
| Figure 2.18: The Images Depicting Various Modes Of Fracture Occur In Prosthetic Dentures ..... | 40           |
| Figure 2.19: Images Of Impact Fracture In The Prosthetic Denture .....                         | 41           |
| Figure 2.20: Images Of Fatigue Fracture In The Prosthetic Denture .....                        | 42           |

|                                                                                                                                                 |    |
|-------------------------------------------------------------------------------------------------------------------------------------------------|----|
| Figure 2.21: Various Types Of Defects That Occur In Prosthetic Denture .....                                                                    | 42 |
| Figure 2.22: Images Of Porosity Defect In The Prosthetic Denture .....                                                                          | 43 |
| Figure 2.23: Images Of Craze Defect In The Prosthetic Denture .....                                                                             | 44 |
| Figure 2.24: Images Of Warpage In The Prosthetic Denture .....                                                                                  | 44 |
| Figure 3.1: Chemical Formula Of (MMA) Monomer .....                                                                                             | 48 |
| Figure 3.2: PMMA Resin Kind (Castavaria) Utilized In This Investigation.....                                                                    | 55 |
| Figure 3.3: Casting Samples For Standard Of Tensile Test Sample. ....                                                                           | 59 |
| Figure 3.4: Representation For Standard Of Compression Test Sample.....                                                                         | 62 |
| Figure 3.5: Representation Of Stress In The Test Sample .....                                                                                   | 63 |
| Figure 3.6: Shear Distribution Impact Testing Sample .....                                                                                      | 65 |
| Figure 3.7: Diagram For Standard Impact Testing Sample .....                                                                                    | 67 |
| Figure 3.8: Specimen Of Impact Test Before And After Conducting The Test.....                                                                   | 67 |
| Figure 3.9: Representation Standard Specimen Of Hardness Test.....                                                                              | 68 |
| Figure 3.10: Schematic Specimen Standard Specimen Of Hardness Test .....                                                                        | 69 |
| Figure 3.11: Representation Of The Corrosion Test Sample. ....                                                                                  | 70 |
| Figure 3.12: Light Optical Microscope .....                                                                                                     | 71 |
| Figure 4.1: Hardness Magnitudes For PMMA Samples After Adding Micro-Sio <sub>2</sub> In Various Ratios.....                                     | 73 |
| Figure 4.2: Hardness Magnitudes For PMMA Samples After Adding Nano-Sio <sub>2</sub> In Various Ratios.....                                      | 73 |
| Figure 4.3: The Differences Between Hardness Magnitudes For PMMA Before And After Adding Sio <sub>2</sub> In Nano And Micro Particle Size. .... | 74 |
| Figure 4.4: Hardness Improvement Rate For PMMA Samples After Adding Various Ratios Of Nano And Micro-Sio <sub>2</sub> .....                     | 75 |
| Figure 4.5: Impact Magnitudes For PMMA Samples After Adding Micro-Sio <sub>2</sub> In Various Ratios.....                                       | 76 |

|                                                                                                                                       |    |
|---------------------------------------------------------------------------------------------------------------------------------------|----|
| Figure 4.6: Impact Magnitudes For PMMA Samples After Adding Nano-Sio2 In Various Ratios.....                                          | 76 |
| Figure 4.7: The Differences Between Impact Magnitudes For PMMA Before And After Adding Sio2 In Nano And Micro Particle Size .....     | 77 |
| Figure 4.8: Impact Improvement Rate For PMMA Samples After Adding Various Ratios Of Nano And Micro-Sio2 .....                         | 77 |
| Figure 4.9: Fracture Toughness Magnitudes For PMMA Samples After Adding Micro-Sio2 In Various Ratios .....                            | 78 |
| Figure 4.10: Fracture Toughness For PMMA Samples After Adding Nano-Sio2 In Various Ratios.....                                        | 78 |
| Figure 4.11: The Differences Between Fracture Toughness For PMMA Before And After Adding Sio2 In Nano And Micro Particle Size .....   | 79 |
| Figure 4.12: Fracture Toughness Improvement Rate For PMMA Samples After Adding Various Ratios Of Nano And Micro-Sio2 .....            | 79 |
| Figure 4.13: Modulus Of Elasticity Magnitudes For PMMA Samples After Adding Micro-Sio2 In Various Ratios.....                         | 81 |
| Figure 4.14: Modulus Of Elasticity Magnitudes For PMMA Samples After Adding Nano-Sio2 In Various Ratios.....                          | 81 |
| Figure 4.15: The Differences Between Elasticity Modulus For PMMA Before And After Adding Sio2 In Nano And Micro Particle Size .....   | 82 |
| Figure 4.16: Modulus Of Elasticity Improvement Rate For PMMA Samples After Adding Various Ratios Of Nano And Micro-Sio2. ....         | 82 |
| Figure 4.17: Compressive Strength Magnitudes For PMMA Samples After Adding Micro Sio2 In Various Ratios.....                          | 83 |
| Figure 4.18: Compressive Strength Magnitudes For PMMA Samples After Adding Nanosio2 In Various Ratios.....                            | 84 |
| Figure 4.19: The Differences Between Compressive Strength For PMMA Before And After Adding Sio2 In Nano And Micro Particle Size ..... | 84 |

|                                                                                                                                   |    |
|-----------------------------------------------------------------------------------------------------------------------------------|----|
| Figure 4.20: Compressive Strength Improvement Rate For PMMA Samples After Adding Various Ratios Of Nano And Micro-Sio2 .....      | 85 |
| Figure 4.21: Tensile Strength Magnitude For PMMA Samples After Adding Micro-Sio2 In Various Ratios .....                          | 86 |
| Figure 4.22: Tensile Strength Magnitud For PMMA Samples After Adding Nano-Sio2 In Various Ratios .....                            | 86 |
| Figure 4.23: The Differences Between Tensile Strength For PMMA Before And After Adding Sio2 In Nano And Micro Particle Size ..... | 87 |
| Figure 4.24: Tensile Strength Improvement Rate For PMMA Samples After Adding Various Ratios Of Nano And Micro-Sio2.....           | 87 |
| Figure 4.25: Appears Kinds Of Bacteria On Specimen PMMA General Medium (Nutrient Agar).....                                       | 89 |
| Figure 4.26: Appears Kinds Of Bacteria Of PMMA- 1% Msio2 Sample On Standard Medium (Nutrient Agar).....                           | 90 |
| Figure 4.27: Appears Kinds Of Bacteria Of PMMA And PMMA- 1% Msio2 Samples On (Blood Agar).....                                    | 90 |
| Figure 4.28: Pure PMMA. ....                                                                                                      | 92 |
| Figure 4.29: (PMMA-1% Micro-Silicon Oxide) Composite .....                                                                        | 93 |
| Figure 4.30: (PMMA-1% Nano-Silicon Oxide) Composite.....                                                                          | 93 |
| Figure 4.31: (PMMA-2% Micro-Silicon Oxide) Composite .....                                                                        | 94 |
| Figure 4.32: (PMMA-2% Nano-Silicon Oxide) Composite.....                                                                          | 94 |
| Figure 4 .33: (PMMA-3% Micro-Silicon Oxide) Composite.....                                                                        | 94 |
| Figure 4.34: (PMMA-3% Nano-Silicon Oxide) Composite.....                                                                          | 95 |
| Figure 4.35: (PMMA-4% Micro-Silicon Oxide) Composite .....                                                                        | 95 |
| Figure 4.36: (PMMA-4% Nano-Silicon Oxide) Composite.....                                                                          | 95 |

## **ABBREVIATIONS**

|       |   |                                        |
|-------|---|----------------------------------------|
| CF    | : | Carbon Fiber                           |
| CFRP  | : | Carbon Fiber Reinforced Polymers       |
| CMC   | : | Ceramic Matrix Composites              |
| FRP   | : | Fiber Reinforced Polymer               |
| MMC   | : | Metal Matrix Composites                |
| PA    | : | Pitch Angle In The Earth Frame         |
| PMMA  | : | Polymethylmethacrylate                 |
| PMC   | : | Polymer Matrix Composites              |
| PP    | : | Polypropylene                          |
| PRP   | : | Platelet-Rich Plasma                   |
| PVC   | : | Polyvinylchloride                      |
| RFI   | : | Resin Film Infusion                    |
| RTM   | : | Resin Transfer Molding                 |
| SEM   | : | Scan Electron Microscopy               |
| VARTM | : | Vacuum-Assisted Resin Transfer Molding |

## LIST OF SYMBOLS

|                 |   |                                   |
|-----------------|---|-----------------------------------|
| $\tau_{\max}$   | : | Max. Shear Stress                 |
| $E$             | : | Modulus Of Elasticity             |
| $E_b$           | : | Modulus Of Elasticity In Bending. |
| $\sigma$        | : | Stress                            |
| $\delta$        | : | Deflection Of Specimen            |
| $\varphi$       | : | Pitch Angle In The Earth Frame    |
| $\varepsilon$   | : | Strain                            |
| $F$             | : | Applied Load                      |
| $b$             | : | Width Of Specimen                 |
| $d$             | : | Thickness Of Specimen             |
| $K_c$           | : | Fracture Toughness                |
| $G_C$           | : | Toughness Of Material             |
| $\omega^B$      | : | Angular Velocity                  |
| $A$             | : | Cross-Sectional Area              |
| $\Delta L$      | : | Elongation                        |
| $x_1, x_2, x_3$ | : | Independent Variables             |
| $L_o$           | : | Original Length                   |
| $L$             | : | Length Of Specimen                |
| $U_C$           | : | Impact Energy                     |
| $X$             | : | Volume Fraction.                  |

|                 |   |                                       |
|-----------------|---|---------------------------------------|
| $Y$             | : | Response                              |
| $Z$             | : | Particles Size                        |
| $I$             | : | Moment Of Inertia                     |
| $R$             | : | Coefficient Of Multiple Determination |
| $SSE$           | : | Sum Of Squared Error                  |
| $SSR$           | : | Regression Sums Of Squares.           |
| $e$             | : | Error Of The Response                 |
| $a_1, a_2, a_3$ | : | Regression Coefficients               |

## 1. INTRODUCTION

The term "composite material" refers to a solid material that is produced once two or more distinct substances, each of which possesses its own characteristics, have been merged to produce a brand-new material whose characteristics seem to be better compared to those of the original materials once applied to a particular purpose. This new substance is referred to as composite material. To be more precise, when people talk about composites, they are referring to a structural material (like plastic) that has another fiber material (like carbon fiber) inserted inside of it [1]. The extraordinary capabilities of composites are accomplished by encapsulating fibers of one substance inside the matrix of another material that serves as the host. Although the structural magnitude of a collection of fibers as a whole is modest, the strength of the individual fibers might be utilized when they are encased in a matrix that performs the function of an adhesive and binds the fibers together while also providing the material with a sense of solidity [2]. Whereas the stiff fibers are responsible for the composite's structural strength, the matrix is responsible for protecting the fibers from physical damage and environmental stress and providing the fibers with thermal stability. The mix of fibers and matrix also lessens the likelihood of a complete fracture; when one fiber breaks, the crack might not expand to adjacent fibers, but a crack that begins in a monolithic (or single) material would often continue to spread until the material fails completely [3]. Figure 1.1 illustrates the various components that make up composite materials.

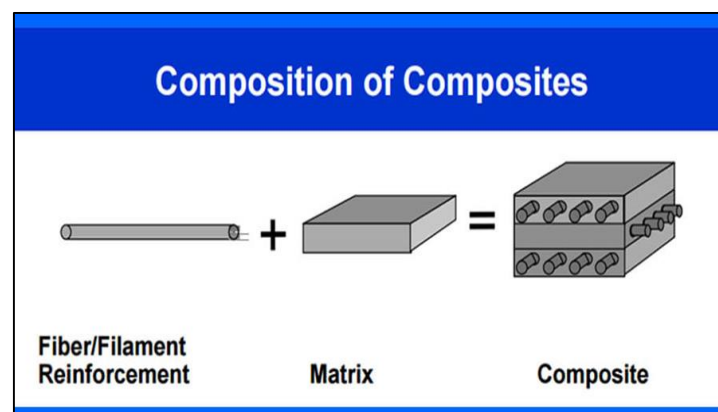


**Figure 1.1:** Components of Composite Materials [4].

The majority of traditional composites are constructed similarly to plywood in that they are made up of thin layers, each of which is reinforced by long fibers put down in a single direction. Plywood is one of the most common types of composite material. These materials can only boast increased strength when the fibers run in the same direction. When producing composites, the fibers were woven into a 3D structure laying along three axes that seem to be mutually perpendicular to one another. This allows the composites to be strong in all directions [5].

The structural part of a composite can be made up of tungsten-boron filaments, aluminum oxide or silicon carbide "whiskers," or even carbon-graphite or glass fibers. The matrix material might be an epoxy resin high-temp plastic, aluminum or another type of metal, or a ceramic including silicon nitride. Another possibility is that the matrix material could be a metal [6]. The most well-known composite is fiberglass-reinforced plastic, which has widely been used in various items, including those utilized in the industrial and domestic spheres. Nevertheless, composites find their most widespread applications in the aerospace sector. Due to their exceptional rigidity, low weight, and resilience to heat, composites are the materials for strengthening aircraft flaps, doors, wings, and engine cowls. In addition to being utilized in rackets and other types of sporting equipment, composite materials might also be found in cutting tools and some components of car engines [6], [7].

## **1.1 TYPES OF COMPOSITE MATERIALS**

Humans have been utilizing composite materials for thousands of years. In the ancient realm, nearly 3400 B.C., the ingenious Mesopotamians, nestled in the cradle of Iraq, orchestrated a groundbreaking feat in engineering—the inception of the earliest artificial composites. Their mastery paved the way for a legacy that would resonate through the corridors of time [8]. To make plywood, the ancient people layered thin strips of wood and glued them on top of each other at varying degrees of angle. After this, in the year 2181 B.C., the Egyptians began to manufacture death masks out of linen or papyrus that had been soaked in plaster [9]. These masks were then worn at funerals. Times, mud bricks, pottery, and boats of each of these cultures were strengthened by adding straw as a material reinforcement.

These masks were then worn at funerals. In later times, mud bricks, pottery, and boats of each of these cultures were strengthened by adding straw as a material reinforcement. After

the advent of the Industrial Revolution, scientists discovered how to polymerize synthetic resins, which allowed them to be cast into solid forms. In the early 1900s, newly discovered information about chemicals permitted for the development of a several various types of plastic [10], including polyester, phenolic, and vinyl. After that, synthetics began to be produced. In the annals of scientific ingenuity, a luminary named Leo Baekeland conceived the revolutionary notion that birthed Bakelite. Endowed with the unique capability of resisting electrical conductivity and bravely enduring soaring temperatures, Bakelite emerged as a versatile marvel with the potential to permeate myriad sectors, leaving an indelible mark on the innovation landscape [11].

The 1930s were a of pivotal decade for developing composites and other advanced materials. Owens Corning was the company that pioneered the use of glass fiber and also established the first fiber-reinforced polymer (FRP) business [12]. Resins developed throughout this period remain in widespread usage even now, and in 1936, the patent for unsaturated polyester resins was issued. After another year had passed, higher-performance resin solutions were finally made available [13], instances of composite materials include [14]:

- a. Plastics strengthened with fibers such as glass fiber or other.
- b. Metallic matrix composite materials.
- c. Ceramics matrix composite materials
- d. Ceramics-metals composite materials.
- e. Concretes.
- f. Wood composites: engineered wood including plywood, and oriented strand board (OSB).

## **1.2 POLYMER**

Polymers, which are sizable molecules, are formed through the chemical bonding of many components. The etymology of the word "polymer" can be traced back to the Greek phrase meaning "many pieces" [15]. Scientists refer to each of these individual components as a monomer, which comes from the Greek word for "one portion." View a polymer as a sequence of monomers, where each monomer links in the chain. These monomers can range from simple structures consisting of one, two, or three atoms to complex cyclic structures including twelve or more atoms. Polymers occasionally exhibit the formation of branched

networks rather than existing as individual chains [16]. The molecules are extremely big, regardless of their shape. They are classified as macromolecules by scientists because of their size. Hundreds of thousands or even millions of atoms might be found in polymer chains. As a polymer chain lengthens, its weight increases. Longer polymers typically exhibit higher melting and boiling points when used in material synthesis. Furthermore, the viscosity of a polymer rises with its length, indicating increased resistance to liquid flow. This phenomenon is attributed to the larger surface area of longer chains, which promotes their affinity for adjacent molecules.

Polymer structures might consist of two distinct parts. All begin with a fundamental chain of ionic connections. Its backbone is sometimes referred to as this. Some of them could additionally include extra components that hang from some (or all) of the links in the chain. A single atom might serve as one of these attachments [17]. Others could be more intricate and are known as pendant groupings. These groups hang off the main chain of the polymer for the same reason that individual charms on a charm bracelet dangle off the bracelet's chain [18]. Because they are more exposed to their surroundings than the atoms that make up the chain itself, these "charms" frequently can regulate how a polymer interacts with both it and other things that are present in the environment. Instead of just hanging from one polymer chain, pendant groups will sometimes actually connect two of them. (Consider how this would resemble a ladder rung extending between the legs.) These connections are called crosslinks by chemists. They often strengthen a substance consisting of this polymer (as plastic). They also increase the polymer's hardness and meltability. Nevertheless, a material gets more flexible the longer the crosslinks last [19].

Polymers have a wide range of structural, chemical, and physical characteristics. Numerous areas, including electronics, medicine, biophysics, and other science and technology sectors, might use them [20]. Biomedical polymers stand out due to their unique application-specific features, reduced in vivo toxicity, ease of processing and sterilization, improved shelf life, and low weight. The present study explores the numerous medical fields where biomedical polymers are utilized [21]. Degradable polymers are employed in therapeutic applications such as surgical sutures and devices, among other uses. Materials possessing the necessary attributes of degradation, biomechanics, biology, chemistry, and physics should be selected in order to fulfil functional criteria.

### **1.3 PROBLEM STATEMENT**

The vulnerability of dentures to fractures is twofold, with flexural fatigue and impact standing as formidable adversaries. Recurrent bending induces flexural fatigue, which paves the way for structural failure. The insidious process unfolds gradually, with each seemingly inconspicuous load contributing to the emergence of small fractures in stress concentration zones. As stress intensifies, these fractures coalesce into a formidable, weakening fissure within the material. The coup de grace occurs during a final loading cycle that surpasses the mechanical threshold of the material's remaining resilient core, culminating in catastrophic breakdown.

Flexural fatigue is frequently the cause of the midline fracture in a denture. A quick blow to the denture or an unintentional drop while coughing, cleaning, or sneezing are the two main causes of impact failures outside of the mouth.

Therefore, the current study uses acrylic resin and polymethyl methacrylate (PMMA) (the materials most often used to make dentures) are utilized. Although this material is not perfect in every way, it is utilized and is popular because of several features rather than a single one. Regardless of its popularity in achieving aesthetic requirements, although it is feasible to develop a prosthesis that is indistinguishable with the appropriate level of clinical proficiency and a diverse selection of adjustable, artificially created acrylic teeth, it still falls short of being ideal in terms of fulfilling the mechanical requirements of a prosthesis. This is evident in the unresolved problem of denture fracture and the accompanying repair costs.

### **1.4 AIMS & OBJECTS**

Due to their mechanical qualities, polymers are often employed in producing of dental materials for teeth. The biocompatibility of the polymer nanocomposite materials was excellent. Compared to bracket materials that are readily accessible on the market, materials with a high filler content showed better micro-hardness, and polymer nanocomposites and Micro had the same thermal conductivity as natural teeth. The objective of the present study was to ascertain the impact of nanoparticles on the mechanical and structural properties of the PMMA mixture, which is utilized in the fabrication of dentures. The compressive strength demonstrates how each mechanical property enhances the qualities of the polymer.

Impact strength has been examined and employed as a dental mold; nanocomposite materials have been thought to be the most significant materials.

## **1.5 THESIS LAYOUT**

The five chapters that make up the present thesis are organized as follows:

The first chapter begins with an introduction that briefly discusses the topic, its importance, the issue, and the work's goal and purpose.

The second chapter is devoted to re-examining specific theoretical ideas related to the research and the literature review. The review's primary points center on the fundamentals of composite materials, biomedical applications of polymeric materials, and their chemistry, as well as the role of external influences influencing the characteristics and processes of composite materials.

A broad explanation of the goods and methods utilized in the experiment is given in the third chapter. The fundamental characteristics and distinctive characterizations of typical laboratory materials are discussed. Both the measurement tools and the basic process for producing specimens are described in detail. Detailed descriptions of testing procedures for examining mechanical characteristics and structures are frequently provided. The study's findings, process optimization, and analysis are presented in Chapter 4. Finally, Chapter 5 presents the dissertation's findings and suggestions.

## 2. LITERATURE REVIEW

### 2.1 INTRODUCTION

In the domains of medicine and dentistry, there are a lot of ready-made biomaterials. The term "biomaterial" refers to any material, artificial or natural, capable of forming an attachment with biological tissues. These materials may be categorized as ceramics, polymers, metals, or composites. Polymeric materials offer a broad range of uses for implants since they may be made with various compositions and can have various characteristics [22] .

Because of their superior mechanical properties, polymers have been an increasingly popular choice in recent years producing dental materials used in tooth restoration. The biocompatibility of the polymer nanocomposite materials is sufficient. Materials with a high filler ratio exhibit higher micro-hardness compared to commercially available polymer resources and bracket nanocomposites. These materials also possess similar thermal conductivity to tooth structure [23]. The features of compressive strength are believed to be crucial; this is described as mastication, a scale that examines brittle materials by the International Organization for Standardization's ISO: 9917 [24].

PMMA is often used to prepare the bases for both complete and partial dentures. The surface roughness of acrylic resins and systemic or local factors have been found to promote the growth of certain pathogens, such as *Streptococcus* mutants and *Candida albicans* [25]. The enhancement of oral hygiene has been accomplished, in general, through the use of antimicrobial mouthwashes and suitable tooth-brushing methods, in addition to using tablets for denture cleansing and prophylactic systemic antibiotic medications. However, all of those methods may be more effective in diminishing the efficacy of those infections. In recent years, there has been significant research interest focused on the use of acrylic resin as a broad-spectrum antibacterial substance [26] . Silver (Ag) salts have long been employed safeguard against Gram-positive and Gram-negative bacteria, fungi, protozoa, and viruses. Silver (Ag) and its compounds are currently being utilized to minimize the chances of infection in burn treatments, hinder bacterial growth on medical components, surgical textiles, bone cement, and dental materials, as well as purify water [27].

## 2.2 FIBER-REINFORCED COMPOSITE MATERIALS

At the forefront of material innovation, composite materials, marrying a polymeric matrix with fiber reinforcement, reign supreme. Their ascendancy is rooted in a delicate equilibrium, marrying the dual virtues of featherlight composition and exceptional mechanical prowess. This dynamic synergy becomes pivotal when the maintenance cost is intricately tied to the interplay between a product's mechanical attributes and weight. In such scenarios, these composite materials emerge as the discerning choice, eclipsing alternatives, particularly their more traditional metallic counterparts [28] .

Most high-performance composite materials use thermosetting matrices or resins as their primary components. Through a sequence of chemical processes collectively as called curing or cross-linking, such resins produce a solid, insoluble, and unmeltable end product. On the other hand, the thermoplastic ones will melt when subjected to heating [29].

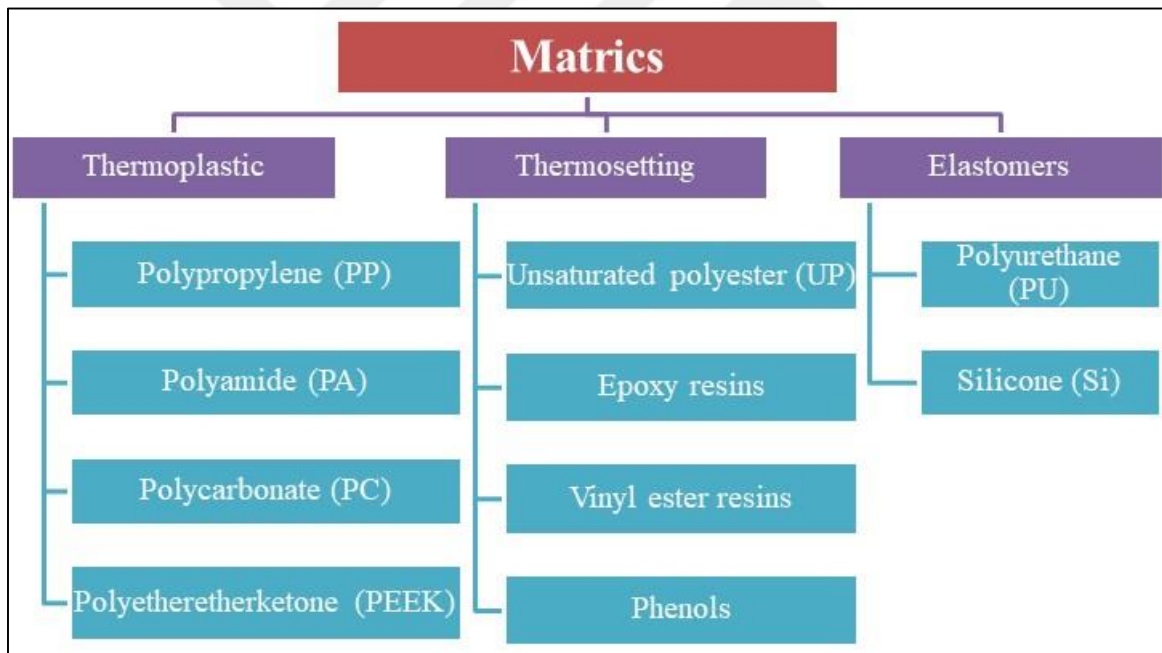


**Figure 2.1:** Composite materials matrices organization [30].

Composites may be divided into one of three categories according to the kind of matrix material they are made of. The abbreviations for these categories of composites are PMC for polymer matrix composites, CMC for ceramic matrix composites, and MMC for metal matrix composites [31]. Metal matrix composites have superior specific modulus, higher

strength, temperature resistance, and a lower coefficient of thermal expansion than monolithic metals. They are intensely used in space crafts, households, and other structural applications [32]. In ceramic matrix composites, natural clays and other ceramics impart toughness and physical strength to the composite and reduce the material cost. Polymer matrix composites are the most common and important type of composite. They are reinforced with other foreign materials to overcome the inferior mechanical characteristics of polymers. They need only simple machinery for processing with moderate temperature and pressure; thus, they have become prominent in structural applications. They have superior physical properties to neat polymers and are less brittle than ceramics[33].

Depending on the type of reinforcement used, polymer composites fall into one of several distinct classes. Structural polymer composites (SPC) include FRP, PRP, and SPC (fiber-reinforced polymer) [34]. In FRP, fibers are the primary source of strength because they are aligned properly over the matrix and absorb stress along their longitudinal directions. Glass fibers, natural fibers, carbon/graphite fibers, and metal oxides are the most commonly used reinforcing agents. Thermoplastic, as well as thermoset polymers, are reinforced with fibers. Particles make reinforced materials, including metals, minerals, carbon black, ceramics, and glass [35]. Within the intricate dance of material composition, particles wield a double-edged influence, diminishing the ductility of the matrix while embodying a trove of commendable attributes. These particles emerge as paragons of durability, possessing remarkable strength, unwavering stiffness, elevated thermal stability, and imperviousness to wear and corrosion. Their prowess extends further, serving as adept electrical and thermal insulators [36]. Enter polymers, architects of flexibility and resilience, harmoniously intervening to alleviate the inherent brittleness of ceramics and glasses. This strategic alliance propels polymers to the forefront of structural applications, displacing metals with finesse. Their ascendancy is underpinned by inherent advantages—streamlined processing and economic viability. The resultant offspring, polymer composites, unfold a panorama of applications as diverse as household utensils to the celestial abodes of spacecraft. This testament to versatility underscores their indelible imprint on the vast canvas of modern material science.

The critical fibers utilized as reinforcements are glass, carbon, boron, ceramic, metal, aramid, and natural fibers such as sisal, hemp, and flax. Fabrics, mats, and roving are all examples

of the many forms that fibers may take, depending on the sort of material from which they are formed. Additives and fillers are two further categories of items found in composite materials like fiber resin and are sometimes used in these materials. They are put in to bestow special qualities on the material or cut down on the price of the material. The overarching goal is to enhance the product's ability to be processed and the final product [37].

### **2.3 IMPACT FACTOR OF MECHANICS OF COMPOSITE MATERIALS**

As disparate materials unite on a grander scale, a composite material emerges—an elegant fusion showcasing the pinnacle attributes inherited from its origins. These composites gracefully unfold across four distinctive categories, each exuding its unique properties: fibrous, laminated, and particle composite materials. The third category, a harmonious medley, artfully weaves elements from any or all of its composite kin [38].

The unique structures of composite materials give rise to distinctive mechanical properties. These materials boast an unparalleled strength-to-density ratio and a discernible stiffness-to-density proportion, allowing them to serve various functions. It's crucial to acknowledge that not all composite materials showcase heightened qualities, though most do. The enhanced characteristics commonly found in composite materials are strength, aesthetics, corrosion resistance, thermal conductivity, fatigue life, and thermal insulation [39].

The mechanics of every composite material are different, and so is the impact factor of each kind. As an illustration, Formica, an example of a compound composite material, operates differently from concrete, frequent and widespread composite material. Composite materials are employed for various construction projects, ranging from bridges to the space shuttle. Composite materials are becoming more widespread because of their numerous benefits. These benefits include not only a decrease in costs and an increase in efficiency, but also the fact that they make possible activities impossible without composite materials [40].

The material characteristics of a composite with a homogeneous body are the same in all directions at a given point in the body. In contrast, the material characteristics of a composite with an isotropic body are the same in all directions at that point. Composite materials may exhibit both orthotropic and anisotropic properties. The orthotropic body has material qualities that vary in three directions and are mutually perpendicular. In contrast, the

anisotropic body contains material characteristics that vary in all directions at a given place inside the body [41] .

## 2.4 PHASES IN COMPOSITES

Often, composites reinforced with fibers and particles are predominantly composed of a continuous or nearly continuous phase known as the matrix. The material dispersed within this matrix is termed the dispersed phase ,as seen in Figure 2.2. When this dispersed phase is introduced to bolster the material's strength, it is commonly referred to as the reinforcing phase. Conversely, if added for cost-effective matrix augmentation without compromising composite qualities, it is labeled a filler, serving a distinct purpose in such instances. Moreover, a phase might function a bonding agent between various layers or phases, commonly acknowledged as the interface [42].

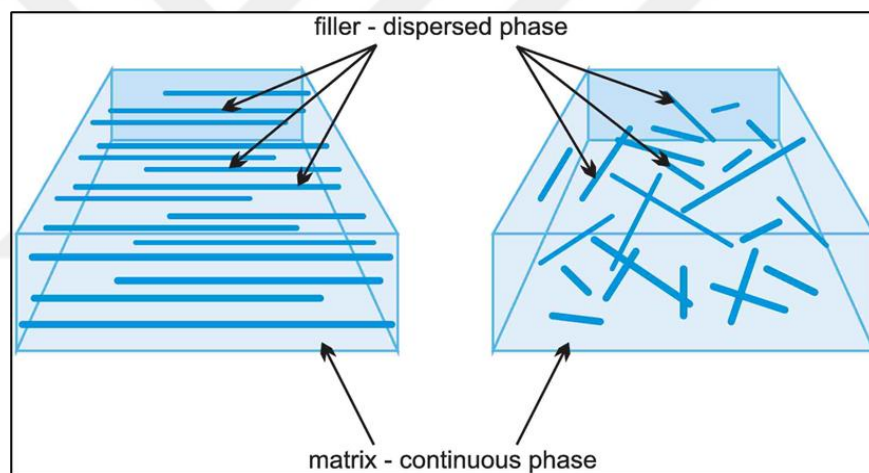


**Figure 2.2:** Clarifying the Composite Phases [43].

When developing composites, the following considerations need to be considered [44]:

- a. The matrix-to-dispersed phase ratio may be adjusted to suit the application requirements for which the composite is designed. The matrix phase may be the bulk material, which may or may not include particles or fibers scattered throughout it. It is also possible for it to be a minor phase, acting more like glue to bind the fibers or particles together, offering rigidity to what would otherwise be highly flexible fiber arrays and providing structure to what would otherwise be unstructured particles. The dispersed phase is shielded from both mechanical and chemical assault by the matrix, which serves another purpose in this

regard. Once the matrix is ductile, even when exposed to heavy wear, it limits the development of fractures between the fibers or particles.

- b. In crafting composite materials, the optimal packing density of particles and fibers within the dispersed phase is elegantly influenced by their size and form. The presence of longer fibers bestows unparalleled reinforcement, while smaller particles generously furnish a more extensive surface area, fostering intimate contact with the matrix. The orchestration of a delicate equilibrium between these factors is an absolute necessity for achieving excellence in composite design.
- c. Additionally, the contact between the matrix and the scattered phase determines how well the composite will operate as a whole. A composite's tensile strength is determined not only by the characteristics of its matrix but also by how effectively the matrix adheres to the particles and fibers that make up the dispersed phase.

## **2.5 COMPOSITE MANUFACTURING METHODS**

There are a few different approaches to taking composite materials through the manufacturing process. The selection of a specific technique for a given component depends on various factors, including the materials, part design, performance requirements, and intended end-use or application.

### **2.5.1 Open Contact Molding**

The fabrication of composite materials using hand lay-up is an example of an open-contact molding process. Fabrics may be woven, knitted, sewn, or bonded after manually injecting resins into the fibers that make them up. After applying a mold release agent to the mold, dry fibers or dry textiles are placed down on the mold, and then liquid resin is poured over the fiber beds and dispersed throughout them [45]. The composite often uses Rollers or brushes, but nip-roller-type impregnators are becoming more popular. These impregnators push resin into textiles utilizing revolving rollers submerged in a bath of resin. A roller or brush is employed to saturate the fibers and remove any trapped air within the lay-ups. Several levels of the fibers in the laminate are saturated with water, and subsequently, the

laminate is left to harden under typical atmospheric conditions. Once these layers had reached their final state of cure, more layers were applied, as seen in Figure 2.3.

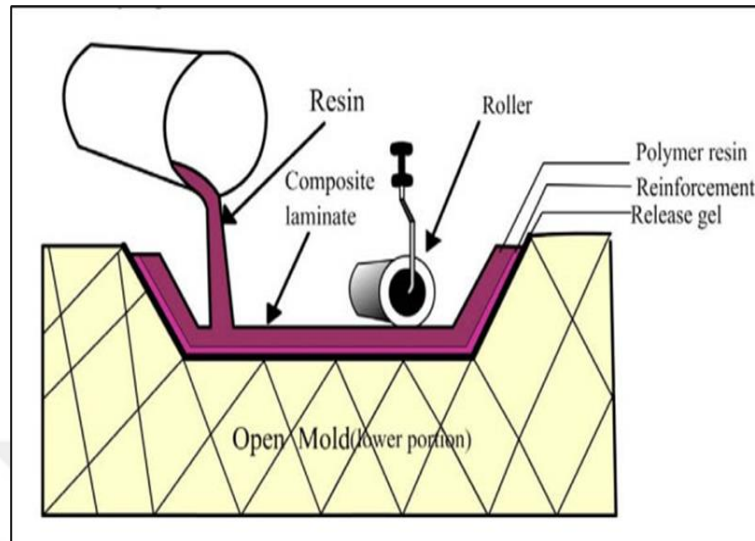


**Figure 2.3:** Process of Hand Lay-up [46].

Spray-up can be utilized as an alternative way for applying composite materials in an open-mold application. The spray lay-up method can be considered an extension of the hand lay-up method. In this operation, the mold is coated with a mold release agent before the continuation of the process. After the mold release agent was put on, a gel coat was shot into the mold to the right thickness for when it was to be used. After that, the gel coat is allowed to harden, and the mold is then ready to be processed. At a viscosity of 500 to 1000 cps, the fiber and the catalyzed resin are sprayed into the mold by a chopper spray gun. As shown in Figure 2.4, the gun first cuts the long fiber tow into shorter bundles of fibers. Then it blows both materials to be deposited concurrently on the surface of the mold. Rollers are used by the personnel to manually compress the laminate as the process of spraying on the coating nears its conclusion. After that, the composite component is cured, cooled, and extracted from the mold [47].

In order to cut down on the amount of labor required, the processes of spray-up and hand lay-up are sometimes combined, which is a typical method for producing glass fiber composite items, including truck cabs, spas, bathtubs, shower stalls, boat decks and hulls, RV components, fenders, and other generally big and noncomplex designs [48] .

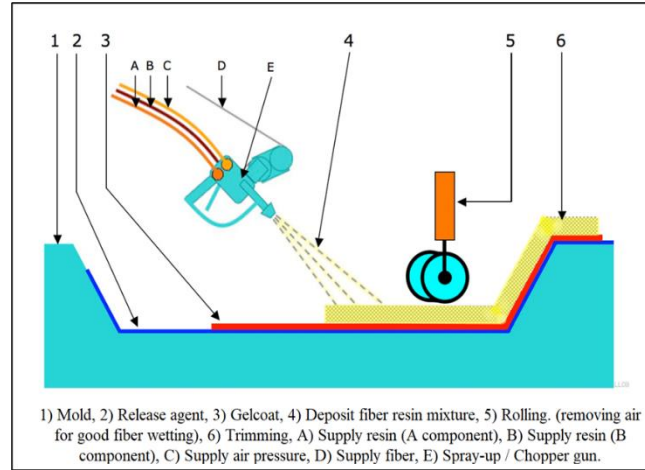


**Figure 2.4:** The Graphic Process of the Spray Lay-Up [49].

### 2.5.2 Resin Infusion Processes

To meet the growing need for speedier production, the industry employs alternative fabrication techniques to replace hand lay-up and promotes the automation of these operations whenever feasible [50]. In addition, the industry has used alternative fabrication techniques to substitute hand lay-up. The technique referred to as resin transfer molding (RTM), alternatively known as liquid molding, is readily comprehensible. In the initial step of this process, the mold is given a coating of mold release. After that, the dry reinforcing, normally performed, is inserted within the mold, and the mold is then closed [51]. After being metered and mixed, low-viscosity resin and catalyst would then be poured into the mold via injection ports at a pressure ranging from low to moderate while following predesigned routes through the preform. When working with thick composite components, selecting a resin with a low viscosity is particularly important so that the resin may swiftly and completely infiltrate into the preform before it gels and cures.

Reaction injection molding, commonly called RIM, involves injecting two streams of a fast-curing resin and a catalyst into the mold. The blending and chemical reactions occur inside the mold rather than in a dispensing head. Automotive sector suppliers have incorporated structural RIM (SRIM) with efficient techniques to produce structural elements that do not necessitate a class-A finish. Figure 2.5 illustrates a depiction of the resin transfer molding (RTM) process [52].

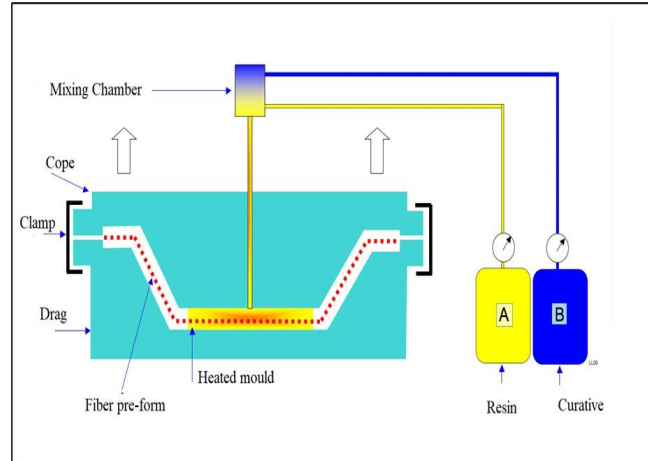


**Figure 2.5:** The Representation of the RTM Process [52].

The type of molding referred to as vacuum-assisted resin transfer molding (VARTM), which can be seen in Figure 2.6, is the one that is expanding at the most rapid rate. In the vacuum-assisted resin transfer molding technique, or VARTM for short, in contrast to the RTM method, in which the resin is pumped under pressure, the vacuum alone is used to pull the resin into the preform. VARTM technology does not need tremendous heating or pressure. VARTM typically works with low-cost tooling, which makes it feasible to create massive and complicated components in a single shot without incurring excessive costs [53].

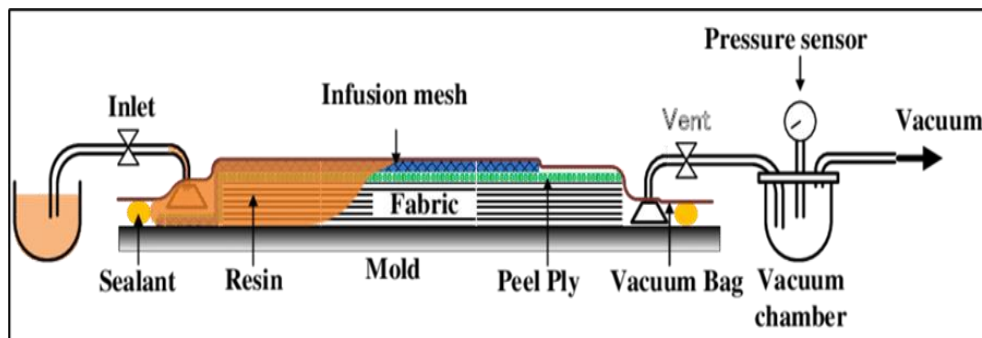


**Figure 2.6:** The Representation of the VARTM Process [54].

A dry preform is placed in a mold with a high-viscosity resin film on top or between numerous layers of the resin film, creating a hybrid process known as resin film infusion (RFI). RFI stands for resin film infusion. Because of the small flow distance, even with very viscous and hardened resins, the resin can liquify when subjected to pressure, vacuum, and heating, resulting in the resin being sucked into the preform. This results in the resin having a uniform distribution. When using resin infusion methods, the fiber quantities may be

increased to as much as 70 percent. Automated controls guarantee few voids and uniform performance replication without trimming. Using infused resins has become a key part of the boatbuilding industry. Without the use of an autoclave, The Boeing Company (located in Chicago, Illinois, USA), NASA, and other small fabricating enterprises have been successful in producing aerospace-quality laminates using this technology [55, 56]. Figure 2.7 illustrates a graphic illustration of the resin film infusion process.

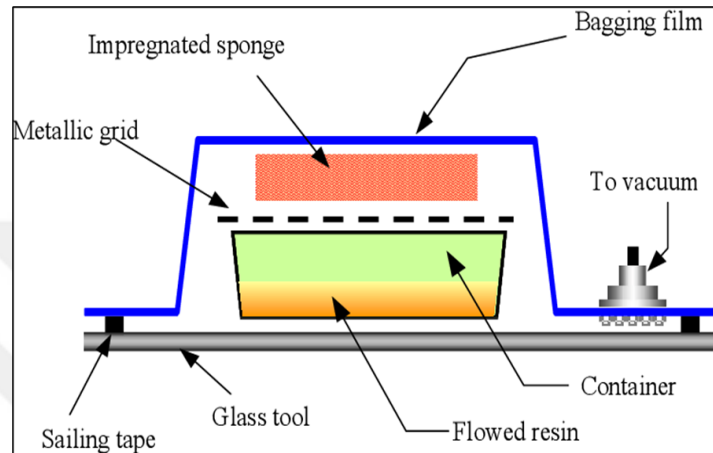


**Figure 2.7:** The Representation of the Resin Film Infusion Process [56].

### 2.5.3 Compression Molding

Manufacturing high-quality composite components in various quantities may be accomplished by a technique known as compression molding, which is both an accurate and potentially quick method. The material may be deposited in the mold by hand or robotically [57]. The two parts of the mold are brought together, and then hydraulic presses are used to provide pressure. Cycle time might vary widely based on the part's dimensions, particularly its thickness. The result of this procedure provides high-strength, intricate pieces that may be made in a broad range of dimensions. Compression molding is a suitable method for shaping composite materials, encompassing compounds like sheet molding compound (SMC), bulk molding compound (BMC), and chopped thermoplastic tapes. Other types of composites involve thermosetting prepreps and fiber-reinforced thermoplastic [58]. Figure 2.8 illustrates the depiction of the compression molding process.

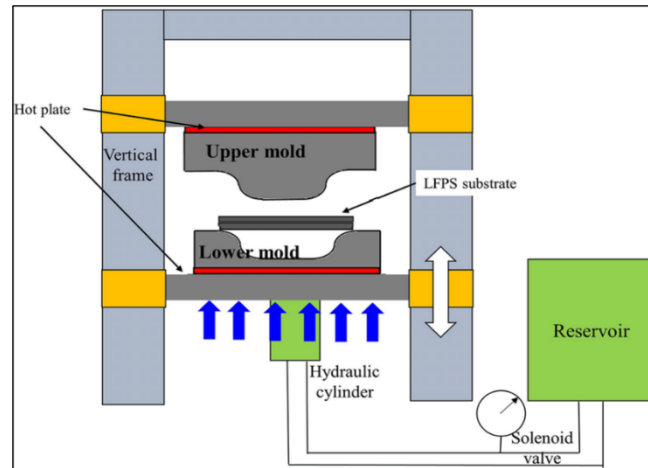


**Figure 2.8:** The Representation of the Compression Molding Process [59].

### 2.5.4 Injection Moulding

As can be seen in Figure 2.9, the process of injection molding is an enclosed one. This method is utilized to produce filled thermoplastics like nylon containing chopped glass fiber because it is rapid, low-volume, and high-pressure. The method of injection molding was used for close to 150 years at this point. In the 1960s, the first reciprocating screw injection-molding machines were developed; these machines remain in use nowadays [60]. In most cases, injection rates range from one to a few seconds, and numerous individual components may be produced in a single hour using molds with several cavities.

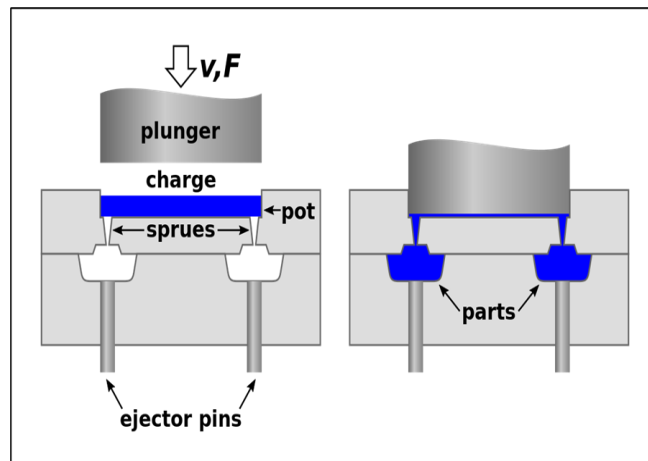


**Figure 2.9:** Simplified Diagram of the Molding Process [60].

### 2.5.5 Filament Winding

As depicted in Figure 2.10, filament winding is a continuous manufacturing process that can be highly automated and consistent with relatively affordable materials. A tool named a mandrel, which is long and cylindrical, is hung horizontally between two supports at each end. A resin bath is used to moisten the dry fibers, which are then passed through the bath again. The fiber application device places fiber onto the tool in an established configuration by moving back and forth along the length of a spinning mandrel with the traverse carriage. Computer-controlled filament-winding machines have been utilized. One instance of a composite material used in aircraft applications is filament winding [61].

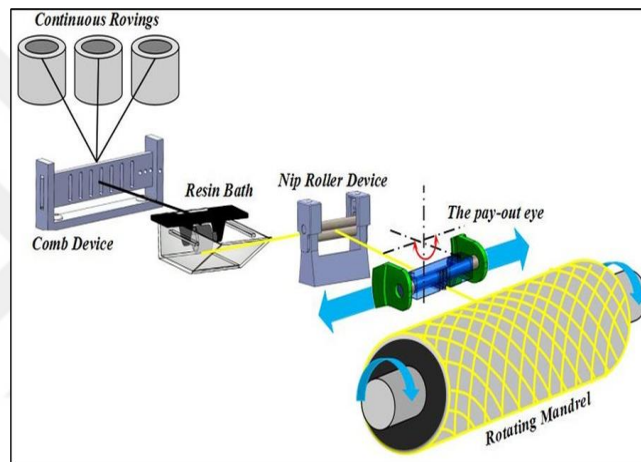


**Figure 2.10:** The Representation of the the Filament Winding Process [62].

### 2.5.6 Pultrusion Process

A technique called composite pultrusion can be used to make long pieces of fiber-reinforced polymer structures with the same cross-sections, a form of manufacturing that is done continuously and could be completely automated. A heated resin-wetting station is used in this procedure, during which a continuous bundle of dry fiber is dragged through the station. After being wetted, the bundle is drawn through heated dies, which shape the pulled fiber's cross-sectional shape. The formation of composites follows the curing of the resin. After that, the portion that has been long cured is sliced in order to make the parts. For this method to work, the element must be straight and have a constant cross-section, like an I-beam, T-beam, frame section, or ladder rail [63]. As seen in Figure 2.11, pultrusion is a manufacturing

technique. Pultrusion is a manufacturing process commonly used for making ladders and moldings, both of which are examples of linear components.

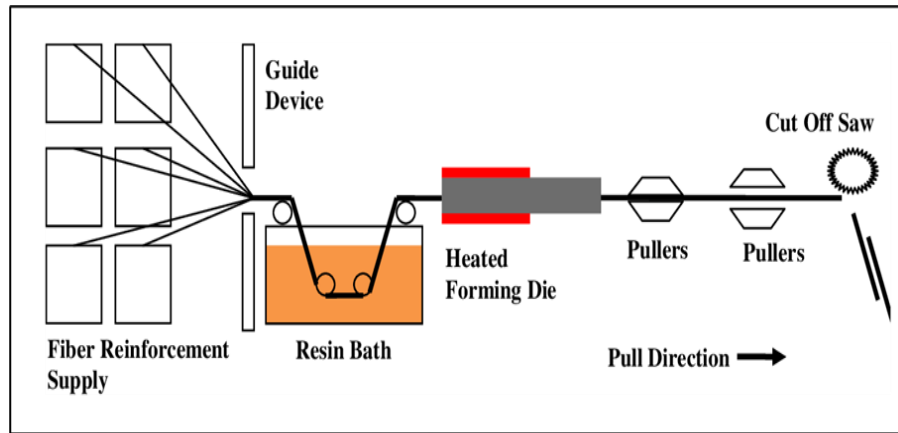


**Figure 2.11:** The Representation of the Pultrusion Process [63].

### 2.5.7 Automated Fibre Placement

As seen in Figure 2.12, one of the most cutting-edge techniques for fabricating and producing composite materials is automation fiber placement, or AFP for short. This technique is only used with continuous fiber-reinforced tape. In order to create a building one ply (layer) at a time using fiber-reinforced tape, a robot must be used to put the tape in place. The width of these tows is typically between 0.125 and 0.25 inches. A band of material made of many thin strips of tape (tows), is inserted in this location.. Because of the use of robots, the operator can exert effective control over all of the process's important variables, resulting in a high degree of control and making it extremely repeatable. Because individual pieces may be positioned at various angles, this technology enables the manufacture of highly customized components [64],[65]. This technique also enables the fabrication of parts that can best handle the needed loads. The processing time is cut in half, and material waste and labor expenses are cut significantly thanks to fiber insertion. The method is often used when fabricating massive thermoset items with intricate contours. Automation tape laying (ATL), also known as the automation tow placement (ATP) technique, is an even faster computerized method of manufacturing in which prepreg tape, as opposed to single tows, is put down constantly to build components [66] .

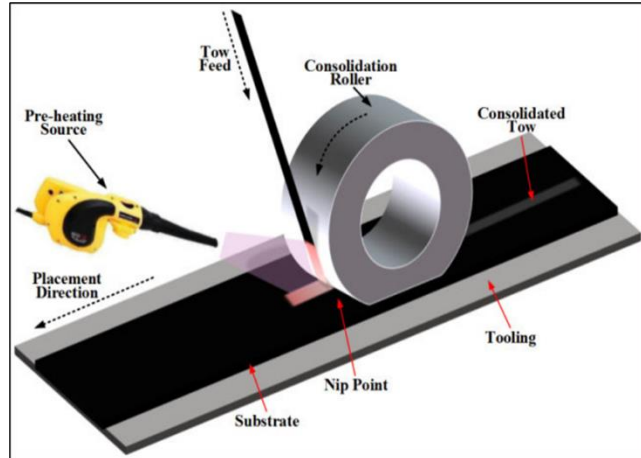


**Figure 2.12:** The Representation of the Automated Fiber Placement Process [67].

### 2.5.8 Additive Manufacturing

Another name for additive manufacturing is the technology of three-dimensional printing. Rapid prototyping principles have been around for more than 20 years, but the introduction of additive manufacturing marks a significant turning point in their evolution. A three-dimensional computer model may be used as the basis for creating a physical item using this technique, which generally involves depositing many successively thinner layers of material. As seen in Figure 2.13, producing a composite structure with a single nozzle requires the utilization of polymer composite filament. This filament consists of the polymer as well as additives, including carbon, particles of glass or rubber microspheres, fiber, wood flour, and other similar materials. This more contemporary method of producing composite parts emerged in attempts to save costs throughout the design-to-prototype phase of product development. More specifically, these efforts targeted toolmaking's time-consuming, labor-intensive, and resource-intensive process [68].

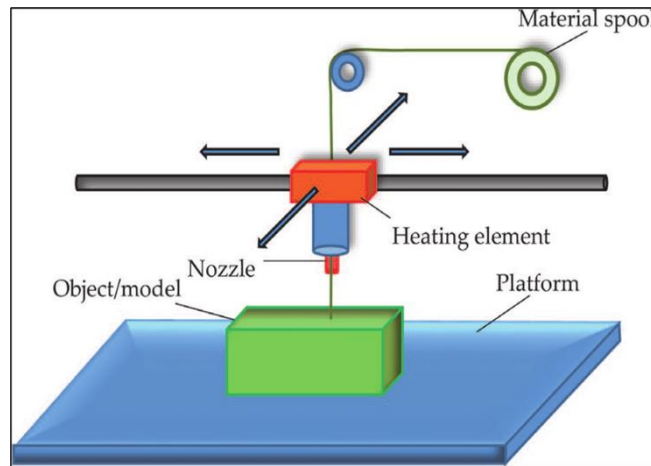


**Figure 2.13:** The Characterization of the 3D Printing Procedure For Polymer Composites[69].

## 2.6 BIOMEDICAL MATERIALS

Biomaterials are substances of artificial or natural origin that have been utilized to guide, complement, or replace the activities of living tissues in the human body. These materials may be found in nature or manufactured in a laboratory. The use of biomaterials stretches far back into ancient cultures. Mummies discovered in Egypt often have prosthetic features such as noses, teeth, ears, and eyes. Wax, glue, and other tissue types were employed in traditional Chinese and Indian techniques for repairing damaged or missing body parts. Over many centuries, the development of synthetic materials, surgical procedures, and methods of sterilization has made it possible to employ biomaterials in various contexts. Medical practice nowadays incorporates a huge variety of technologies and implantations. Biomaterials in the form of implantable devices (dental implants, intraocular lenses, heart valves, vascular grafts, joint replacements, bone plates, ligaments, and sutures) and healthcare equipment Blood tubes, artificial hearts, biosensors, and pacemakers have been extensively employed to replace and restore the function of damaged or deteriorating tissue or organs, to assist in the healing process, to facilitate recovery, to rectify anomalies, and so improve the quality of life for patients. The Institute of Materials in London released a paper in 1995 estimating that the global market for all types of medical devices, such as diagnostic and therapeutic equipment, is \$100 billion annually.

Within this business, the international market for biomaterials is anticipated to be over \$12 billion, with a mean worldwide increase of 7–12 percent annually. Biomaterials are

anticipated to function well in hostile environments inside human bodies. For instance, the pH of bodily fluids in the various tissues may fluctuate anywhere from 1 to 9 and can even go as low as 1. The bones undergo a stress of roughly 4 MPa during everyday activities, but the tendons and ligaments encounter peak strains in the range of 40–80 MPa. This difference in stress levels is because bones are more rigid than other connective tissues. When leaping, the peak load placed on a hip joint may be as high as ten times that of the body's weight, while the mean load placed on it can be up to three times that of the body's weight. Most significantly, these stressors are recurrent and vary in intensity based on the actions performed, such as standing, sitting, running, stretching, and climbing. It is predicted that the stress cycles associated with finger or hip joint motion may reach as high as  $10^6$  cycles in a year. However, the stress cycles associated with the motion of a normal heart can range anywhere from  $0.5 \times 10^7$  to  $4 \times 10^7$  cycles. This information provides a general indication of the acute and immediate biological environment that the biomaterials need and survive and function properly. It should go without saying that the patient's activities and circumstances also affect the biological environment.

Although no existing definition of biomaterials can be considered flawless or exhaustive, these definitions have nevertheless served as a great reference or point of departure for the ongoing conversation. It was unavoidable that such a definition would eventually require revision to consider the growth of the dynamic biomedical field and the revolution that has taken place inside it. For instance, a greater focus is being placed on developing alternative therapeutic techniques, including preventing and treating significant hereditary illnesses. The area of biomaterials faces new kinds of difficulties as a result of these developments in medical science. Applications requiring vision, unorthodox thinking, and creative design techniques include controlled distribution of medicines (vaccines and drugs), non-virally and virally mediated delivery agents for gene therapy, and the creation of functional tissues. Most notably, researchers require substances engineers and scientists are familiar with, sensitive to cellular, molecular, biochemical, and genetic issues, and capable of working effectively in teams of professionals that involve surgeons, physicians, geneticists, biochemists, and molecular biologists in order to achieve the challenges that are currently being faced and those that will be faced in the future in the field of biomaterials. Metallics and alloys, polymers, and ceramics are examples of synthetic materials that are utilized in biomedical

applications in the present day. Because the structures of various materials are distinct, their characteristics are distinct, and as a result, their applications in the body are distinct. Table 2.1 highlights the practical applications of biomaterials.

**Table 2.1:** Biomaterials Usage.

| <b>Problem Area</b>                          | <b>Instances</b>                                  |
|----------------------------------------------|---------------------------------------------------|
| Substitution of the damaged part or diseased | The artificial hip joint, kidney dialysis machine |
| Assist in healing                            | Screws, bone plates, and sutures                  |
| Enhance function                             | Cardiac pacemaker, intraocular lens               |
| Help to diagnosis                            | Catheters and probes                              |
| Help to treatment                            | Drains, Catheters                                 |
| Correct functional abnormality               | Cardiac pacemaker                                 |

### **2.6.1 Metallic Biomaterials**

Metals are often used in biomaterials because of their high thermal and electrical conductivity and superior mechanical qualities. Metals can swiftly transport electrical charge and heat energy because certain electrons in metals have their own identities. The present mobile free electrons provide the binding force that keeps the positive metal ions together. This attraction is strong, as shown by the densely packed atomic structure that results in high melting points and the specific gravity of most metallic materials. This arrangement also demonstrates that most metals have a high melting point. Because the metallic link is fundamentally non-directional, the location of the metal ions may be changed without disrupting the crystal structure, which results in a solid that can be deformed plastically [70].

Due to their superior mechanical characteristics and resistance to corrosion, certain materials are utilized as passive replacements for hard tissue substitutes, including knee joints and total hips, as well as for fracture healing aids, including dental implantation, spinal fixation devices, and bone screws and plates. These applications include total hip and knee joints.

Some metallic alloys are employed for more active roles in devices, including the cochlea, vascular stents, orthodontic arch wires, and catheter guide wire implantation. Including implantation, various medical devices are used. 'Vanadium steel' marked the first metal alloy intentionally crafted for human applications, notably in the production of bone fracture plates (often referred to as Sherman plates) and screws. The human body can only tolerate extremely minimal quantities of metals used in manufacturing alloys for medical implants. These metals encompass tungsten (W), molybdenum (Mo), niobium (Nb), tantalum (Ta), titanium (Ti), nickel (Ni), cobalt (Co), chromium (Cr), and iron (Fe). In some cases, these metallic elements in their naturally occurring states are essential for functions such as red blood cell production (Fe) or the synthesis of vitamin B-12. Nevertheless, the body cannot handle elevated concentrations of these metals [71].

Consider cobalt, an illustrative case in point. Its susceptibility to corrosion in an in vivo setting poses a substantial hurdle to maintaining biocompatibility when employed in metallic implants. The disintegration of the implant material not only diminishes its effectiveness but also gives rise to adverse effects on nearby organs and tissues, courtesy of the corrosive by-products.

### **2.6.2 Ceramic Materials**

The disciplines that involve the creation and utilization of solid objects primarily composed of inorganic and non-metallic materials are collectively known as ceramics. Ceramics are produced using inorganic, refractory polycrystalline substances, which can include carbides, metallic oxides, and silicates, as well as various refractory compounds like hydrides, sulfides, and selenides. These ceramics may also contain metallic and non-metallic elements and ionic salts such as NaCl, CaCl, and ZnS, which can be found in oxides like  $\text{Al}_2\text{O}_3$ , MgO,  $\text{SiO}_2$ , and  $\text{ZrO}_2$ . Covalently bound ceramics like diamonds and carbonaceous structures like graphene and pyrolyzed carbons are exceptions to the rule above. Humans have used ceramics in the shape of pottery for long periods of time. Due to their intrinsic fragility, propensity for notches or microcracks, poor tensile strength, and low impact strength, their application has been relatively limited until recently [6].

Nevertheless, new methods for creating ceramics have made them popular as "high-tech" materials during the last century. In recent years, people have learned that bones may be

replaced or enhanced using ceramics and composites. The later uses of ceramics are thus considered to be bioceramics. Ceramics are used as dental crowns because of their comparatively high compressive strength, relative inertness to bodily fluids, and aesthetically pleasing look. Certain carbon materials have been utilized for implantation, specifically for applications involving the interface with blood, such as heart valves. Ceramics are used as reinforcements in composite metallic implants and for applications involving tensile loading, such as artificial ligaments and tendons, due to their high specific strength as fibers and biocompatibility [6].

Ceramics seem more difficult to shear plastically than metals and polymers because of the bonding's (ionic) nature and the small number of slip systems. At room temperature, these properties render ceramics non-ductile and cause almost minimal creep [6]. Ceramics are thus particularly prone to notches or microcracks since, upon crack initiation, they would fracture elastically rather than flex (or give) plastically. The material weakens significantly since the stress concentration at the fracture tip is several times greater than the stress in the substance further away from the crack. The latter makes it challenging to foresee the material's tensile strength (ceramic).

Additionally, ceramics have lower tensile strength than compressive strength. When ceramic is flawless, it will be very robust, even under strain. The tensile strength of flawless glass fibers is double that of high-strength steel [6].

In reality, the measure of hardness was calibrated versus ceramic materials since ceramics are often quite hard. High melting points and poor electrical and thermal conductivity are other distinguishing features. These qualities result from the chemical bonds that exist inside ceramics. There are three types of ceramic materials used to make implants: those that are non-absorbable (relatively inert), bioactive or surface reactive (semi-inert), and biodegradable or resorbable. Table 2.2 provides an overview of ceramics used in the field of biomedical applications.

**Table 2.2:** Ceramic Utilized for Biomedical Purposes.

| Ceramic                                | Chemical Formula                                | Comment       |
|----------------------------------------|-------------------------------------------------|---------------|
| Alumina                                | $\text{Al}_2\text{O}_3$                         | Bio-inert     |
| Zirconia                               | $\text{ZrO}_2$                                  |               |
| Pyrolytic carbon                       |                                                 |               |
| Bioglass                               | $\text{Na}_2\text{OCaP}_2\text{O}_3\text{-SiO}$ | Bio-active    |
| Hydroxyapatite (Sintered at high temp) | $\text{Ca}_{10}(\text{PO}_4)_6(\text{OH})_2$    |               |
| Hydroxyapatite (Sintered at low temp)  | $\text{Ca}_{10}(\text{PO}_4)_6(\text{OH})_2$    | Biodegradable |
| Tricalcium phosphate                   | $\text{Ca}_3(\text{PO}_4)_2$                    |               |

### 2.6.3 Polymeric Biomaterials

Covalent bonding along the backbone chain creates extraordinarily long chain molecules in polymers. Primary covalent bonding forces link long chains together via cross-links between chains or secondary covalent bonding forces through van der Waals and hydrogen bonds. The lengthy chains are readily twisted and incredibly flexible. The long-range ordering of chains may also be hampered by each chain's side groups, branching, and co-polymeric chains or blocks.

Medical disposables, dressings, encapsulants, prosthetics, dental items, implantation, tissue-engineered products, extracorporeal devices, and orthodoses with metal and ceramic substitutes have extensively used synthetic polymeric materials [72]. The primary benefits of polymeric biomaterials over ceramic or metal materials are their accessibility with the appropriate physical and mechanical characteristics, ease of secondary processing, capacity to be manufactured into various forms (latex, film, sheet, fibers, etc.), and acceptable cost. Like other biomaterials, polymeric biomaterials must have the following features:

biocompatibility, sterilizability, sufficient physical and mechanical characteristics, and manufacturability. Table 2.3 offers a summary of the uses of polymeric biomaterials.

**Table:2.3:** Polymeric Biomaterials Usage.

| Synthetic Polymers               | Uses                                                                                                         |
|----------------------------------|--------------------------------------------------------------------------------------------------------------|
| Polyvinylchloride (PVC)          | Cannulae, connectors, catheter bottles, dialysis devices, IV set, surgical packaging, blood and solution bag |
| Polyethylene                     | Orthopedic implants, flexible containers, pouches, catheters, nonwoven fabric, and pharmaceutical bottles.   |
| Polypropylene (PP)               | Artificial vascular grafts, nonwoven fabric, suture, blood oxygenator membrane, and Disposable syringes      |
| Polymethylmethacrylate (PMMA)    | Bone cement, implantable ocular lens, membrane for blood dialyzer, reservoirs, and Blood pump                |
| Polystyrene (PS)                 | Filterwares, roller bottles, and Tissue culture flasks                                                       |
| Polyethylene terephthalate (PET) | Implantable suture, mesh, artificial vascular grafts, and Heart valve                                        |
| Polytertrafluoroethylene (PTFE)  | Artificial vascular grafts and Catheter                                                                      |
| Polyurethane (PU)                | The film, tubing, and components                                                                             |
|                                  | Packaging film, catheter, suture, and Mold parts                                                             |

## 2.7 DENTAL APPLICATIONS

Each tooth has a crown and a root, separated by the gingiva (gum). The mandibular (lower) or maxillary (upper) bones each include an alveolus, which is a socket where the root is positioned. Teeth have a thin (less than 1 mm) coating of highly mineralized (90 percent) dental enamel on their surface (the hardest substance detected in the body). Enamel's calcium

salts were structured as tiny prisms parallel to the surface, supported and underlain by dentine, which was less mineralized (70 percent). They had tiny liquid-filled tubules that passed through to the pulp chamber. The nerve is carried via the pulp chamber, which rises to its core through the tooth's root. Instead of enamel, cementum, a mineralized substance resembling bone, covers the surface of the tooth's root section. The teeth had an asymmetrical, anisotropic, and nonhomogeneous structure. Throughout mastication, chewing or teeth are subjected to various quantities and kinds (torsion, flexural, compression, and combined variants) of forces. Forces used during mastication and trauma range from 100N to 450N [73].

Dental therapy is a frequently performed medical practice on individuals. Dental treatments encompass procedures such as the restoration of cavities, sometimes referred to as "dental caries," and the replacement of damaged or rotting teeth. Prosthetic and dental therapies encompass a variety of treatments such as orthodontics, preventive care, prosthetics, crowns and bridges, endodontics, luting, cavity filling, cavity lining, and periodontal treatment. These treatments entail the use of diverse materials. These compounds are commonly known as biomaterials. The choice of material depends on how well it can mimic the mechanical, aesthetic, and physical characteristics of native tooth structures. Therefore, only consider the many areas where composite materials are already being utilized or have a strong potential for utilization [74] .

Dental restorative materials are used to heal cavities in teeth, as the name implies, and sometimes to conceal discoloration (through veneering) or to improve irregularities in shape and alignment. For the restoration of decaying teeth, materials, including silicate types of cement, acrylic resins, zirconia, alumina, gold, and amalgam, are often employed. Due to aesthetic considerations, front teeth are not usually favored for gold and amalgam restorations. The long-term toxicity of silver-mercury amalgam fillings is another issue of concern. For anterior teeth, silicate cement and acrylic resin have been employed. They have subpar mechanical qualities, which shortens their useful lives and increases the likelihood of clinical failures [75].

The transparent dental composite resins, which have a refractive index that matches the teeth, have replaced these materials, and are commonly used to treat both front and back teeth. The

dental composite resin utilizes BIS-GMA as its matrix polymer, with additional fillers like colloidal silica, barium glass, and quartz. BIS-GMA is formed through the reaction of bis (4-hydroxyphenol) with glycidyl methacrylate. Triethylene glycol dimethacrylate, a low-viscosity liquid, is used to reduce viscosity, while BHT (butylated trioxolanes, also known as 2,4,6-tri-tert-butylphenol), an inhibitor, is used to stop premature polymerization.

A thermochemical starter, like benzoyl peroxide, or a photochemical starter, like benzoin alkyl ether, that turns into free radicals when it comes in contact with UV light from a dentist's lamp, may both start the polymerization process. Instead of BIS-GMA, urethane dimethacrylate resin is used in various composites. The weight of the filler particles ranges from 33 to 78%, and their sizes range from 0.05 to 50  $\mu$ m. Glass fillers lessen the shrinkage that occurs when resin polymerizes and the mismatch in the coefficient of thermal expansion between composite resin and teeth. They provide dental composite resins with a high degree of stiffness and strength and exceptional wear resistance. Utilizing silane-coupling agents, the fillers and resin are strongly bonded [76].

For a restorative material to be successful, the following features are crucial: The material should have a viscosity that is low enough to completely fill the cavity, controllable polymerization, a thermal expansion coefficient similar to that of the enamel and dentine to prevent leakage at the interface margins, low shrinkage, and strong resistance to creep, wear, and water absorption. Their radio opacity is crucial once dental composites are utilized as posterior restorative materials. It would be almost impossible to detect caries beneath a non-radio-opaque composite, enabling the process to go on for too long without being stopped because excessive radio-opacity may conceal cavities behind the restoration; the ideal radio-opacity for composites needs to be clarified. However, the composite must at least match the enamel's radioopacity. Research is ongoing to create dental composite resins with increased functionality [76].

### **2.7.1 Recent Development in The Polymer Blend**

Finding novel applications for mixed characteristics in the biological and pharmaceutical fields requires careful investigation. Enhancing the tensile strength of polymer blends as prosthetic foot material reinforced by carbon fiber was the main emphasis of Hadi and Oleiwi's [77] study. Artificial limbs, often known as prosthetic feet, are manufactured items

that provide amputees with a substitute for their amputated limb and partially restore its function. In recent years, advanced orthopedic medicine and prosthetic devices have benefited from technical advancements created by polymer mix materials. The self-curing polymer mix PMMA/SR that may be utilized to make prosthetic feet at an affordable cost and with acceptable mechanical qualities forms the basis of this study. One easy way to increase the tensile strength of such a polymer mix for this purpose is to reinforce the PMMA/SR polymer blend with carbon fiber (CF).

Subsequently, the manufactured specimens underwent tensile strength testing, and the influence of carbon fiber reinforcing on the tensile strength of polymer blends was quantified as a significant improvement for prosthetic foot material. Polymer blends consisting of PMMA and SR in ratios of 90:10, 80:20, 70:30, 60:40, and 50:50 was created. Carbon fibers, ranging from 5% to 15% (CF), were used as reinforcements in each blend [78].

PMMA and SR were employed as polymer blends in this study as a viable material for a prosthetic foot. PMMA is a linear thermoplastic polymer. Short carbon fibers were utilized as reinforcement in experiments to enhance the tensile strength characteristics of polymeric mixtures utilized as prosthetic foot materials. These improvements included increases in tensile strength, elastic modulus, and elongation. In contrast, tensile strength and elasticity decrease as rubber content increases for polymer blends and the utilization of cold processing [79].

The following study focuses on nanocomposite systems and polymer blends for articular cartilage applications in tissue engineering. Naturally occurring polymers may provide traits like cell signaling, low toxicity, biodegradability, and biocompatibility, while manufactured polymers can offer physical and mechanical characteristics and thermal stability. Nevertheless, several of them lack sufficient mechanical properties to sustain the development of cartilage tissue.

Polymer blending is a widely used method whenever changing a characteristic is necessary since it is a low-cost technology that provides materials with a broad range of customized qualities and enhanced specialized characteristics. The basic goal of mixing is to increase the variety of features while removing any negative aspects. The benefits of polymers are often preserved when natural and synthetic polymers are combined. In this study, collagen

and chitosan are combined with a polymer. Instances in this category are collagen, hyaluronan, chitosan and hydroxyapatite, collagen, and chondroitin sulfate nanocomposite. The bioactivity of synthetic polymers like polyvinyl alcohol may be improved by mixing them with other synthetic polymers. Keep in mind that the mechanical functioning of the manufactured articular cartilage should be identical to that of the original tissue; thus, the anisotropic, nonlinear, viscoelastic, and inhomogeneous qualities of manufactured articular cartilage [80].

### **2.7.2 Characterization Technique of Polymer Blend**

Scan electron microscopy is a good demonstration of polymer mix characterization technology. The cryogenically cracked and smooth-cut surfaces of the blended specimens were identified using a Jeol ESEM SEM machine at an accelerating voltage of 20 kV. Atomic force microscopy is next. The Dimension 3100 Nanoscope V was used to tap the sliced surface of the samples to capture the AFM pictures (Veeco, USA). Budget Sensors Bulgarian silicon-SPM sensors with a resonance frequency of 280 kHz and a spring constant of around 40 N/m were utilized. The radius of the tip is less than 10 nm. Transmission electron microscopy serves as the other illustration [81].

Using transmission electron microscopy (TEM), the NR/NBR nanocomposites were examined to evaluate the filler dispersion quality and morphological features (JEM-2100 HRTEM). The micrographs were created with a 200 kV accelerating voltage and a point-to-point resolution of 0.194 nm. Bulk specimens' thin slices Leica's Ultracut UCT ultra-microtome was used to generate cryocut specimens, which were then put on 300 mesh Cu grids with a 35mm diameter and subjected to analysis devoid of staining [82].

Another common approach for the characterization of polymer blends is X-ray diffraction. X-ray diffraction (XRD) tests were conducted on the clay-filled specimens in the biologically modified clay powder sand. X-ray diffraction of the NR/NBR nanocomposite was performed using the SIEMMENS D 5000 with radiation Cu K alpha at 40 kV and 30 mA to determine the distance between the clay layers. In addition, the characterization of the polymer mix uses tensile characteristics. The tensile properties of the samples were analyzed using a Tinius Olsen universal testing machine with a crosshead speed of 500 mm/min, in accordance with the ASTM D 412-98 standard, at a temperature of 25 °C. The Young's

modulus, tensile strength, and elongation at the break of each system were calculated using five samples in the form of dumbbells. The slope of the first linear area of the stress-strain curve was determined to be the tensile modulus. Stress relaxation measures come last. A universal testing machine was used to assess the mix nanocomposites' stress relaxation (T50KT). To explore the effects of several factors that affect the NR/NBR nanocomposite, including loading, filler polarity, blending content, mixing circumstances, filler nature, temperature, and methods of preparation, stress relaxation tests were performed [83]. The viscoelastic testing was done using a Tinius Olsen testing machine (H50KT) equipped with an ambient chamber. Temperature control was possible in the environmental chamber. The specimen was held between two sets of jaws spaced 12 mm apart while the environmental chamber was adjusted to the proper temperature (70 degrees Celsius). The sample was given another 30 to 40 minutes to acclimate to the situations within the chamber. After equilibration, the specimen was subjected to tensile tension by the upper grasp being moved at a constant pace (500 mm min<sup>-1</sup> crosshead speed). Move the grip once the appropriate starting strain of 50 percent has already been attained.

## **2.8 PMMA**

PMMA is an engineering plastic category that includes other polymers such as poly (methyl methacrylate). It is a thermoplastic that is clear in appearance. PMMA is also referred to as acrylic or acrylic glass. It is sold under the trade names and brand names Perspex, Perclax, Lucite, Astariglas, Acrylite, Plexiglas, and Crylux, amongst many others. It is also recognized as a chemical compound with the formula PMMA (see below). As a lighter and more break-resistant alternative to glass, this kind of plastic is frequently utilized in the form of sheets. Additionally, it is useful as a casting resin, an ingredient in inks and coatings, and for many other applications [84].

In situations where UV tolerance, polishability, transparency, flexural strength, and tensile strength are prioritized over heat resistance, chemical resistance, and impact strength, polymethyl methacrylate, or PMMA, is a more cost-effective alternative to polycarbonate, often known as PC.

In addition, unlike polycarbonate, polymethylmethacrylate, or PMMA, does not include any potentially hazardous subunits of bisphenol-A, making it a far superior material for laser

cutting [8]. It is often favored because it has moderate qualities, is simple to handle and process, and is inexpensive. In the presence of a load, non-modified PMMA exhibits brittle behavior, particularly when subjected to an impact load, and is more prone to scratches than traditional inorganic glass. On the other hand, improved PMMA is occasionally capable of achieving great scratch and impact resistance. Figure 2.14 presents the chemical composition of polymethyl methacrylate.

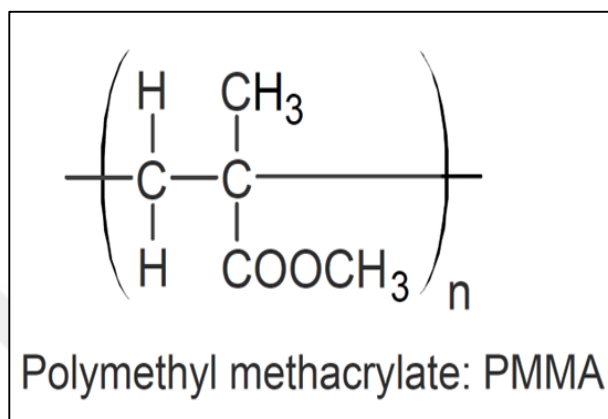


**Figure 2.14:**Chemical Composition of Polymethyl Methacrylate[85].

PMMA has a density of 1.17 to 1.20 grams per cubic centimeter and a melting point of 320 degrees Fahrenheit. Compared to other polymers and plastics, it has high scratch resistance and does not undergo any reactions when in contact with an aqueous solution. Exposed to aromatic or chlorinated hydrocarbon, ester, or ketone compounds frequently can be traced back to a compromised surface on a material manufactured from PMMA. This can also be the case when the surface is degraded in any other way. Polymethyl methacrylate is a substance that is non-biodegradable, extremely biocompatible, and recyclable in every possible way.

PMMA is a plastic that falls within the category of Group 7. The versatility of PMMA extends to diverse recycling approaches. Notably, pyrolysis takes center stage, requiring the combustion of PMMA at high temperatures in an oxygen-deprived setting. On the other hand, depolymerization, facilitated by molten lead, produces the MMA monomer with an impressive purity surpassing 98 percent [86]. Despite this achievement, the drawback emerges from the use of lead, giving rise to toxic by-products. The consequential limitation on acrylic application deems the process environmentally unfeasible.

Acrylic that has been recycled may be shaped into sheets that can then be utilized in a variety of industries, including the advertising business, the medical industry, and the building industry for windows and doors. In its solid state, acrylic is a non-toxic alternative to PC that does not contain the chemical BPA. PMMA, which is inherently compatible with human flesh, has been a common part of contacting lenses. It has also been utilized for the fabrication of dentures and bone replacements [79].

### **2.8.1 Properties**

Polymethyl methacrylate (PMMA) is a material that exhibits both high-strength and low-weight characteristics. The density of the substance falls within the range of 1.17 to 1.20 g/cm<sup>3</sup>, which is notably lower than that of glass. PMMA exhibits superior impact strength compared to polystyrene and glass. However, it falls short in comparison to other synthetic polymers, including polycarbonate. At a temperature of 460 degrees Celsius (860 degrees Fahrenheit), PMMA undergoes combustion, resulting in the generation of low-molecular-weight compounds including carbon dioxide, water, carbon monoxide, and formaldehyde.

PMMA possesses a high refractive index, allowing it to transmit as much as 92% of visible light, even at a thickness of 3 millimeters. However, it does reflect approximately 4 percent of light from each of its surfaces, with a refractive index of 1.4905 at 589.3 nm. PMMA is effective in absorbing ultraviolet (UV) radiation with wavelengths below 300 nanometres, similar to regular window glass. Some manufacturers enhance PMMA's absorption in the 300–400 nm range by incorporating coatings or additives. PMMA is transparent to infrared light with wavelengths up to 2,800 nanometres but becomes opaque to longer-wavelength infrared light up to 25,000 nanometres. Specific colored variations of PMMA block visible light while permitting specific infrared wavelengths to pass through, making it suitable for applications like remote control or heat-sensing sensors.

PMMA expands and dissolves in various organic solvents because its ester groups are so simple to hydrolyze; it has a low resistance to various other compounds. Despite this, its resistance to the elements is greater than that of most other plastics, including polyethylene and polystyrene. As a result, it is often the material of choice for applications that take place outside.

The maximal water absorption ratio for PMMA is between 0.3 and 0.4% based on its weight. The tensile strength of a material diminishes as its ability to absorb water increases. It has a thermal expansion coefficient that is rather high, coming in at  $(5-10) \times 10^{-5} \text{ }^{\circ}\text{C}^{-1}$ .

### **2.8.2 Modification of Properties**

Pure poly (methyl methacrylate) homopolymer is only sometimes offered for sale as an end product since it needs to be designed to function better in most contexts. Instead, customized formulations consisting of various proportions of additional comonomers, additives, and fillers were generated for situations where particular qualities were needed. These formulations may then be used. For example, it is customary to add a small amount of acrylate comonomers to PMMA grades designed for heat processing. This addition helps to stabilize the polymer and prevent depolymerization (also known as "unzipping") during most of the processing stage. To increase the material's resistance to impact, comonomers like butyl acrylate are often added.

In their study, Salih et al. [134] investigated various aspects of PMMA prosthetic complete denture base materials reinforced with different types of particles. Their research showed that the flexural properties got better when the amount of nanohydroxyapatite (nHA) and  $\text{ZrO}_2$  particles went up. Recent studies have indicated that the addition of 3wt%-treated  $\text{TiO}_2$  nanofillers to PMMA significantly enhances impact resistance, flexural strength, hardness, and surface roughness. Furthermore, Hameed and Rahman [135] conducted research on the impact of  $\text{ZrO}_2$  nano powder on autoclaved-cured acrylic resin. Their results demonstrated that incorporating salinized  $\text{ZrO}_2$  had a positive effect on both transverse and impact strength of the denture base nanocomposite, which was reinforced with a 5% wt. fraction of nano- $\text{ZrO}_2$ . Additionally, the results indicated a slight increase in apparent porosity while hardness and surface roughness decreased with an increasing fraction of nano- $\text{ZrO}_2$ .

- a. In order to enhance the material's ability to withstand greater temperatures, comonomers like methacrylic acid can be included in the polymer, hence increasing its glass transition temperature. This modification enables the material to be utilized in applications that need elevated temperatures, such as lighting.

- b. Plasticizers can be included in a substance to enhance its processing characteristics, reduce the temperature at which it undergoes the glass transition, enhance its impact characteristics, and improve its mechanical characteristics, such as its elasticity modulus.
- c. Dyes can be utilized to bestow color for decorative purposes or to provide protection against or filter out the impacts of UV radiation.
- d. The use of fillers might result in improved cost-effectiveness.

### 2.8.3 Applying PMMA Dentistry

Throughout their fascinating history, dentures have been made from many different materials. For example, while never made of wood, George Washington's dentures were made from bone, ivory, human teeth, and many other materials at various points in his life. Nevertheless, for nearly 80 years, we have been using the same denture material, a hard plastic called polymethyl methacrylate, or PMMA. Nowadays, dental zirconia blocks have become people's favorites. However, some believe that the future of dentures is a new, flexible material. The increasing demand for appearance in the modern world has led to the popularity of aesthetic restorations. To meet the needs of patients, the dental field has reintroduced multilayer, acetal PMMA dental products. Figure 2.15 illustrates the utilization of PMMA teeth.



**Figure 2.15:** Using of PMMA Teeth [87].

#### **2.8.4 PMMA Popularity**

There are many good reasons for the rapid adoption of PMMA. The benefit of PMMA is that it can be used for both gum-colored abutments and colored teeth. Since it is transparent, it has good dental aesthetic qualities. Furthermore, PMMA has a high degree of color fastness, which means that with proper care (e.g., no homemade whiteners), your dentures will stay beautiful for years. It also has many functional benefits. PMMA can be precisely matched to the impressions of the patient's mouth. It is a very durable material that can be repaired when damaged. Furthermore, the base is made of the same material as the teeth, which can be attached tightly, making them very stable. PMMA could be better as it is very brittle; however, it has good toughness, meaning when dropped, it can break, which is a particular problem for people with arthritis. Some people find that PMMA can cause dentures to irritate the gums. Also, the hardness of PMMA makes it susceptible to variable occlusal forces or oscillating shifts, which can lead to fracture.

#### **2.8.5 Multilayer Dental PMMA**

First, multilayer dental PMMA can increase its users' attractiveness and aesthetic magnitude. They are manufactured using CAD/CAM technology perfectly to fit well in the user's mouth without needing regular replacement. The multi-layers consist of voids and blocks available in various colors but can be mixed well to achieve a perfect result. They are refined to obtain the most natural look and are customized according to the patient's requirements.

Wearing PMMA multi-layers allows the teeth to enjoy greater stability. It can be used for up to several months without changing its color. The polymerization makes it monomer-free, which indicates that it is safe for allergic patients. In addition, they are resistant to plaque even when the patient wears them frequently and for long periods of time. Multilayer dental PMMA has shown positive results as temporary models, crowns, and bridges for longer periods. It is possible to use cement for coloring in dental multilayer PMMA. Figure 2.16 depicts the application of PMMA in the dental field.



**Figure 2.16:** Applying PMMA in the Dental Field [87].

## 2.9 FRACTURE OF DENTURES

Research conducted on denture base material has revealed that the primary issue encountered is the fracture of dentures. According to a survey, a significant proportion of dentures, ranging from 63 to 68 percent, have been reported to break within a few years of their fabrication. It is noteworthy that a greater number of partial dentures have been affected as compared to complete dentures, as reported in a study [72].

Several investigations were conducted across three labs, revealing that 33 percent of the repairs were attributed to deboned teeth. In contrast, 29 percent of the repairs were associated with midline fractures frequently observed in upper complete dentures. Of the total fractures observed, 62% were identified as non-upper partial denture repairs. In comparison, the remaining 38% were classified as other types of fractures, most of which were repairs of upper partial dentures. The primary cause of this phenomenon is attributed to impact failure resulting from the accidental dropping of the denture on a hard surface or fatigue failure resulting from repeated deformation of the denture due to occlusal forces, as reported in [88]. The image depicting a fracture in a prosthetic denture is presented in Figure 2.17.



**Figure 2.17:** Images for Various Locations of Fracture for the Prosthetic Denture [88].

### **2.9.1 Causes of Fracture**

The etiology of midline fractures in dentures is examined from clinical and materials science perspectives. Establishing prosthodontic fundamentals in constructing and maintaining dentures may prevent numerous midline fractures. The issue of acrylic resin denture fracture remains a persistent challenge, with failure likely stemming from a combination of factors rather than the inherent characteristics of the denture base materials. The stress generated within the denture is a critical factor in this phenomenon. The maxillary denture experiences bending deformation and is subjected to tensile stress. Upon analysis of the causes of acrylic denture fracture, it has been observed that additional factors contribute to the formation of areas of stress concentration. These factors include the presence of a large notch, a thin denture, and a poorly fitting denture. Insufficient physical fitness and imbalanced occlusion are contributing factors to heightened denture deformation [89].

### **2.9.2 Modes of Fracture**

The primary distinguishing factor among the fracture modes is the extent to which the stress occurs relative to the polymer chain's capacity to deform, which reduces the stress concentration near the inclusion, as cited in reference [90]. The images depicting various modes of fracture that can occur in prosthetic dentures are presented in Figure 2.18.

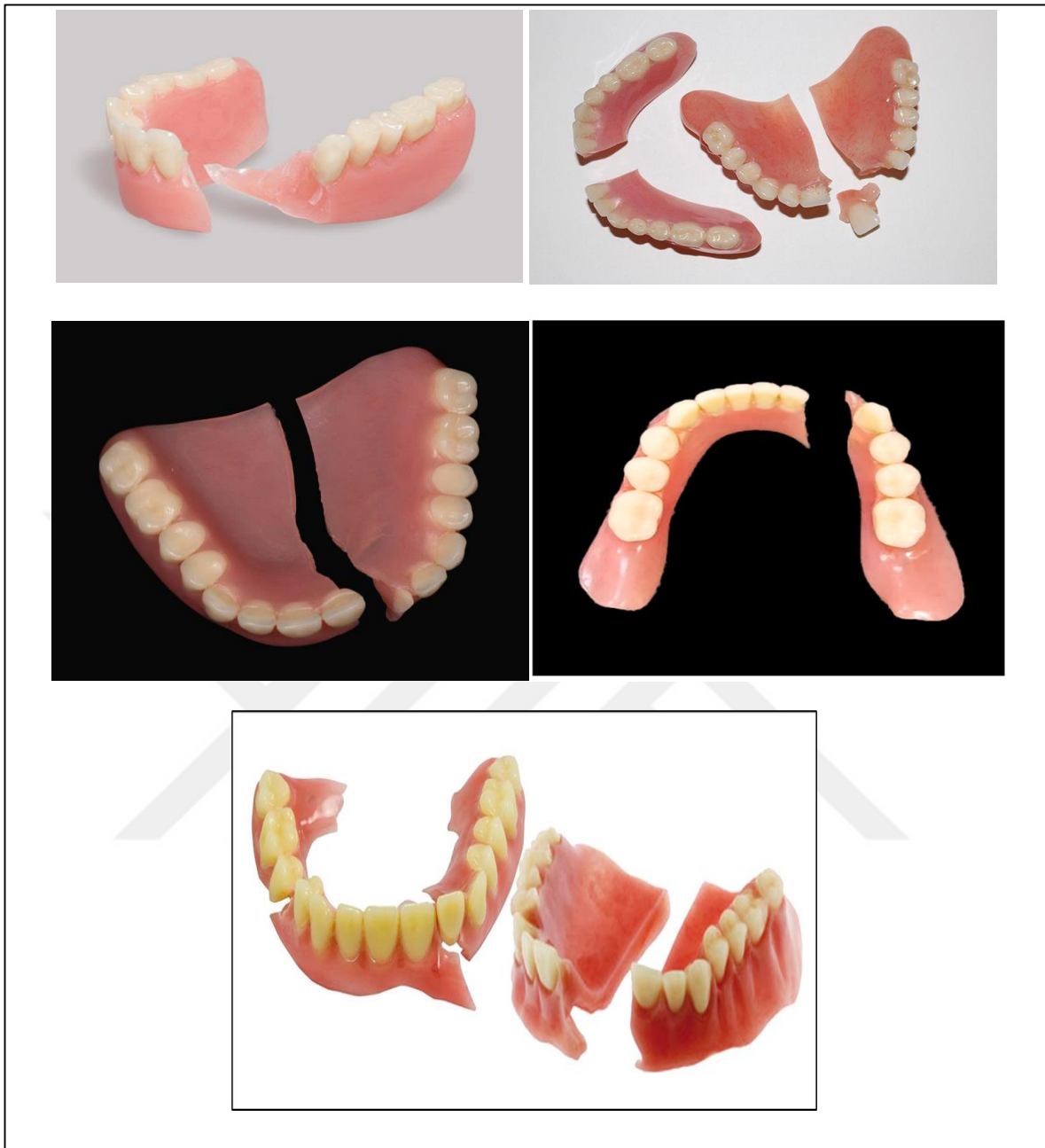


**Figure 2.18:** The Images Depicting Various Modes of Fracture That Occur in Prosthetic Dentures [90].

### 2.9.2.1 Impact fracture

The fracture by impact is based on the impact point and force direction applied which varies in each cause. On being dropped, tensile and compressive forces are set up in the denture and their positions vary with the point of impact. This specific kind of fracture typically occurs through coughing, which exerts enough force to dislodge the denture from the oral

cavity, or accidental dropping of the denture onto a hard surface such as the floor or sink. Furthermore, it is plausible that such an incidence could transpire when the individual is engaged in a forceful mishap [91]. The impact fracture images that arise in prosthetic dentures are illustrated in Figure 2.19.



**Figure 2.19:** Images of Impact Fracture in the Prosthetic Denture [91].

#### **2.9.2.2 Fatigue fracture**

The fracture of a denture base frequently transpires through a fatigue mechanism whereby minor flexural stresses, over an extended duration, culminate in minute cracks propagating during the denture. This is often observed in cases where the denture has been poorly fitted or inadequately designed, as noted in reference [90].

The study on fatigue failure in denture base polymers observed that inadequate adaptation to minor tissue increases denture flexure. Additionally, the presence of stress concentrators reduces the material's strength, particularly under alternating stress conditions as opposed to static stress conditions [90]. The onset of catastrophic failure can be traced back to the surpassing of the mechanical strength of the remaining material during the final loading cycle, as elucidated in the provided reference.

The occurrence of midline fractures in complete denture base material is attributed to flexure fatigue, which can be triggered by changes in tissue like alveolar resorption. This leads to the deflection of the right and left halves of the denture in a superior direction, with the midline of the plate acting as a fulcrum. According to research findings [92], a single bite has the potential to lead to a fracture, which may be further exacerbated by the gradual deterioration of the material over time. The illustrations of fatigue fractures occurring in prosthetic dentures are depicted in Figure 2.20.



**Figure 2.20:** Images of Fatigue Fracture in the Prosthetic Denture [91].

## 2.10 TYPES OF DENTURE BASE MATERIALS DEFECTS

Many types of defects are found in composite prosthetic dentures; Figure 2.21 shows various types of defects that occur in the denture base materials.

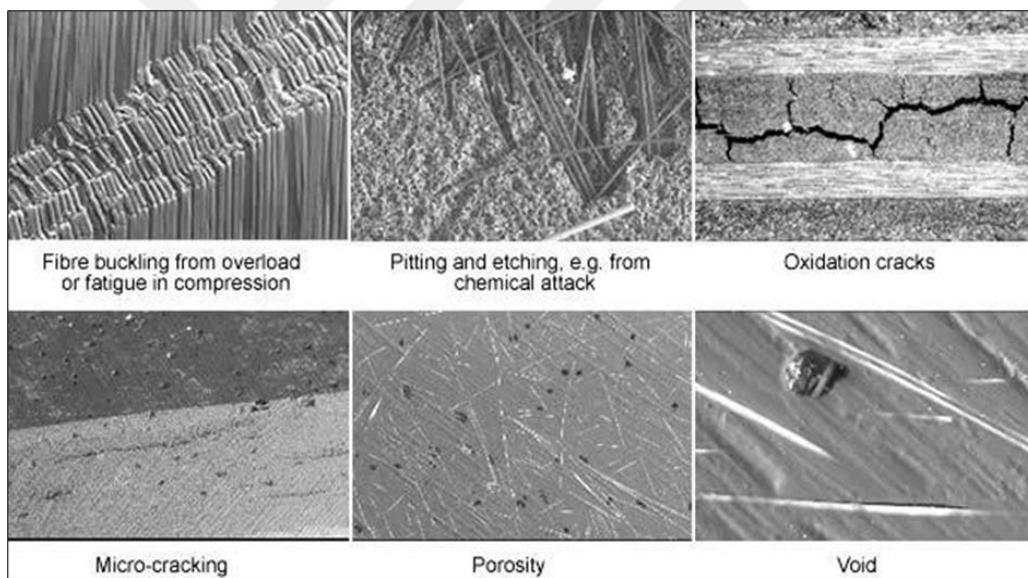


**Figure 2.21:** Various Types of Defects that Occur in Prosthetic Denture [93]

### 2.10.1 Porosity

The appearance of porosity throughout the manufacturing process is a common issue likely to be encountered with acrylic resin dentures. The phenomenon of porosity in acrylic resin is multifaceted, as it is influenced by various factors such as the material composition, polymerization technique, and flashing technique. The considerable porosity of an acrylic

resin prosthesis denture can result in substantial weakening, high internal stresses, and potential distortion of the denture base, as noted in reference [94]. Porosity in polymerization can be attributed to two primary factors. The first kind, shrinkage porosity, is related to contraction porosity. Figure (2.22) demonstrates the images of porosity that happen in prosthetic dentures. The volatilization of the monomer causes the second kind and is commonly referred to as gaseous porosity [95]. When porosity is presented on its surface:

- a. The unsightliness of the denture base's appearance is a concern.
- b. The challenge of effectively cleaning dentures results in compromised denture hygiene and, subsequently, oral hygiene.
- c. Weaken the acrylic resin denture base materials.

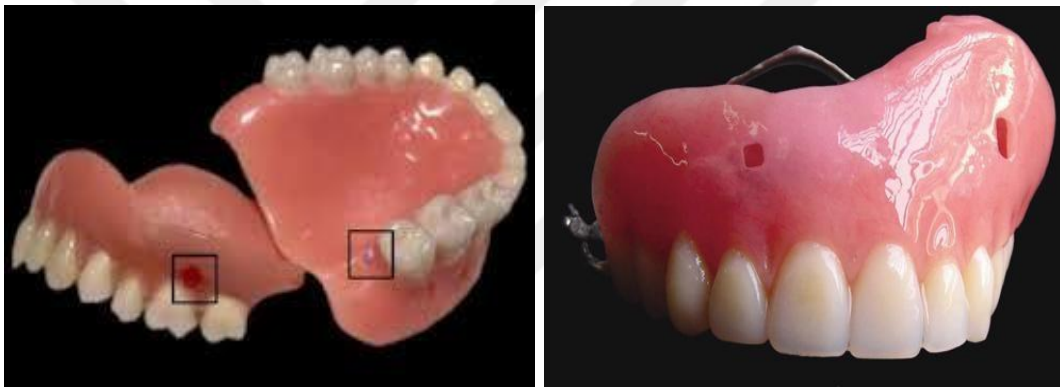


**Figure 2.22:** Images of Porosity Defect in the Prosthetic Denture [95].

### 2.10.2 Crazeing

The creation of surface cracking on the denture base resin by crazing has a weak effect on the resin and reduces its esthetic qualities. Figure 2.23 demonstrates the images of crazing that happen in prosthetic dentures. The cracks formed can cause fractures, causing crazing, since:

- a. Mechanical stress (tensile stress).
- b. Attack by solvent.

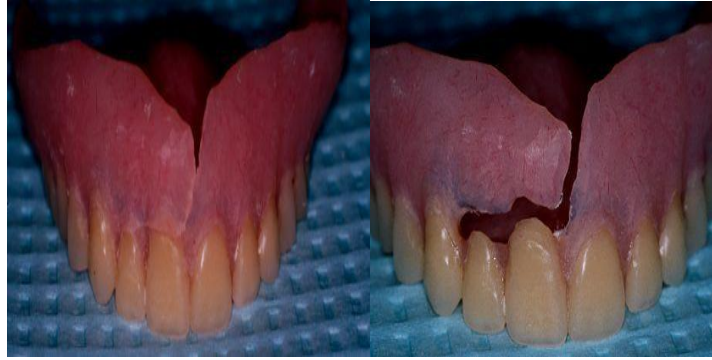


**Figure 2.23:** Images of Crazing Defect in the Prosthetic Denture [95].

### 2.10.3 Warpage in Denture

Denture warpage, which may compromise the denture's fit, is characterized by a deformation or alteration of the denture's shape that can happen throughout processing or at other stages. The images of warpage that arise in prosthetic dentures are illustrated in Figure 2.24.



**Figure 2.24:** Images of Warpage Defect in the Prosthetic Denture [95].

### **3. EXPERIMENTAL STUDIES**

#### **3.1 INTRODUCTION**

Denture base material is a specific type of biomaterial that requires excellent characteristics, compatibility, performance, color stability, and dimensional stability. It must also be aesthetically pleasing and suitable for use in the oral cavity. This chapter centers on the materials employed in this study for the preparation of PMMA composites and hybrid laminated composite specimens of the prosthetic denture. It also provides a detailed discussion of the specifications of these materials. A description of the procedure and composition of these composites' specimens was made with various reinforced materials and a detailed description of the test instruments used.

#### **3.2 CLASSIFICATION OF DENTURE BASE MATERIALS**

The categorization of denture base materials hinges on the material type, broadly classified into metallic and non-metallic categories. The metallic category spans a spectrum of elements, including titanium, aluminum, gold, nickel chromium, and cobalt chromium. On the other hand, non-metallic materials, extensively documented in the literature, encompass a diverse array, such as polymethyl methacrylate acrylic resin, ceramic materials, porcelain, and a range of polymer materials like epoxy, phenol formaldehyde, polycarbonate, and nylon [96].

In addition, denture base materials are classified into several categories and classes depending on their chemical composition and processing method. This information is shown in Table 3.1, which provides details on the various resin materials and their respective polymerization temperatures. The two main types of denture base resins used in dental prosthodontics are heat-curing and cold-curing polymers [97].

**Table 3.1:** Classification and Polymerization Temperature of Denture Base Materials According to EN ISO 20795-1:2008.

| Types                                            | Characteristics                                                                                                               |
|--------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------|
| Type 1 - Heat-curing polymers.                   | Polymerization temperature $>65^{\circ}\text{C}$                                                                              |
| Type 2 - Self-curing polymers.                   | Polymerization temperature $<65^{\circ}\text{C}$<br>The curing mechanism is based on the chemical reaction of the components. |
| Type 3 - Thermoplastic materials.                | Polymers that are moldable when heated.                                                                                       |
| Type 4 - Light-curing materials.                 | Curing with UV radiation and/or visible light.                                                                                |
| Type 5 - Materials for microwave polymerization. | Heat-curing systems polymerized with microwaves.                                                                              |

### 3.2.1 Composition of Acrylic Denture Base

Acrylic denture base material is usually supplied in gel (plastic cake) form, which is rarely used. However, as progress kept being made, the current PMMA denture base materials were developed. These are made up of polymer beads and monomer liquid methyl methacrylate, or MMA. This particular type is the most prevalent and extensively utilized. Polymer is composed of particles of pre-polymerized PMMA, which exist in either spherical or granular forms in different sizes. Originally, polymer powder was produced by grinding blocks of PMMA. However, it was soon found that a smoother, more consistent dough resulted from the use of a spherical polymer. Most acrylic resin denture bases used today are based on this PMMA/MMA system [98].

### 3.2.2 Powder

An acrylic polymer is composed of poly (methyl methacrylate) treated with a tiny quantity of ethyl, butyl, or alkyl methacrylate. This modification enhances the polymer's resistance to impact-induced fractures [98].

- a. Initiator: Benzoyl peroxide or di-isobutylazobitrile is usually added partly (0.5% to 1.5%) to act in the polymerization of the residual monomer as a catalyst; also, to overcome the effect of inhibitors, The decomposition, either through heating or chemical means,

catalyzes the polymerization reaction. This decomposition releases peroxides, which act as free radicals during the liquid monomer's polymerization process when is added to the powder in the dough stage of the denture base material [99].

- b. Plasticizer: These materials do not enter the polymerization reaction to assist dough formation but are added to polymers or monomers with low molecular weight. Ester dibutyl phthalate was used for many years as an external plasticizer, but today, internal plasticizers such as high-molecular-weight acrylic ester monomers are used. To enhance the polymer's solubility in the monomer and create a pliable and durable polymer, it is necessary to reduce its strength, hardness, and softening point. This will also enable the monomer to permeate the mold more quickly during the dough stage, facilitating the plastic molding process through the application of heat and pressure. An inherent drawback is that they can seep into oral secretions, solidifying the denture foundation [100].
- c. Inorganic matters , which are added with the use of coupling agents like glass fibers, alumina whiskers, polyethylene woven yarn, and polyamide fabric, have also been used to reinforce acrylic polymers to increase stiffness, decrease the coefficient of expansion, and increase thermal diffusivity [100].
- d. Opacifier: zinc or titanium oxide is added to the polymer; the latter is more effective and increases the opacity of the denture base material. The radio-opacity of denture plastics helps in locating fractured fragments in the upper respiratory or digestive tract. This is provided by of several incorporating several glasses and ceramics containing heavy metals, such as barium and strontium zirconium [98].
- e. Dye and Pigments: the organic dyes have been added to make the denture radiopaque to facilitate the aspirated fractured pieces since the accident, like barium, radiopaque glass fillers, bismuth, urinal salts, or zirconyl dimethacrylate at concentrations of 10 to 15%. [100].
- f. Pigments are used for color; pure polymers such as poly (methyl methacrylate) are clear and quite adaptable to a wide range of pigmentations, so organic pigments like mercuric sulfide, cadmium sulfide, and ferric oxide are added during polymerization or after to

obtain a tissue-like appearance, i.e., to match the shade of the oral tissue. Due to their toxicity, the utilization of cadmium salts is limited. Therefore, these pigments are either incorporated into polymer beads during the polymerization process or mixed with the polymer beads manually after polymerization [98].

### 3.2.3 Liquid

a. The monomer utilized in this context is methyl methacrylate, which exists in a liquid state under standard room-temperature conditions. It is capable of being altered through the incorporation of other polymers during the process of polymerization, which can be induced through the application of heat, light, or even minute amounts of oxygen. This substance serves as the fundamental unit for polymerization and is distinguished by its colorless (transparent) nature, high flammability, and extreme volatility. It is a low-viscosity liquid that has a boiling point of 103 degrees Celsius. It is recommended that MMA be stored in dark brown glass bottles to prolong its shelf life by preventing spontaneous polymerization due to heat exposure or exposure to visible or ultraviolet light. This is because the rapid diffusion of monomers into polymer beads can cause swelling, leading to the extraction of low-molecular-weight polymers such as benzoyl peroxide into the monomer. These polymers become trapped in the interstices between polymers, where they can later initiate the curing of the dough mixture [100]. Figure 3.1 shows the chemical formula of the MMA monomer.

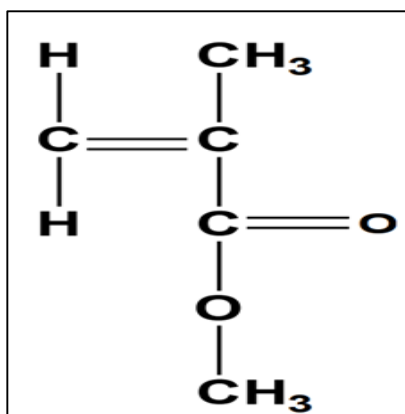


**Figure 3.1:** Chemical Formula of (MMA) Monomer [100].

- b. Inhibitor: which was added with a concentration of (0.003% to 0.7%) hydroquinone to prevent the monomers from polymerizing during storage and to give the clinician adequate working time [98].
- c. Accelerator: the accelerator is used to speed up the decomposition of benzoyl peroxide to perform polymerization at room temperature, like tertiary amine sulfonic acids, at a concentration of 1% to the liquid [98].
- d. Cross-linking agent: The most common cross-linking agents are dimethacrylate, either glycol dimethacrylate or 1,4-butanediol dimethacrylate, which are added with a percentage (2–4%) to link long polymer molecules together to form bridges between the linear macromolecules as a three-dimensional network that provides greater resistance to surface cracking, the resistance of denture to organic solvent, improving strength, fatigue properties in terms of crazing, and decreasing solubility and water sorption of the resin [99], [100].

### **3.2.4 Pour Acrylic Resins (Fluid Acrylic Resins) Denture Base**

The chemical constitution of pour-type denture resin bears a resemblance to that of chemically activated acrylic resins. The primary distinction lies in the magnitude of the polymer powder. The denture resin of the pour kind, also known as fluid resins, is characterized by the presence of significantly reduced powder particles. Upon combination with the monomer, the resultant slurry exhibits a high degree of fluidity. The amalgamation is expeditiously introduced into an altered plaster cast and permitted to undergo polymerization while subjected to pressure [99].

Advantages of the fluid resin technique include [101]:

- a. No increase in the vertical dimension.
- b. Short time-consuming during processing.
- c. Reduced likelihood of harm to artificial teeth and the foundation of dentures during the removal process.
- d. Decreased expenses for materials and time required for processing.
- e. Streamlining the flasking, deflasking, and finishing procedures.
- f. Excellent reproduction of surface details.
- g. Improved adaptation accuracy to underlying soft tissue.

Potential disadvantages of the fluid resin technique include [100]:

- a. Air entrapment with the denture base material, which was attributed to incorrect sprue positioning or to pouring resin that was too viscous.
- b. Poor bonding of the resin with acrylic resin teeth.
- c. Teeth movement.
- d. Technique sensitivity.

This type of acrylic resin takes advantage of the flow features of a polymer-monomer mixture at an early stage. The denture produced is less accurate than that of the heat-cured type because of the high polymerization shrinkage. This type of resin is characterized by lower impact and fatigue strength, higher flexural bond strength, lower water sorption, and higher solubility.

### **3.2.5 Techniques of Acrylic Resin Polymerization**

Several techniques have been proposed for the polymerization of acrylic resin based on the mechanism of the chemical reaction that generates free radicals. The classification of curing methods includes heat curing techniques such as water baths and microwaves, chemical curing methods such as self-curing, and light-curing techniques [102].

#### **3.2.6 Heat-Activated Acrylic Denture Base**

The polymerization reaction of such materials requires thermal energy, which can be obtained by using a water bath or microwave oven. They found that there were no significant differences in these properties between the two curing cycles [103].

##### **a. Water Bath Curing**

It is commonly accepted that the input heat and resulting exothermic heat might exceed the boiling point of the monomer prior to the completion of the process. This can lead to the entrapment of vapor within the rapidly polymerizing resin, ultimately resulting in the development of internal porosity.

- a. A particular method for processing denture base resin is to expose it to long curing cycles in a water bath at a constant ambient temp of 74 degrees centigrade for a duration of 8 hours or more, without any terminal boiling treatment.
- b. An additional method involves extended curing periods involving immersion in a water bath at a temp of 74 degrees centigrade for a duration of 7 hrs, followed by a temperature elevation to 100 degrees centigrade for a period of 1 hr.
- c. A third methodology entails utilizing abbreviated curing cycles, whereby the resin is subjected to a temperature of 74°C for a duration of roughly 1.5 hr, followed by elevating the temp of the water bath to 100 degrees centigrade and processing for an additional 0.5 hr [100].

The polymerization cycles that have ensued have demonstrated considerable success in the production of denture bases with varying dimensions, configurations, and gauges.

#### b. Microwave Curing

The application of microwave energy has the potential to induce heat within the resin. The magnetrons are the electromagnetic waves generated by a generator. When processing resins by microwave irradiation, these attempts faced some problems such as the reflection of microwave by metal flask. A perforated metal flask was used to solve this problem, but the result was not satisfactory since the obtained resin was porous and under-cured. A plastic reinforced flask (PRF) was used to solve this problem; the results indicated that there was no reflection of microwave irradiation, and the acrylic resin material was cured successfully.

The advantage of this technique is the shorter polymerization processing time than is needed with the conventional method. It also indicates the physical properties, less residual monomer, less porosity, and minimizes dimensional changes of microwave resins compared with water bath-cured and chemical-cured acrylic resin [104].

The optimal curing of acrylic resin is contingent upon the appropriate selection of microwave power and polymerization duration. The molecules of methyl methacrylate exhibit the ability to align within the electromagnetic field of microwave radiation. Microwaves selectively target monomers, resulting in a proportional decrease in

monomer concentration as the degree of polymerization increases. Consequently, a diminishing quantity of monomer absorbs an equivalent quantity of energy, resulting in a heightened level of activity for the molecules [105] .

### **3.2.7 Chemically (Self) Activated Acrylic Denture Base**

The denture base materials that undergo auto-polymerization exhibit chemical similarity to those that are heat-cured, with the only difference being the mode of initiation of polymerization. Chemical activation, rather than thermal energy, is utilized to expedite the process of polymerization. This is achieved by introducing a reducing agent, or catalyst, into the monomer. Typically, tertiary aromatic amines, including dimethyl-para-toluidine and tertiary aromatic amines sulfonic acids, are employed for this purpose. The present decreasing agent can react with benzoyl peroxide at ambient temperature to generate an ample number of peroxy-free radicals that facilitate the initiation of monomer polymerization in the denture base material, thereby referred to as cold curing. Upon completion of the curing process, the resin retains a certain amount of unreacted monomer, as noted in reference [100]. The color stability of chemically activated resins is associated with the existence of tertiary aromatic amines, which can be prone to oxidation and consequent alteration in color that impacts the visual aspect of the resin. The use of stabilizing agents can mitigate the discoloration of these resins by preventing oxidation [100].

### **3.2.8 Rapid Heat Polymerized Acrylic Resin**

The aforementioned materials are commonly referred to as hybrid acrylics, which undergo polymerization through boiling water shortly after being inserted into a denture flask. The initiator was formed by combining chemical and heat-activated initiators, facilitating expeditious polymerization while mitigating the formation of porosity, which may otherwise be anticipated [106].

### **3.2.9 Visible Light Activated Acrylic Denture Base**

PMMA, an amorphous polymer, exhibits high transparency, brittleness, and stability towards water-based media and UV radiation. This system of curing denture base resin through the

use of radiation energy, such as visible light-cured resin (VLCR) or infrared rays, has been used in dentistry applications since 1983, including fixed and removable restoration denture bases. Also, an argon laser was used for resin polymerization. The transverse, tensile, and compressive strengths have been higher than those prepared by the light-curing system [99]. The features and composition of heat- and chemically-curing PMMA resins were reviewed in Tables 3.2 and 3.3, respectively.

**Table 3.2:** Comparing Compositions of Heat Activated and Chemically (Self) Activated PMMA Resins [107].

| Heat Activated PMMA Resin (Two Component System) |                     | Chemically (Self) Activated PMMA Resin (Two Component System) |                     |
|--------------------------------------------------|---------------------|---------------------------------------------------------------|---------------------|
| Powder System                                    |                     | Powder System                                                 |                     |
| Poly (methyl methacrylate)                       | Main constituent    | Poly (methyl methacrylate)                                    | Main constituent    |
| Benzoyl peroxide                                 | Initiator           | Benzoyl peroxide                                              | Initiator           |
| Mercuric sulphide<br>Cadmium sulphide            | Dyes                | Mercuric sulphide<br>Cadmium sulphide                         | Dyes                |
| Zinc oxide, titanium oxide                       | Opacifiers          | Zinc oxide, titanium oxide                                    | Opacifiers          |
| Dibutyl phthalate                                | Plasticizer         | Dibutyl phthalate                                             | Plasticizer         |
| Dyed particles-glasses, beads                    | For aesthetics      | Dyed particles-glasses, beads                                 | For aesthetics      |
| Liquid System                                    |                     | Liquid System                                                 |                     |
| Methyl methacrylate                              | Plasticizes polymer | Methyl methacrylate                                           | Plasticizes polymer |
| Dibutyl phthalate                                | Plasticizer         | Dibutyl phthalate                                             | Plasticizer         |
| Glycol dimethacrylate (1-2) %                    | Cross-linking agent | Glycol dimethacrylate (1-2) %                                 | Cross-linking agent |
| Hydroquinone (0.006) %                           | Inhibitor           | Hydroquinone (0.006) %                                        | Inhibitor           |
|                                                  |                     | Dimethyl-para-toluidine                                       | Activators          |

**Table 3.3:** Comparison of Properties of Heat and Chemically (Self) Cured PMMA Resin [100].

| Heat Cured Acrylic Resins                                      | Chemically Cured Acrylic Resin                                                           |
|----------------------------------------------------------------|------------------------------------------------------------------------------------------|
| High molecular weight                                          | Comparatively lower molecular weight                                                     |
| Heat is necessary for polymerization                           | Heat is not the primary source for polymerization                                        |
| The porosity of the cured resin is less                        | Porosity in the cured resin is much greater                                              |
| Stronger cured material                                        | Strength is less compared to heat-cured resins                                           |
| Lower residual monomer content                                 | Higher residual monomer content                                                          |
| Shows less distortion, decreases creep and initial deformation | Comparatively higher distortion, increased creep, slow recovery, and greater deformation |

### 3.3 MATERIALS AND SAMPLE PREPARATION

#### 3.3.1 Matrix material (PMMA denture base resin)

In this study, PMMA cold curing has been utilized as a novel fluid resin matrix, specifically the type known as Castavaria, produced by the Vertex™ Dental Company. The purpose of this was to fabricate specimens in the form of hybrid and non-hybrid laminated composites for prosthetic dentures. Vertex™ Castavaria is a versatile self-polymerizing acrylic that can be utilized for various purposes such as pouring, relining, rebasing, and repairing.

This category of materials possesses several distinct characteristics in comparison to other forms of PMMA polymers. These features include a softer texture, lower molecular weight, long-term color stability, reduced shrinkage, a stable polymerization cycle resulting in optimal outcomes, and the ability for the acrylic to remain pourable and malleable for an extended duration. However, materials with low strength and hardness pose challenges throughout the fabrication process. The utilization of Vertex™ (Castavaria) has been demonstrated in this investigation, as depicted in Figure 3.2. Table 3.4 presents the mechanical and physical characteristics of polymethyl methacrylate (PMMA) utilized in the present investigation.

**Table 3.4:** Various Mechanical Features of Pour PMMA Polymer Utilized in This Investigation  
Based on (Vertex–Dental Company).

| Characteristics                        | Value  |
|----------------------------------------|--------|
| Young's Modulus (GPa)                  | 1.63-3 |
| Impact Resistance (kJ/m <sup>2</sup> ) | 8.3    |
| Flexural Strength (MPa)                | 79     |
| Flexural Modulus (GPa)                 | 2.3    |
| Water Sorption (µg/mm <sup>3</sup> )   | 23.2   |
| Solubility (µg/ mm <sup>3</sup> )      | 1.8    |
| Water Absorption (%)                   | 2.5    |
| Density (g/cm <sup>3</sup> )           | 1.19   |



**Figure 3.2:** PMMA Resin kind (Castavaria) that Utilized in This Investigation.

### 3.3.2 Reinforcing Materials

In the course of this investigation, the reinforcing materials utilized encompassed both micro and nanoparticles of (SiO<sub>2</sub>).

### 3.3.2.1 Particles reinforcement

Two different types of micro and nanoparticles of SiO<sub>2</sub> were chosen for this study, each with varying concentrations of 0%, 1%, 2%, 3%, and 4% by weight, it has been added to the polymer powder (acrylic powder).

## 3.4 SPECIMENS GROUPING

In the present investigation, PMMA composite materials and hybrid laminated composite materials have been produced and categorized into several categories based on the amount of reinforcement materials, as presented in Table 3.5.

**Table 3.5:** Sets of PMMA Composite Materials and Hybrid Laminated Composite Materials that Were Produced in This Investigation.

| Samples ID | Group 1                        |                             |      |
|------------|--------------------------------|-----------------------------|------|
|            | Samples details                | Wt. %Micro SiO <sub>2</sub> | PMMA |
| Control    | PMMA                           | 0                           | 100  |
| Mc1        | PMMA-1% $\mu$ SiO <sub>2</sub> | 1                           | 99   |
| Mc2        | PMMA-2% $\mu$ SiO <sub>2</sub> | 2                           | 98   |
| Mc3        | PMMA-3% $\mu$ SiO <sub>2</sub> | 3                           | 97   |
| Mc4        | PMMA-4% $\mu$ SiO <sub>2</sub> | 4                           | 96   |
| Samples ID | Group 2                        |                             |      |
|            | Samples details                | Wt. %Nano SiO <sub>2</sub>  | PMMA |
| Control    | PMMA                           | 0                           | 100  |
| NA1        | PMMA-1% nSiO <sub>2</sub>      | 1                           | 99   |
| NA2        | PMMA-2% nSiO <sub>2</sub>      | 2                           | 98   |
| NA3        | PMMA-3% nSiO <sub>2</sub>      | 3                           | 97   |
| NA4        | PMMA-4% nSiO <sub>2</sub>      | 4                           | 96   |

### **3.5 GENERAL PREPARATION OF TEST SPECIMENS**

#### **3.5.1 Mould Preparation**

The mold utilized in this investigation is composed of a glass mold measuring 20cm × 20cm × 0.4cm and is overlaid with a glass plate to ensure a polished surface for the samples being prepared. Thermal silicon was employed to seal any voids that could potentially exist in the mold.

#### **3.5.2 Proportioning and Mixing of Acrylic**

The PMMA composite materials were fabricated utilizing the Vertex™ Castavaria. According to the manufacturer's instructions, the recommended ratio for combining cold-cured acrylic resin is 17 grams of polymer powder (PMMA) with 10 milliliters of monomer liquid (MMA), resulting in a volume-based proportion of 1.7 grams per 1 milliliter or a weight-based proportion of 1.7 grams per 0.95 grams.

The significance of this ratio was associated with regulating the manipulability of the amalgam and alterations in dimensions during solidification, and it was regarded as one of the factors affecting the cytotoxicity of acrylic resin. Various transformations occur during the blending of powder and liquid due to the polymer's dissolution in the monomer.

The process of blending monomer and polymer acrylic materials involves several distinct stages, namely hard, rubbery, full dough, sticky, and granular or sandy. The attainment of the dough stage in the polymer and monomer blend is contingent upon the solubility of the polymer powder in the monomer liquid and the elevation of temperature, as indicated by reference [108].

The Vertex™ Castavaria is a pliable substance that can be molded for an extended duration. The solution consists of liquid methyl methacrylate (MMA), which is placed into a pristine and desiccated container, namely a glass beaker. Subsequently, dry polymethyl methacrylate (PMMA) powder is gradually added to the liquid MMA. The blend is consistently agitated at ambient temperature utilizing the mechanical mixing apparatus (brabender plastograph mixer) at a velocity of 20 revolutions per minute (rpm) until it attains the dough phase. The resulting slurry is subsequently poured into the middle of an open mold in a thin, straight

line. The manufacturer specifies a maximum time of approximately 4.5 minutes for this process. During the process of pouring a mixture into a glass mold, it is necessary to gently rock and vibrate the mold from side to side to eliminate any gas bubbles from the specimens. Additionally, the remaining mixture should then be poured into the mold hole until the glass mold is completely filled. The aforementioned blend was enclosed in an airtight receptacle and allowed to rest on a laboratory bench at a temperature of 30 degrees Celsius for a duration of 8–13 minutes following the commencement of the mixing procedure. This was done in order to enhance the viscosity of the liquid, resulting in a hardened and matte surface upon pouring.

### **3.5.3 Curing Cycle Employed**

As per the manufacturer's guidelines, the process of polymerization curing involved placing the closed mold within pressure vessels, commonly known as autoclaves. Consequently, all specimens were subjected to an autoclave at a temperature of 55 degrees Celsius and a pressure of 2.5 bar for a duration of 30 minutes, in accordance with the manufacturer's instructions. This was done to ensure the complete polymerization of the samples under the given conditions. This method offers the benefit of achieving polymerization within a brief duration, enabling post-curing of samples, and yielding a low residual monomer level.

### **3.5.4 Cooling Process**

Upon completion of polymerization, the mold underwent a curing process. Subsequently, it was removed from the autoclave and placed on a bench to cool for approximately 30 minutes at ambient temperature. This allowed for the completion of cooling and the full hardening of the sample. Following the cooling process, the specimens were carefully removed from the mold and subjected to a cleaning procedure. The casting samples subsequent to the de-mold process are depicted in Figures 3.3.



**Figure 3.3:** Casting Samples For Pure PMMA and PMMA Composite Strengthened By Micro and Nano ( $\text{SiO}_2$ ) Particles.

### 3.5.5 Finishing and Polishing

After a complete cooling of the specimen, all the specimens underwent the process of finishing and polishing. All flat-shape access, smooth surfaces, flashes of acrylic, and removal of all remaining small scratches with a straight acrylic bur were used, followed by the finishing of the specimens with silicon carbide or sandpaper grit papers (grades 120-220-320-500) using continuous water cooling. Polishing was achieved by utilizing a fine cloth coated with diamond paste of a grade measuring  $2\ \mu\text{m}$ , or alternatively, a stiff bristle brush (grade 360). Except for the surface roughness specimens without any finishing or polishing.

## 3.6 CONDITIONING OF THE ACRYLIC SPECIMENS

Following the completion of comprehensive cooling, finishing, and polishing procedures on the samples, it is crucial to store all designated test samples in distilled water at a controlled temperature of  $37 \pm 1$  degree Celsius for a duration of two days. This preparatory step aligns with the specifications outlined in ADA requirements No. 12 of 1991. The prescribed duration and conditions of storage serve the dual purpose of eliminating any residual monomer and mitigating residual stress. Moreover, this process ensures the preservation of denture base materials in an environment partially simulating oral conditions [109].

### 3.6.1 Preparation of Hybrid Laminated Composites Specimens

Various techniques are employed in the fabrication of hybrid polymer matrix-laminate composite materials. The present investigation employed the hand layout technique. The following presentation illustrates the procedural steps involved in preparing samples [110]:

- a. Weighing of reinforced material (micro and nano ( $\text{SiO}_2$ )) by utilizing electronic balance with accuracy (0.0001) digits.
- b. Weighing of the reinforced particles micro and nano ( $\text{SiO}_2$ ) and calculated the weighing of both particles by the same method in point (2).
- c. Weighting of the acrylic resin polymer powder (PMMA) and monomer liquid (MMA) resin and calculating the volume fraction according to the required volume of casting and based on the volume fraction of reinforced material by the same method using point (2).
- d. To achieve a uniform mixture, it is necessary to continuously blend the acrylic resin (PMMA) powder with strengthened particle micro and nano ( $\text{SiO}_2$ ) at room temperature utilizing a mechanical mixing device (brabender plastograph mixer) operating at a speed of 20 rpm.
- e. The process involves blending a combination of acrylic powder PMMA and micro- and nano- $\text{SiO}_2$  with MMA liquid resin, following the standard acrylic mixing procedure, until the mixture reaches the dough stage. The volume fraction of the mixture varies depending on the sample group. The procedure involves the utilization of a metallic spatula to effectively scrape the sample against the inner surface of the container, thereby eliminating any trapped air within.

### 3.7 MECHANICAL PROPERTIES

The mechanical attributes of a substance delineate its response to external forces. These traits play a pivotal role in delineating the material's applicative range and anticipated lifespan, thus aiding in its classification and identification. It's crucial to recognize that the mechanical features of a material are dynamic and responsive to factors such as temperature, rate of applied load, and other environmental conditions, rather than being static values.

### 3.7.1 Tensile Test

The tensile test is a commonly employed method for obtaining substantial insights into the utilization, performance, classification, choice, and development of materials. Polymers exhibit viscous-elastic behavior, whereby the strain experienced by the polymeric material is directly proportional to the applied stress. The restoration of a material to its initial dimension might not always happen upon the removal of stress. This phenomenon can be attributed to the intrinsic property of polymer molecules to exhibit intermolecular mobility, allowing them to undergo sliding motion in response to an externally applied force. The mechanical response of polymers is closely associated with the inter-chain mobility exhibited by the constituent polymer chains when subjected to external loading. When thermoplastic polymers like PMMA are subjected to stress beyond their yield strength, the intermolecular Vander Waals bonds between the molecules in different chains are disrupted [111]. The stress-strain relationship characterizes the correlation between the externally applied stress and the consequent strain, with each material exhibiting a distinct stress-strain curve. The stress applied in the aforementioned curve pertains to longitudinal stress that is exerted on the test sample. The stress-strain curve, specifically the tensile curve, may be utilized to derive the subsequent data [111].

- a. Ultimate tensile strength (MPa).
- b. Yield Stress (MPa).
- c. Elasticity Modulus (MPa).
- d. Elongation Percentage.
- e. Poisson's Ratio

The Poisson's ratio can be mathematically expressed as the negative lateral strain ratio and the axial strain in a uniaxial stress state. The aforementioned property may be computed and represented by the subsequent equation [73]:

$$\text{Poisson's Ratio } (\nu) = -\frac{\epsilon_{\text{lateral}}}{\epsilon_{\text{axial}}} \quad (3.1)$$

The tensile test had been performed in accordance with the ASTM D638-03 standard, employing a universal testing machine, specifically an Instron model. The crosshead speed, or strain rate, had been set to 5 mm/min, and a load of 5 kN was applied until the sample

experienced failure. The standard specimen for conducting a tensile test is depicted in Figure 3.4.

In accordance with the guidelines provided by reference [112], it is necessary to store all test samples in distilled water at a temperature of  $(37 \pm 1)$  degrees Celsius for a duration of 48 hours subsequent to the completion of polishing and finishing procedures. Each test was conducted under ambient conditions at a temperature of 30 degrees Celsius. The majority of tests were performed using five samples, and the final outcomes were determined by calculating the mean of the five samples [113].



**Figure 3.4 a:** Specimen of Tensile Test Before Conducting the Test.

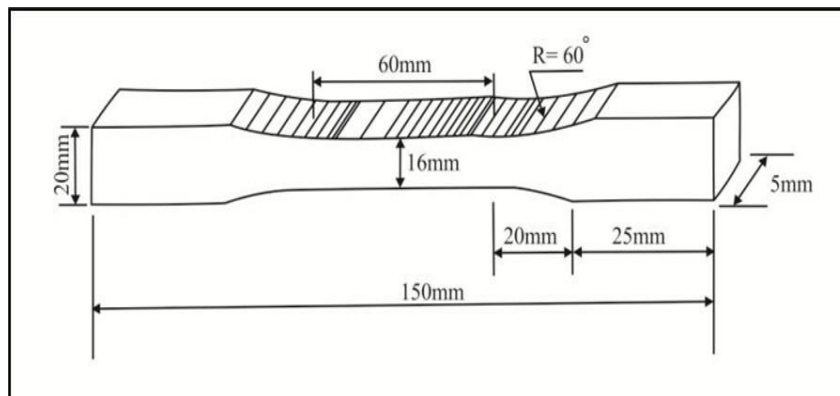


**Figure 3.4 b:** Representation for Standard of Tensile Test sample [114].

### 3.7.2 Compression Test

Poly methyl methacrylate has adequate compressive and tensile strength for complete or partial denture applications [99]. Poly methyl methacrylate exhibits sufficient tensile and compressive strength to be suitable for both partial and complete denture applications. The

compressive strength of a material refers to the level of stress necessary to cause the sample to rupture, indicating the degree of resistance to fracture when subjected to a compression load. The determination of magnitude in compression testing is comparatively challenging, as several materials do not demonstrate prompt fracture under compression, unlike tensile testing. The occurrence of compression failure in composite materials is contingent upon the characteristics of both the matrix and the strengthened materials, as noted in reference [115].

The compression test was conducted in accordance with the guidelines set forth in ASTM D695, utilizing a consistent tensile machine with a crosshead strain rate of 5 mm/min. The sample had been subjected to an applied load of 25 kN until it experienced a break [116]. The compression test's standard for the sample is depicted in Figure 3.5.

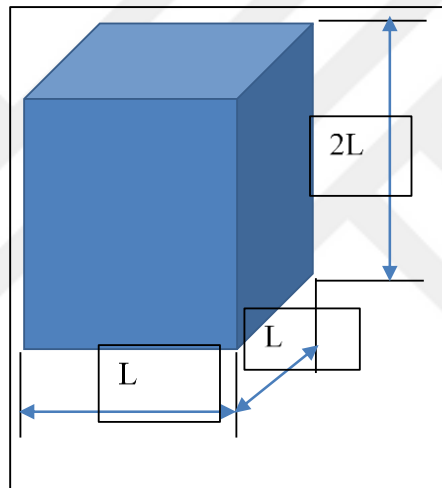


**Figure 3.5:** Representation for Standard of Compression Test sample

### 3.7.3 Flexural Test

Although dentures are subjected to complex and many stresses at the same time, which is the tensile stress that happens at the outer surface (lower surface) of the specimen and the compressive stress that happens on the inner surface (upper surface), as well as the maximum shear strength hence the term "maximum shear strength" that occurs at its interface, The failure of composite materials is influenced by various types of stresses, which are dependent on the reinforcement components and the interaction of strength between the matrix and strengthened materials.

In this test, the specimen is exposed to slow stress, while the specimen in the impact test is exposed to fast stress. Therefore, the flexural strength was verified by applying an increasing load to the flat plane of the laminate until a fracture occurred along a line at the center of the specimen. Flexural strength is probably the most important clinically related property because measurement of these loads allows uniform stress distribution within the interface and also measures the stiffness and fracture resistance of materials to flexural loads. Therefore, through the flexural test the flexural elasticity modulus, from its drawing (load-deflection) curve by the next formula [117] could be calculated :

$$E_B = \frac{PL^3}{4bd^3\delta} = \frac{mL^3}{4bd^3} \quad (3.2)$$

Whereas:  $E_B$  is Flexural Modulus (MPa),  $\delta$  is the beam deflection with a max of the zero and neutral axis at the external beam surface (mm) ,  $P$  is Applied Load (N),  $L$  is Support Span (mm),  $b$  is Width of Sample (mm) ,  $d$  is Depth (Thickness) of specimen (mm) and,  $m$  is Slope of the tangent in the Load- Deflection Curve (N/mm).

The flexural strength of polymer composite is adversely affected by many factors: strain rate, temperature, moisture, and residual monomer. And can be calculated for a rectangular cross-section can be calculated and expressed by the following equation [118]:

$$F.S = \frac{3PL}{2bd^2} \quad (3.3)$$

Whereas:  $F.S$  is Flexural Strength (MPa),  $P$  is Load caused Fracture (N),  $L$  -is Support Span (mm). Flexural strain could be determined and expressed by the following formula [119]:

$$\epsilon_f = \frac{6Dd}{L^2} \quad (3.4)$$

Whereas:

$\epsilon_f$  is Flexural Strain (%),  $D$  is Max Samples Deflection (mm) , Maximum shear stress  $\tau_{max}$  or interfacial shear strength could be determined and expressed by the following formula [120]:

$$\tau_{max} = \frac{3P}{4bd} \quad (3.5)$$

Where:  $\tau_{max}$  is Maximum Shear Stress (MPa).

The high concentration of continuous fibers and good adhesion to the polymer matrix showed an increase in the flexural strength of PMMA [121]. Figure 3.6 demonstrates the location of shear stress in the specimen at three –point bend test.

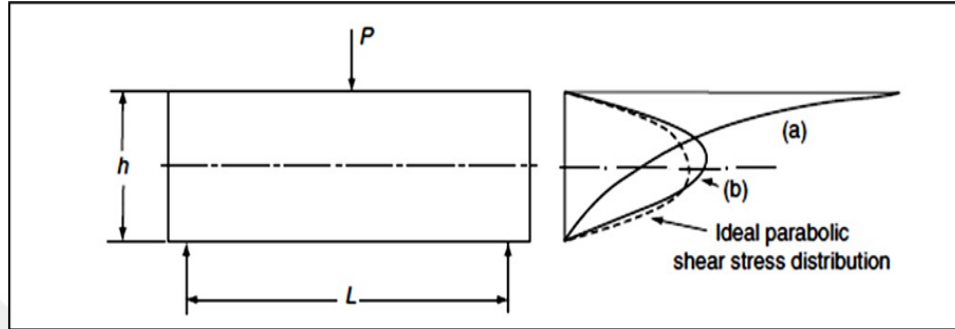


**Figure 3.6:** Shear Distribution Stress in the Test sample [121].

#### 3.7.4 Impact Test

The impact characteristics of materials revolve around their capacity to absorb and dissipate energy, serving as a metric to assess a material's strength when facing impact or shock loading. The impact strength of acrylic denture base materials stands as a critical property, given their susceptibility to fractures upon accidental drops on hard surfaces.

Denture-base acrylic resins undergo various stressors. Intraorally, repetitive forces during mastication can lead to fatigue-related phenomena, while extraorally, high-impact forces may occur due to inadvertent dislodgement of the prosthesis. Consequently, the fracture of the denture base becomes a potential outcome.

The denture base material must exhibit adequate strength to resist fracture upon inadvertent impact while also maintaining its other desirable features. Determining the reasons for denture fractures can be challenging due to the numerous variables involved, such as denture function, handling, and processing [120].

Fracture etiology has been associated with factors such as monomer, residual porosity, the existence of cracks, or inadequate adaptation of the prosthesis to the residual ridge. The impact strength of denture-based resins, such as hot-cured and cold-cured PMMA acrylic

resins, can be improved by adding reinforcement materials to improve the impact strength. Also, the energy required to fracture a specimen generally decreases as the rate of loading increases [88].

The measure of impact strength is denoted in units of kJ/m<sup>2</sup> and is determined by splitting the energy of impact by the cross-sectional area at the point of fracture. This relationship can be mathematically represented using the following [120]:

$$G_c = \frac{U_c}{A_c} \quad (3.6)$$

Where:  $G_c$  is Impact Material Strength (kJ/ m<sup>2</sup>),  $U_c$  is Energy of Impact (kJ) , and  $A_c$  is Cross-Sectional Area of sample (m<sup>2</sup>).

Fracture toughness assessment was utilized to demonstrate the distinctions between traditional and high-impact denture resins. The fracture toughness of a material, which pertains to its capacity to withstand fracture in the presence of a crack, may be mathematically determined and represented by the subsequent formula [122]:

$$K_c = \sqrt{G_c E_B} \quad (3.7)$$

Whereas:  $K_c$  is Fracture Material Toughness (MPa. m<sup>1/2</sup>) or (N/m.m<sup>2/3</sup>) ,  $E_B$  is Flexural Modulus (MPa). The smaller value of fracture toughness the less material toughness.

The polymer materials such as PMMA have low fracture toughness between 1.6-2.15 MPa. m<sup>1/2</sup>. Material Modulus (MPa).

The ISO-180 standard is followed for conducting the impact test, utilizing a pendulum Izod/Charpy impact testing machine of the XJU series. In the Izod test, a cantilevered beam specimen is clamped at one end and held vertically. The specimen is subjected to an impact energy of 5.5 J from a pendulum with an impact velocity of 3.5 m/s, resulting in its fracture.

The samples utilized for impact testing may possess or lack a notch. The unnotched Izod impact test is a singular-point evaluation that quantifies a material's capacity to withstand impact from a pendulum in motion. The Izod impact is a measure of the minimum amount of kinetic energy required to initiate and propagate a fracture in the sample until it ultimately fractures. The standard sample for impact testing is depicted in Figure 3.7, Figure 3.8 [123].

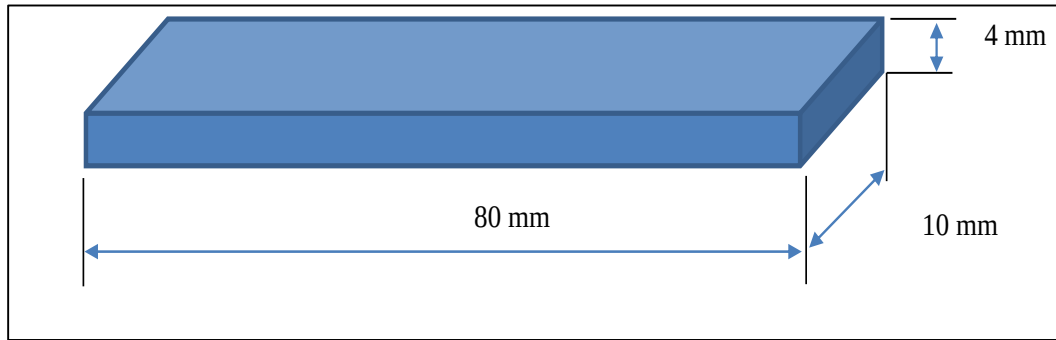


**Figure 3.7:** Diagram for Standard Impact Testing Sample.



**Figure 3.8:** Specimen of Impact Test before and After Conducting the Test.

### 3.7.5 Hardness Test

The material's hardness serves as an indicator of its overall mechanical characteristics. The property of hardness pertains to a solid substance and denotes its capacity to resist surface damage caused by workability, penetration, indentation, wear, cutting, and scratching resulting from the application of a sharp point. It is also indicative of the material's surface durability. The magnitude of hardness is regarded as a measure of potency and coherence of structure and is utilized as an indirect means to anticipate the resistance to wear of dental substances.

Assuming that it denotes the level of susceptibility of the denture base material to abrasion and scratching. The mechanical strength of a material is closely related to its hardness. Consequently, materials with lower hardness values tend to exhibit lower yield strength. In the case of PMMA, the hardness is typically measured using the Shore D scale. The hardness

test is contingent upon various factors, including the magnitude of the test load, the duration of the dwell time, the nature of the interatomic or intermolecular bonds, the condition of the surface, the temperature, the type of solution, and the configuration of the indenter. There exist various factors that impact the hardness levels of polymer composite materials, including but not limited to the velocity of elastic recovery, the size of particles, particles' volume fraction, chemical makeup, chain structure (including cross-linking), and chain structure [124].

The ASTM D2240 standard is followed for conducting the hardness test, utilizing the Dorumeter hardness test equipment of Shore D type. The load applied during the test is maintained at 50 N, and the measuring process involves a depressing time of 15 seconds. In order to conduct zone testing and measure the depth of indentation, it is imperative that the surface of the specimens be smooth. The scale utilized for this purpose typically features a range of hardness numbers, with graduations ranging from 0 to 100. The magnitude of hardness exhibits a high degree of sensitivity with respect to factors such as the sample thickness, the sample diameter, and the distance from the edge, particularly when the latter exceeds 12 mm.

Thus, it is necessary for the specimen to have a minimum thickness of 4mm and a diameter greater than 30mm. The specimens underwent seven tests at different positions simultaneously, and the resulting average magnitude was recorded. The standard specimen for hardness testing is depicted in Figure 3.9, and Figure 3.10.

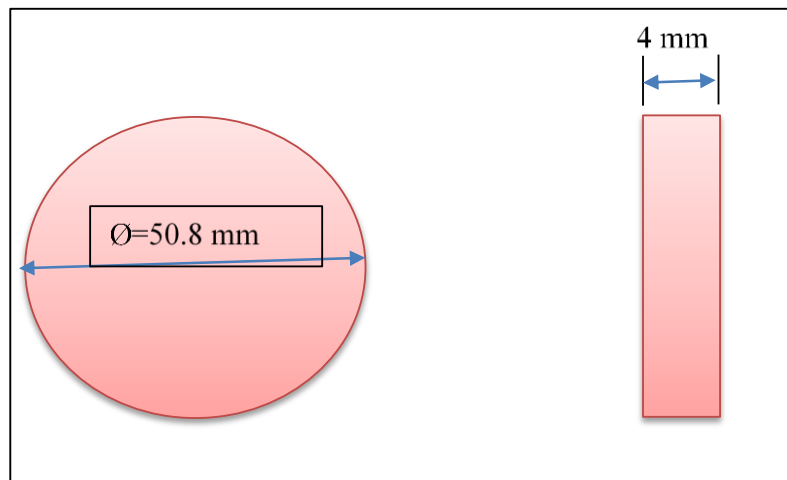


**Figure 3.9:** Representation of Standard Hardness Test Sample.



**Figure 3.10:** Schematic Specimen for Standard Specimen of Hardness Test.

### 3.7.6 Corrosion Test

The present study involves an investigation of the corrosion properties of specimens immersed in a solution of saliva. Table 3.6 presents the chemical analysis of the saliva solution.

**Table 3.6:** Chemical Analysis of Saliva Solution [125].

| NO. | Component                                           | (gM. /L) $\times 10^{-3}$ |
|-----|-----------------------------------------------------|---------------------------|
| 1   | NaCl                                                | 8000                      |
| 2   | CaCl <sub>2</sub>                                   | 140                       |
| 3   | KCl                                                 | 400                       |
| 4   | NaHCO <sub>3</sub>                                  | 350                       |
| 5   | Glucose                                             | 1000                      |
| 6   | MgCl <sub>2</sub> .6H <sub>2</sub> O                | 100                       |
| 7   | Na <sub>2</sub> HPO <sub>4</sub> .2H <sub>2</sub> O | 60                        |
| 8   | KH <sub>2</sub> PO <sub>4</sub>                     | 60                        |
| 9   | Mg SO <sub>4</sub> .7H <sub>2</sub> O               | 60                        |

The open circuit potential was measured using an experimental setup consisting of a glass electrolytic cell with a capacity of 500 mL. The samples were subjected to immersion in a saliva solution during the testing process. The assessment of the functioning electrode potential was conducted utilizing a saturated calomel electrode (SCE). A voltmeter is utilized

in a state of saturation to establish a connection between a functional electrode and a reference electrode. A duration of 3 hours was allocated for the open circuit potential assessment for each of the specimens. The electrochemical experiments were conducted using 3-electrode cells that were filled with electrolytes that closely resembled the composition of saliva. The Pt electrode was utilized as the counter electrode, while the SCE was employed as the reference electrode. The specimen electrode, conforming to ASTM guidelines, was chosen as the functioning electrode.

The polarization potentiodynamic curves were generated and the Tafel plots were utilized to determine the corrosion potential and the corrosion current density ( $i_{corr}$ ) by analyzing the cathodic and anodic branches. The experiment was conducted by incrementally varying the potential at a scanning rate of 0.40mV/s, starting from an initial potential of 250mV below the open circuit potential and continuing until a potential of 250mV above the open circuit potential was reached.

The formula presented below was utilized to determine the corrosion rate evaluation [126]

$$\text{Corrosion Rate (mpy)} = 0.13 i_{corr} (EW)/A \cdot \rho \quad (3.8)$$

$EW$  is stands for the equivalent weight ( $g/eq$ ), density ( $g/cm^3$ )  $\rho$  0.13 = metric and time conversion factor, stands for the area ( $cm^2$ ),  $i_{corr}$  is Stands for the current density ( $\mu A/cm^2$ ).

Figure 3.11 illustrates a representation of a standard corrosion test sample.

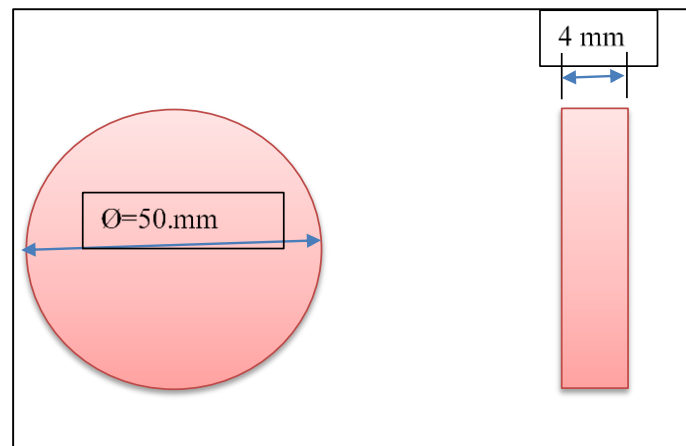


**Figure 3.11:** Representation of Standard Corrosion Test Sample.

### 3.8 MORPHOLOGY TESTS

#### 3.8.1 Light Optical Microscope (LOM) Test

Optical microscopy was employed to examine the microscopic structure, with the aim of identifying extant phases and determining the size and form of the grains. This was achieved through a process of grinding, polishing, and etching in a solution (swab). The experiment was conducted at the lab for preparing specimens, utilizing a BEL-PHOTONICS microscope, as depicted in Figure 3.12. This lab is situated within the Department of Metallurgy's Laboratories for Thermal Transactions at the University of Babylon.



**Figure 3.12:** Light Optical Microscope.

## **4. RESULTS AND DISCUSSIONS**

### **4.1 INTRODUCTION**

This chapter delves into and focuses on the empirical outcomes of the study, intricately discussed through tables and figures. It encompasses the meticulous fabrication of PMMA composite and laminated materials employed in prosthetic denture bases. PMMA serves as the matrix, fortified with an array of nano- and micro-particles of  $\text{SiO}_2$ .

A myriad of targeted examinations have been conducted to meticulously assess the distinctive attributes of these composite materials. The resultant findings align seamlessly with the experiment's objectives. Visual representation is achieved by graphing the outcomes on curves, employing sophisticated curve-fitting software to accentuate the nuanced specifics.

### **4.2 MECHANICAL TESTS**

#### **4.2.1 Hardness Test Results**

The impact of incorporating ceramic particles of varying sizes, specifically micro and nano-silica, with varying volume fractions, on the hardness of the PMMA matrix is demonstrated in Figures 4.1 and 4.2. The Figures illustrate a positive correlation between the volume fraction and hardness magnitudes for both particle sizes in the PMMA composite materials. The observed phenomenon can be attributed to the brittleness and elevated hardness of the micro and nano-silica particles in comparison with the isolated PMMA resin. In addition, concerning the phenomenon of wettability and the resultant bonding strength between the matrix and stated particles, it could be observed that such interactions enhance the surface hardness of the material by impeding the matrix movement in the direction of the applied stress [127].

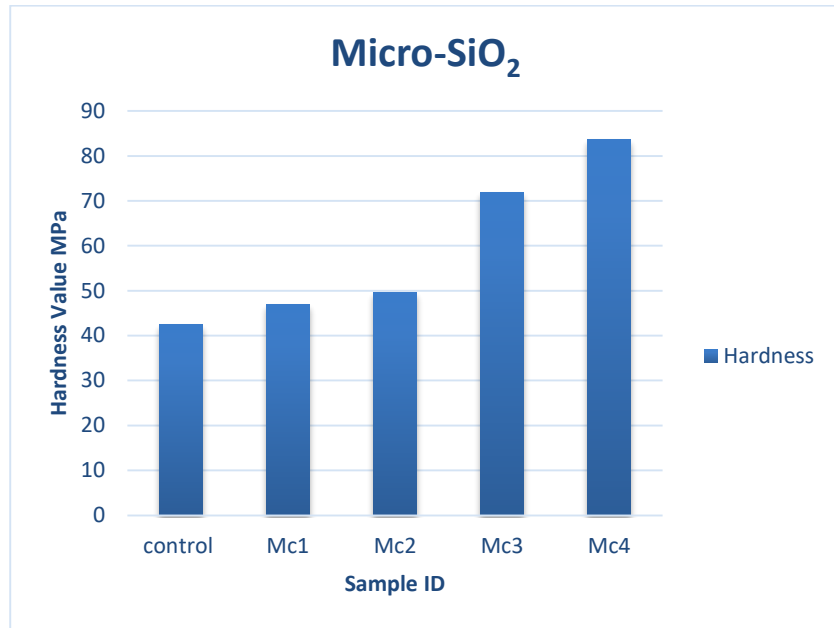


**Figure 4.1:** Hardness Magnitudes for PMMA Samples After Adding Micro-Sio<sub>2</sub> In Various Ratios.

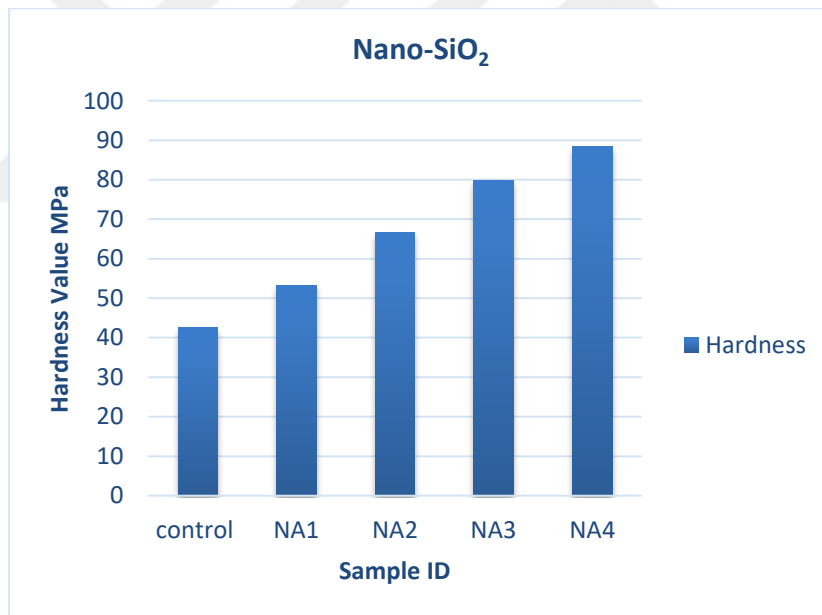


**Figure 4.2:** Hardness Magnitudes For PMMA Samples After Adding Nano-Sio<sub>2</sub> in Various Ratios.

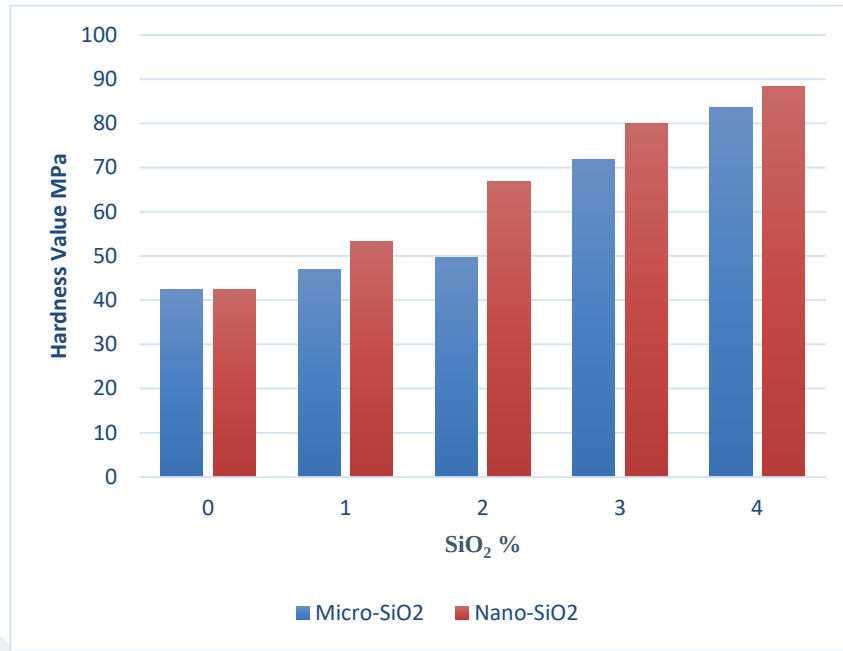


**Figure 4.3:** The Differences Between Hardness Magnitudes For PMMA Before and After Adding SiO<sub>2</sub> in Nano And Micro Particle Size.

As depicted in Figure 4.3, nano-SiO<sub>2</sub> particles have a discernible impact on the PMMA composite samples' hardness, surpassing that of micro-silica particles. Figure 4.4 shows the Hardness improvement rate, Consequently, the hardness magnitudes of the first set of samples (PMMA-nano-SiO<sub>2</sub>) composite exceed those of the second group of samples (PMMA-micro-SiO<sub>2</sub>) composite.

The observed phenomenon can be attributed to the enhancement of the mechanical characteristics concomitant with incorporating SiO<sub>2</sub> nanoparticles. The results indicate that incorporating 4% nano-SiO<sub>2</sub> into PMMA composite materials significantly increased hardness magnitudes. Specifically, the hardness magnitudes increased from 42.5 MPa (for the PMMA control sample) to 88.4 MPa for the PMMA-4% nano-SiO<sub>2</sub> composite materials. This represents an improvement rate of 108%.

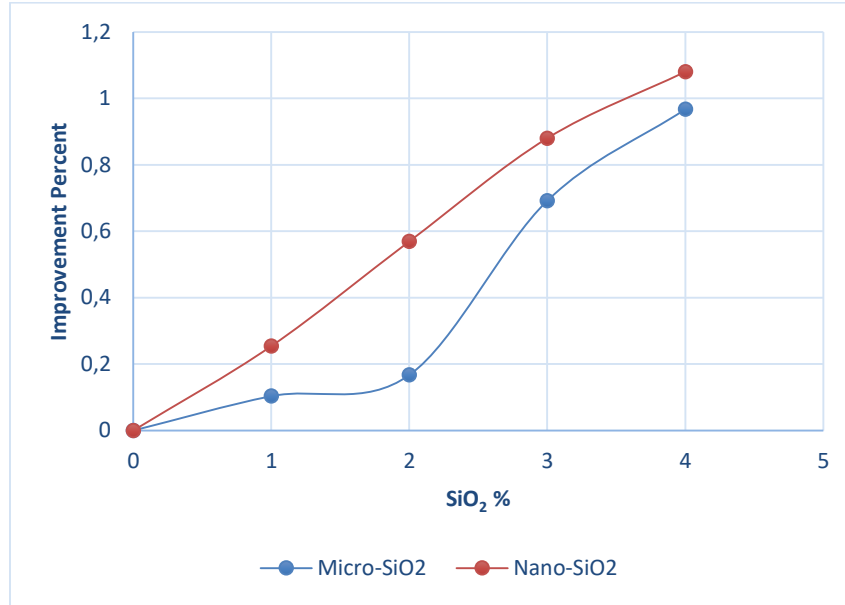


**Figure 4.4:** Hardness Improvement Rate For PMMA Samples After Adding Various Ratios of Nano And Micro-SiO<sub>2</sub>.

#### 4.2.2 Impact Test Results

The current investigation performed an impact assessment on PMMA composite specimens utilized as materials for prosthetic denture bases. Figures 4.5 and 4.6 illustrate the impact strength magnitudes resulting from the inclusion of ceramic particles of micro- and nano-silica kinds, with different volume fractions as seen in Figure 4.7, on the impact strength of the PMMA matrix. The presented figures demonstrate a negative correlation between the volume fraction and impact strength magnitudes for both types of particles in the two PMMA composite material groups. The observed phenomenon can be attributed to an escalation in the number of particles, which serve as sites for the accumulation of stress, resulting in the formation of regions of localized stress levels that culminate in structural failure.

Moreover, the inherent characteristic of said particles is brittleness and reduced resistance to impact loads when compared to PMMA resin. This may also be attributed to micro- and nanoparticle aggregation, which possesses high surface energy [128].

Furthermore, using nano-SiO<sub>2</sub> gives better results than using similar ratios, but with a smaller microparticle size, as demonstrated in Figure 4.8.

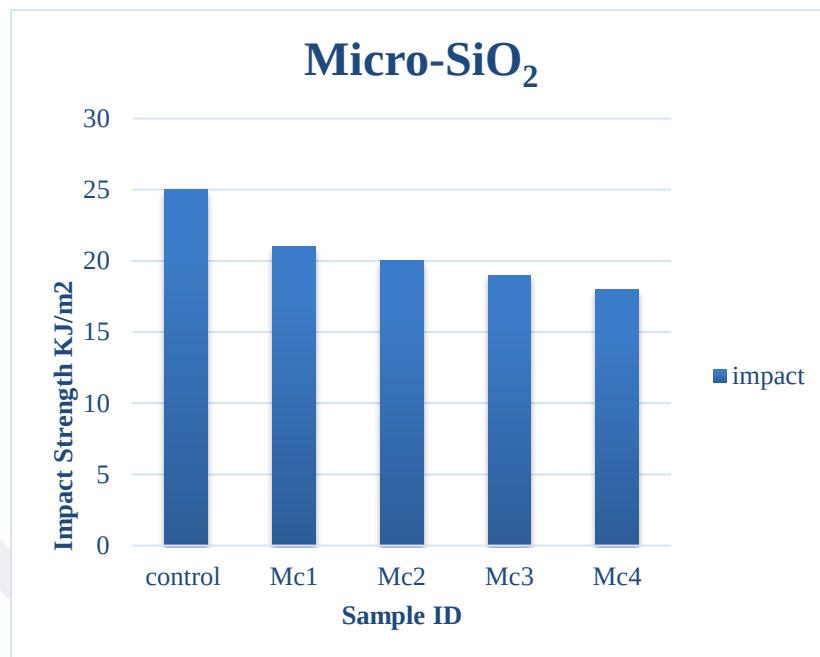


**Figure 4.5:** Impact Magnitudes for PMMA Samples After Adding Micro-SiO<sub>2</sub> in Various Ratios.

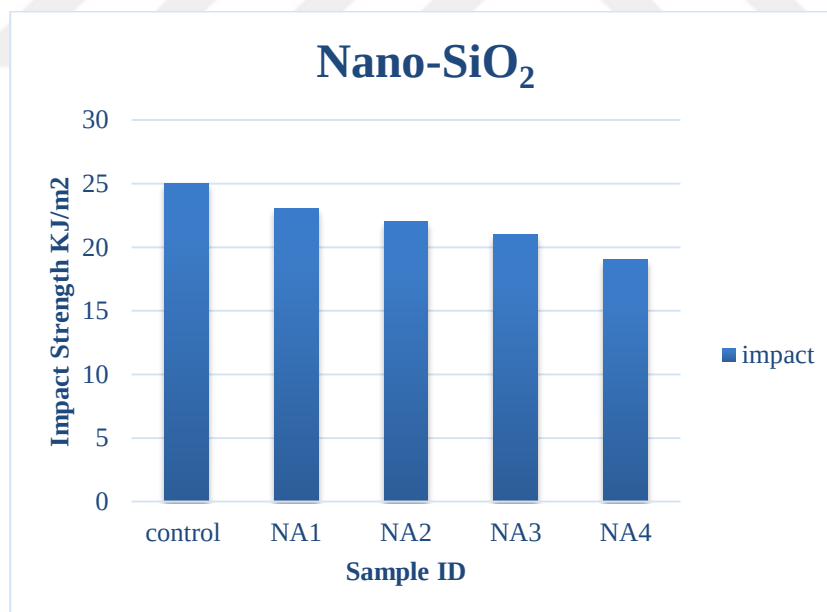


**Figure 4.6:** Impact Magnitudes for PMMA Samples After Adding Nano-SiO<sub>2</sub> In Various Ratios.

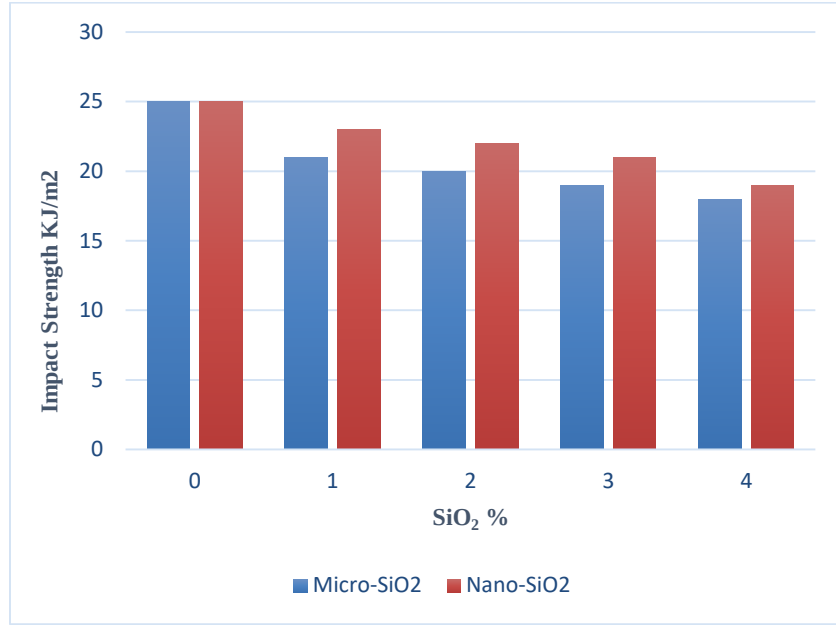


**Figure 4.7:** The Differences Between Impact Magnitudes For PMMA Before and After Adding SiO<sub>2</sub> in Nano and Micro Particle Size.

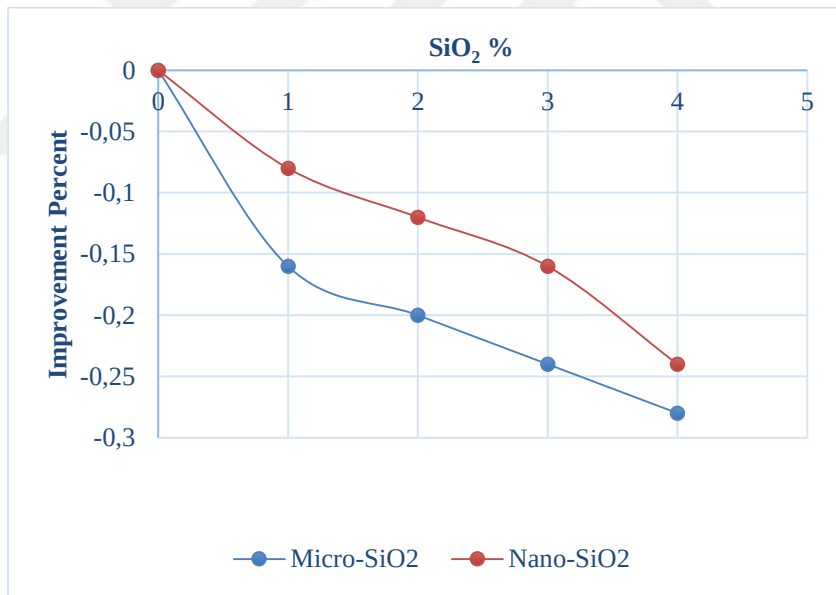


**Figure 4.8:** Impact Improvement Rate For PMMA Samples After Adding Various Ratios of Fracture Toughness.

Figures 4.9 and 4.10 depict the impact of incorporating ceramic particles of both micro- and nano-silica types, with varying volume fractions, on the fracture toughness of the PMMA

matrix. The figures illustrate a decrease in fracture toughness magnitudes with an increase in volume fraction for both kinds of particles in both sets of PMMA composite materials.

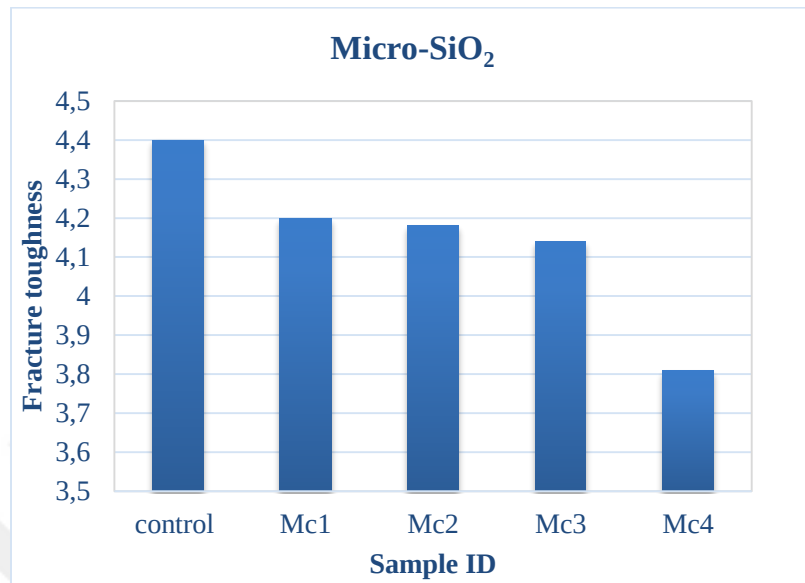


**Figure 4.9:**Fracture Toughness Magnitudes For PMMA Samples After Adding Micro-Sio<sub>2</sub> in Various Ratios.

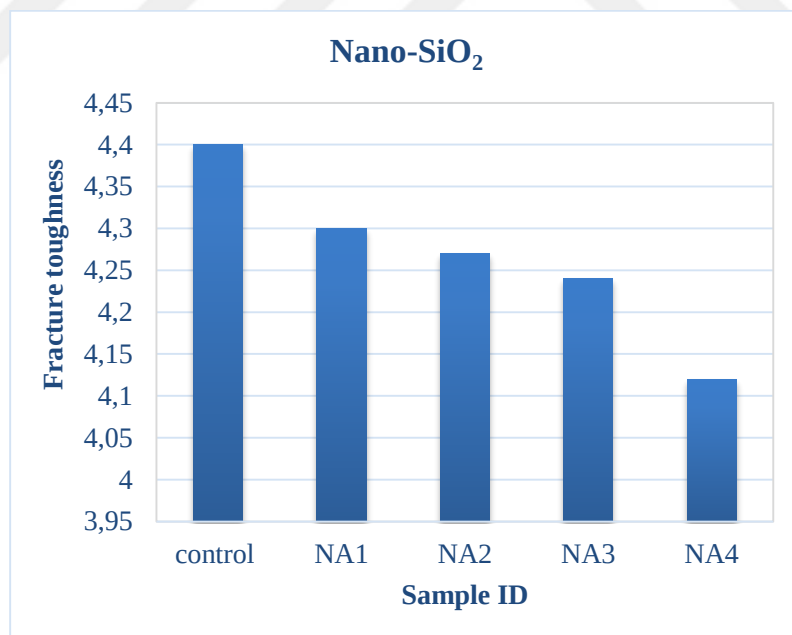


**Figure 4.10:** Fracture Toughness Magnitudes For PMMA Samples After Adding Nano-Sio<sub>2</sub> in Various Ratios.

Furthermore, using nano-SiO<sub>2</sub> gives better results than using similar ratios, but with a smaller microparticle size, as demonstrated in Figure 4.11. Figure 4.12 demonstrates the enhancement in fracture toughness for PMMA samples following the incorporation of different ratios of nano- and micro-SiO<sub>2</sub>.

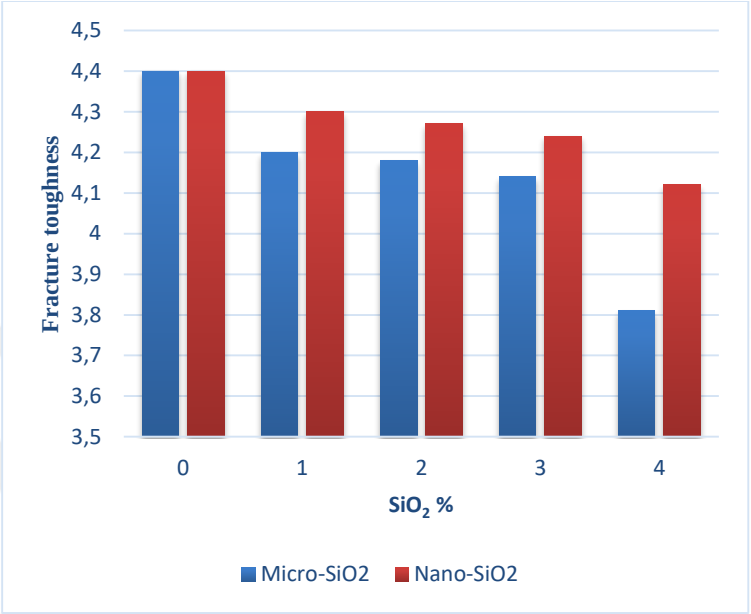


**Figure 4.11:** The Differences Between Fracture Toughness For PMMA Before and After Adding SiO<sub>2</sub> in Nano and Micro Particle Size.

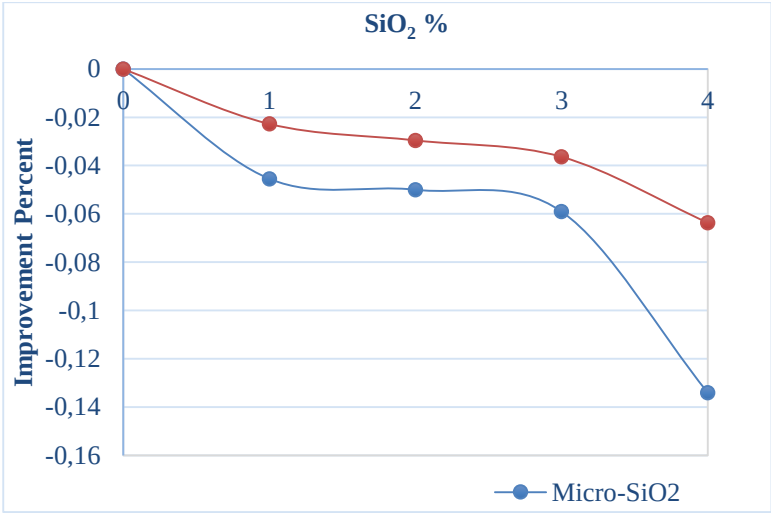


**Figure 4.12:** Fracture Toughness Improvement Rate For PMMA Samples After Adding Various Ratios of Nano and Micro-SiO<sub>2</sub>.

### 4.2.3 Modulus of Elasticity

Figures 4.13 and 4.14 depict the magnitudes of the elasticity modulus for PMMA that has been infused with ceramic particles ranging from micro- to nano-silica varieties. Figures 4.13 and 4.14 depict the correlation between the elastic modulus of nSiO<sub>2</sub> and μSiO<sub>2</sub> particles in PMMA resin and the elastic modulus of the samples in the first and second sets. The findings indicate that there is a positive correlation between the volume fraction of particles and the magnitudes of the elasticity modulus for both sets of particles. This phenomenon could potentially be attributed to the reinforcing mechanism as well as the bonding strength and complete interfacial adhesion between the reinforcement substances and PMMA matrix, as previously discussed.

Furthermore, the elastic modulus of nSiO<sub>2</sub> and μSiO<sub>2</sub> particles exhibits a significant increase in comparison to that of PMMA resin. The aforementioned particles hinder the slippage of PMMA chains by acting as pinning sites, thereby necessitating a significant amount of stress to cause the bowing of the chains in the confined interstitial regions between the particles [123].

The impact of incorporating (nSiO<sub>2</sub> and SiO<sub>2</sub>) particles on the composite's elasticity modulus of samples is evident from Figure 4.15, with a more pronounced effect observed for (nSiO<sub>2</sub> and SiO<sub>2</sub>) particles compared to other particles. The composite samples belonging to the second set (nSiO<sub>2</sub>-PMMA) exhibit greater magnitudes of elasticity modulus in comparison to the composite samples belonging to the first group (μSiO<sub>2</sub>-PMMA). This is due to the enhancement, which is related to the incorporation of SiO<sub>2</sub> particles. Thus, the improvement rate of elasticity modulus for PMMA with both (nSiO<sub>2</sub> and μSiO<sub>2</sub>) is compatible with SiO<sub>2</sub> ratios, as shown in Figure 4.16.

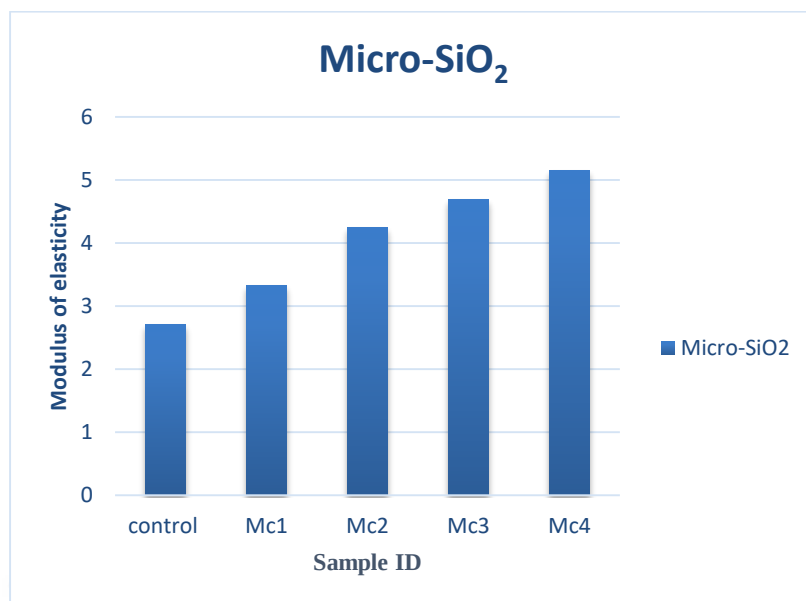


**Figure 4.13:** Modulus of Elasticity Magnitudes For PMMA Samples After Adding Micro-Sio<sub>2</sub> in Various Ratios.

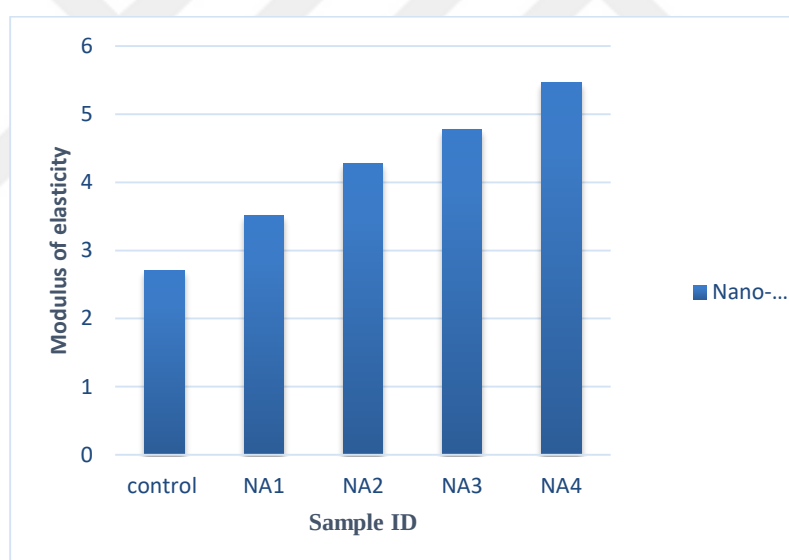


**Figure 4.14:** Modulus of Elasticity Magnitudes For PMMA Samples After Adding Nano-Sio<sub>2</sub> in Various Ratios.

In Figure 4.15, we can see how the elasticity modulus of PMMA changed before and after nano and microparticles of SiO<sub>2</sub> were added.

Furthermore, Figure 4.16 details the rate of improvement in the modulus of elasticity for PMMA samples after the inclusion of various ratios of nano- and micro- SiO<sub>2</sub>.

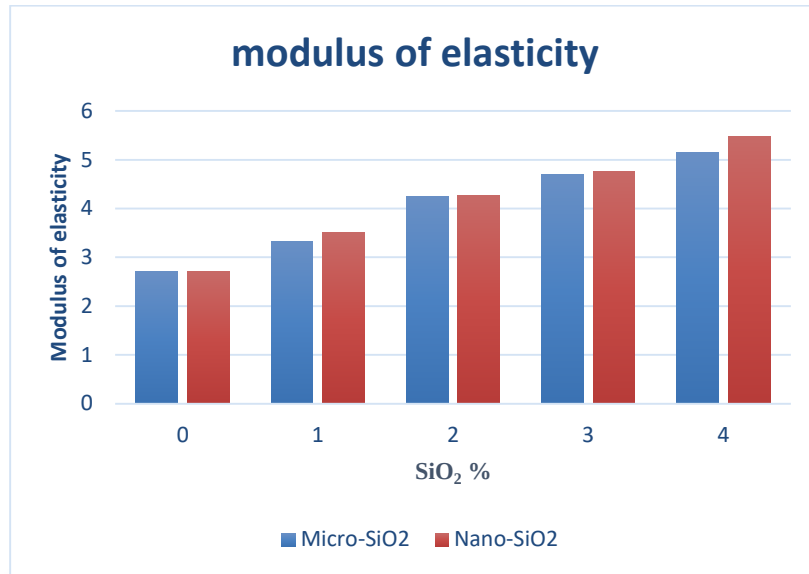


**Figure 4.15:** The Differences Between Elasticity Modulus For PMMA Before and After Adding SiO<sub>2</sub> in Nano and Micro Particle Size.

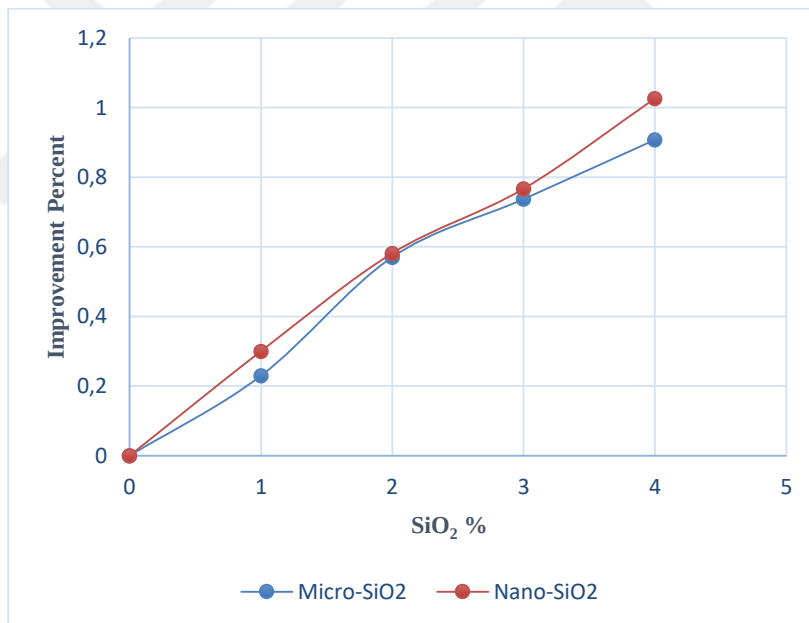


**Figure 4.16:** Modulus of Elasticity Improvement Rate For PMMA Samples After Adding Various Ratios of Nano and Micro-SiO<sub>2</sub>.

#### 4.2.4 Compressive Strength

Figures 4.17 and 4.18 depict the correlation between the volume fraction of particles composed of (nSiO<sub>2</sub> and  $\mu$ SiO<sub>2</sub>) in PMMA resin and the compression strength of the samples

belonging to the initial and subsequent groups. The observed trend indicates that the compression strength magnitudes exhibited a positive correlation with the volume fraction of particles for both sets of particles, without distinction between particle kinds. This is due to the mechanism of strengthening and the characteristics of bonding. The observed phenomenon may be attributed to the superior compressive strength exhibited by nSiO<sub>2</sub> and SiO<sub>2</sub> particles in comparison to PMMA resin.

The impact of incorporating (nSiO<sub>2</sub> and  $\mu$ SiO<sub>2</sub>) particles on the compression strength of the composite specimen is more significant than that of the HA particle, as illustrated in Figure 4.19. The compressive strength magnitudes and rates of the first group (SiO<sub>2</sub>-PMMA) composite samples were found to be lower than those of the second group (nSiO<sub>2</sub>-PMMA) composite samples, as observed. The reason for the enhancement of mechanical features is attributed to the incorporation of SiO<sub>2</sub> particles, which possess a high compressive strength in comparison. Thus, the improvement rate of compressive strength for PMMA with both (nSiO<sub>2</sub> and SiO<sub>2</sub>) is compatible with SiO<sub>2</sub> ratios, but using nanoparticles gives better results compared with SiO<sub>2</sub>, as shown in Figure 4.20.



**Figure 4.17:** Compressive Strength Magnitudes For PMMA Samples After Adding Micro-Sio<sub>2</sub> in Various Ratios.

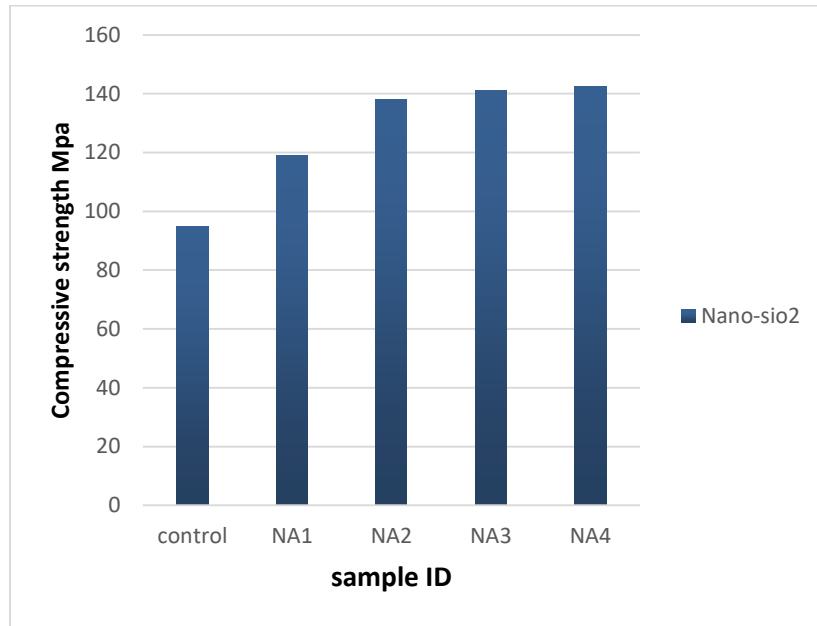


**Figure 4.18:** Compressive Strength Magnitudes For PMMA Samples After Adding Nano-Sio<sub>2</sub> in Various Ratios.

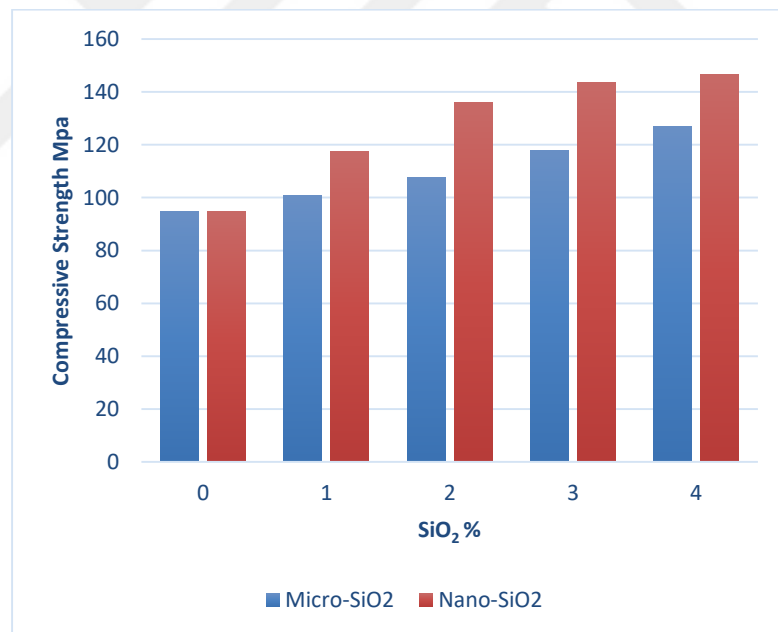


**Figure 4.19:** The Differences Between Compressive Strength For PMMA Before and After Adding SiO<sub>2</sub> in Nano and Micro Particle Size.

Figure 4.20 displays the improvement rate in compressive strength for PMMA samples after incorporating various ratios of nano- and micro- SiO<sub>2</sub>.

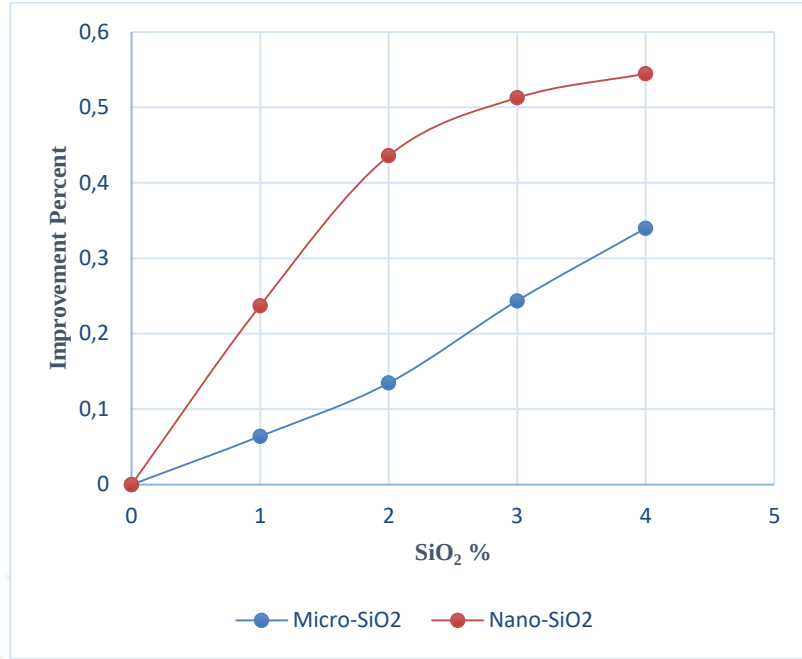


**Figure 4.20:** Compressive Strength Improvement Rate For PMMA Samples After Adding Various Ratios of Nano and Micro-SiO<sub>2</sub>.

#### 4.2.5 Tensile Strength

Figures 4.21 and 4.22 depict the magnitudes of tensile strength observed in PMMA samples that have been infused with ceramic particles of both micro and nano-silica varieties. Figures 4.22 and 4.23 depict the correlation between the volume fraction of nSiO<sub>2</sub> and  $\mu$ SiO<sub>2</sub> particles in PMMA resin and the tensile strength of the specimens belonging to the first and second groups. The observed trend indicates that the tensile strength magnitudes exhibited a positive correlation with the volume fraction of particles for both sets of particles, irrespective of the particle kind. This phenomenon could be attributed to the bonding strength, reinforcing mechanism, and the formation of a complete interface between the strengthening substances and the PMMA matrix, as previously discussed.

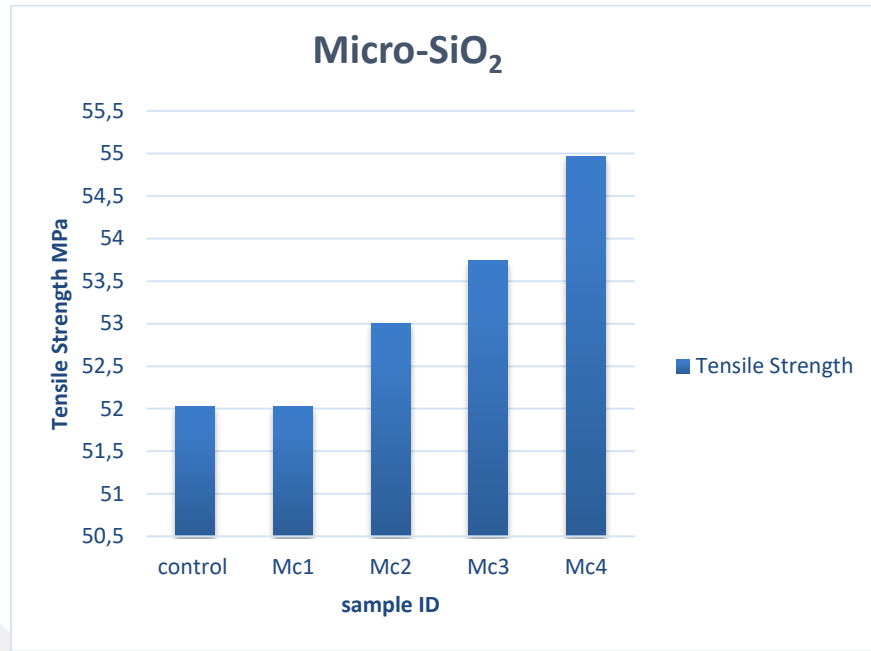


**Figure 4.21:** Tensile Strength Magnitudes For PMMA Samples After Adding Micro-SiO<sub>2</sub> in Various Ratios.

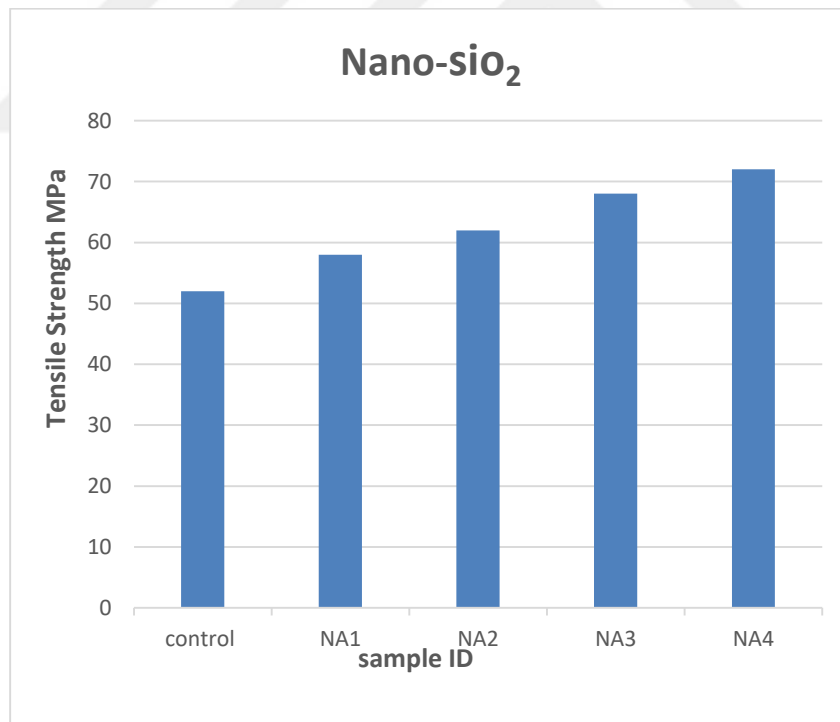


**Figure 4.22:** Tensile Strength Magnitudes For PMMA Samples After Adding Nano-SiO<sub>2</sub> in Various Ratios.

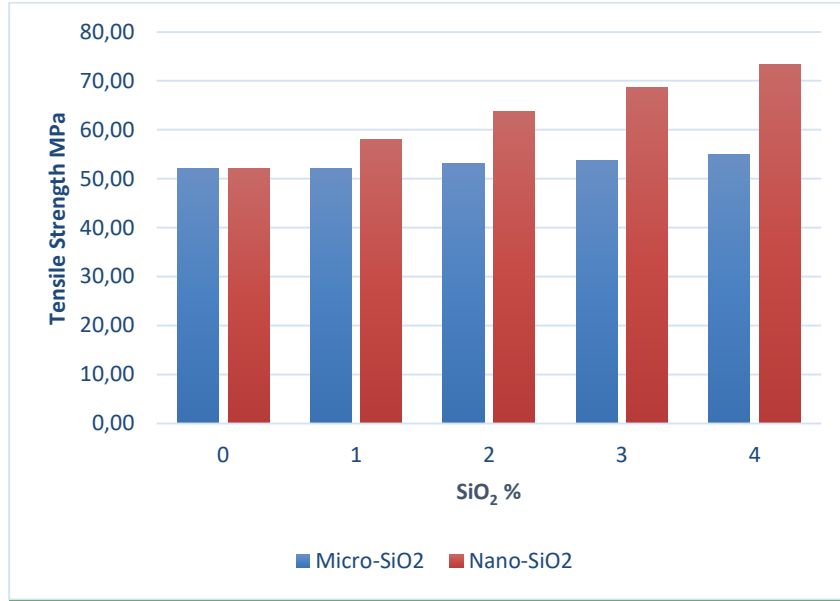


**Figure 4.23:** The Differences Between Tensile Strength For PMMA Before and After Adding SiO<sub>2</sub> in Nano and Micro Particle Size.

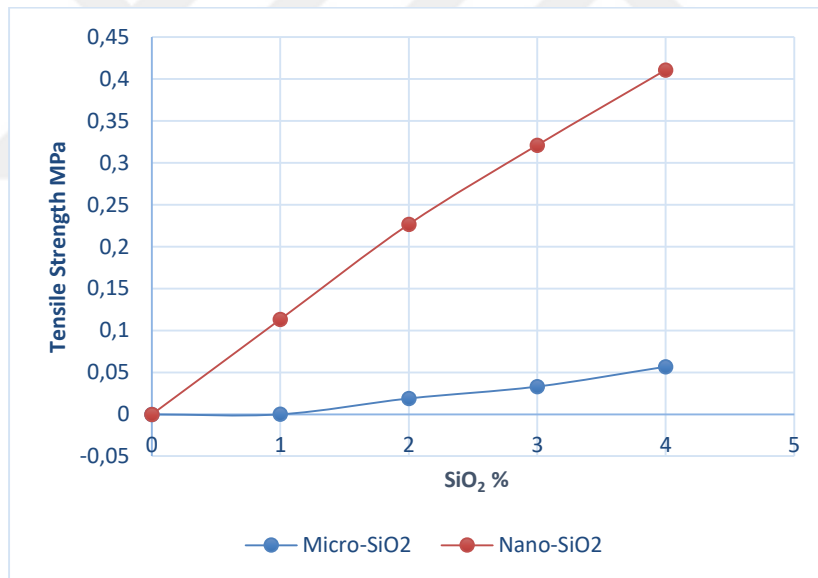


**Figure 4.24:** Tensile Strength Improvement Rate For PMMA Samples After Adding Various Ratios of Nano and Micro-SiO<sub>2</sub>.

In Table 4.1, the hardness, impact, fracture toughness, modulus of elasticity, compressive strength, and tensile strength results for various samples are summarized. First of all, the control sample exhibited a hardness of 42.5, an impact value of 25, and a fracture toughness of 4.4. Additionally, the modified concrete samples (Mc1, Mc2, Mc3, and Mc4) illustrated

an increase in hardness values: Mc1 (46.9), Mc2 (49.6), Mc3 (71.9), and Mc4 (83.6), while their impact values decreased from 21 to 18. But for fractures, toughness descends slowly from (4.2) to (3.81). Moreover, the new admixture samples (NA1, NA2, NA3, NA4) displayed hardness values of 53.3, 66.7, 79.9, and 88.4, respectively. However, their impact values fell from 23 to 19, just like dropping fracture toughness from (4.3) to (4.12). After that, we can illustrate the gradual growth of the modulus of elasticity value from (3.3) to (5.1) for micro samples and the comparison from (3.5) to (5.48) for nano samples. When the compressive strength column is seen, the number is sharply peaking: 95, 100, 113, 119, and 127 in the order of micro, and 119, 138, 141, and 142 for nano. The tensile strength slightly went up for Mc from 52 to 54.9, but it clearly appears that it rocketed to 72.4 from 58.

**Table 4.1:** Summary of the Obtained Results.

| <b>Samples</b> | <b>Hardness</b> | <b>Impact</b> | <b>Fracture toughness</b> | <b>Modulus of elasticity</b> | <b>Compressive strength</b> | <b>Tensile Strength</b> |
|----------------|-----------------|---------------|---------------------------|------------------------------|-----------------------------|-------------------------|
| Control        | 42.5            | 25            | 4.4                       | 2.73                         | 95                          | 52                      |
| Mc1            | 46.9            | 21            | 4.2                       | 3.3                          | 100                         | 52                      |
| Mc2            | 49.6            | 20            | 4.18                      | 4.18                         | 113                         | 53                      |
| Mc3            | 71.9            | 19            | 4.14                      | 4.79                         | 119                         | 53.7                    |
| Mc4            | 83.6            | 18            | 3.81                      | 5.1                          | 127                         | 54.9                    |
| NA1            | 53.3            | 23            | 4.3                       | 3.5                          | 119                         | 58                      |
| NA2            | 66.7            | 22            | 4.27                      | 4.19                         | 138                         | 63                      |
| NA3            | 79.9            | 21            | 4.24                      | 4.81                         | 141                         | 68.5                    |
| NA4            | 88.4            | 19            | 4.12                      | 5.48                         | 142                         | 72.4                    |

### 4.3 ANTIBACTERIAL TEST RESULTS

The antibacterial activity can inhibit the growth of Streptococcus bacteria. The antibacterial efficacy of nanocomposites has been evaluated using zone of inhibition and bacterial amount measurement techniques, which have demonstrated their non-toxic nature [129], [130], [131].

Following the inoculation of specimens onto various media such as blood agar, MacConkey agar, Mannitol salt agar as depicted in figure 4.25, and nutrient agar (as illustrated in figures 4.26 and 4.27), the resultant colonies were subjected to culture-based analysis. Subsequently, the specimens underwent microscopic examination after being subjected to Gram staining. The differential stain is employed to differentiate between gram-negative and gram-positive bacteria. Subsequently, biochemical assays were employed to authenticate the identification of the bacteria that were unearthed. These assays encompassed the Catalase test, which was employed to identify Gram-positive Staphylococcus aureus, and the IMVC test, which was applied to detect Gram-negative bacteria such as E. coli (Pseudomonas aeruginosa, Enterobacter sp.) [132], [108].

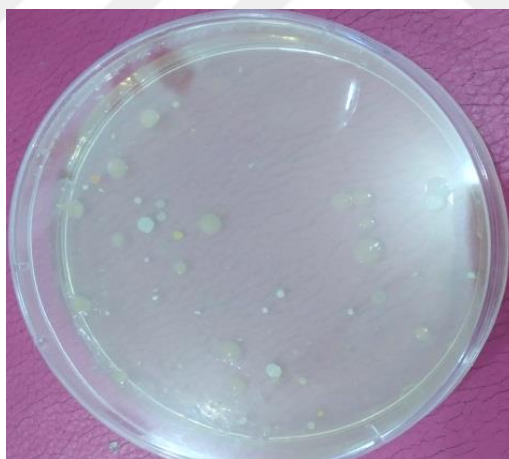


**Figure 4.25:** Different Kinds of Bacteria Appear on the Specimen PMMA General Medium (Nutrient Agar).

Table 4.2 provides a breakdown of the various types of bacteria isolated from the specimens.

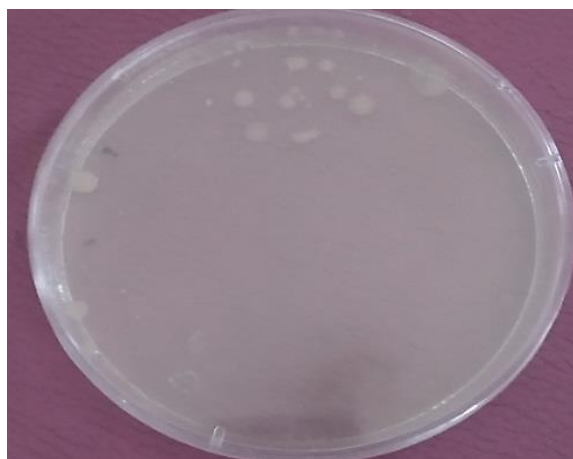


**Figure 4.26:** Appears Kinds of Bacteria of PMMA- 1% Msio<sub>2</sub> Sample on Normal Medium (Nutrient Agar).

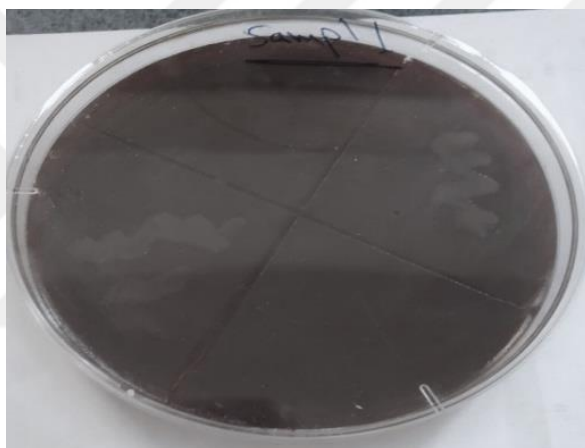


**Figure 4.27:** Appears Kinds of Bacteria of PMMA And PMMA- 1% Msio<sub>2</sub> Samples on (Blood Agar).

**Table 4.2:** Isolated Bacteria Kinds from the Specimens.

| Specimen                 |                       | Bacteria Kind   |                        |
|--------------------------|-----------------------|-----------------|------------------------|
|                          | Staphylococcus aureus | Enterobacter sp | Pseudomonas aeruginosa |
| PMMA                     | +                     | -               | +                      |
| PMMA- 1% $\text{SiO}_2$  | -                     | -               | -                      |
| PMMA- 1% $\text{mSiO}_2$ | -                     | +               | +                      |

**Table 4.2:** Isolated Bacteria Kinds from the Specimens “Table Continued”.

|                           |   |   |   |
|---------------------------|---|---|---|
| PMMA- 2%nSiO <sub>2</sub> | - | - | - |
| PMMA- 2%mSiO <sub>2</sub> | - | - | - |
| PMMA- 3%nSiO <sub>2</sub> | - | - | - |
| PMMA- 3%mSiO <sub>2</sub> | - | - | - |
| PMMA- 4%nSiO <sub>2</sub> | - | - | - |
| PMMA- 4%mSiO <sub>2</sub> | - | - | - |

#### 4.4 MORPHOLOGY TESTS

The changes in surface morphology are evaluated for the following prepared specimens:

- a. PMMA.
- b. (PMMA-1% Micro-silicon oxide) composite.
- c. (PMMA-1% Nano-silicon oxide) composite.
- d. (PMMA-2% Micro-silicon oxide) composite.
- e. (PMMA-2% Nano-silicon oxide) composite.
- f. (PMMA-3% Micro-silicon oxide) composite.
- g. (PMMA-3% Nano-silicon oxide) composite.
- h. (PMMA-4% Micro-silicon oxide) composite.
- i. (PMMA-4% Nano-silicon oxide) composite.

The present study investigated the morphological characteristics of a composite material subsequent to a mechanically induced fracture. LOM micrographs were utilized to analyze samples of polymer composites with varying compositions.

The morphology of polymer composites plays a crucial role in determining their characteristics. The aforementioned factors—component proportion, particle shape, particle size distribution, particle size, melt viscosities of components, and processing situations—are determinants of the outcome. The majority of heterogeneous systems exhibit a morphology characterized by the dispersion of one phase within another phase. The formation of the matrix phase usually occurs through the predominant component with a higher volume proportion. At a particular volume proportion, the strengthened and matrix phases exhibit interchangeability, known as phase inversion. This phenomenon holds significance as the composite's features, including stiffness and impact strength, undergo advantageous modifications [133].

Furthermore, micro- or nanoparticles and microscopic particles in the reinforcement of polymers could have various influences on polymer composites. Compatibilization occurs when both components are well-adhered to the particles. These particles can accumulate in one of the components, and morphological change can occur since the modified component ratio corresponds to phase inversion [133].

Figures 4.28–4.36 show the difference in image morphology between the surface and surface morphology of PMMA composites, and PMMA-1%  $\mu\text{SiO}_2$  and PMMA-1%  $\text{nSiO}_2$ . From these figures, it has been detected that there was a clear variation in the surface of the composite specimens.

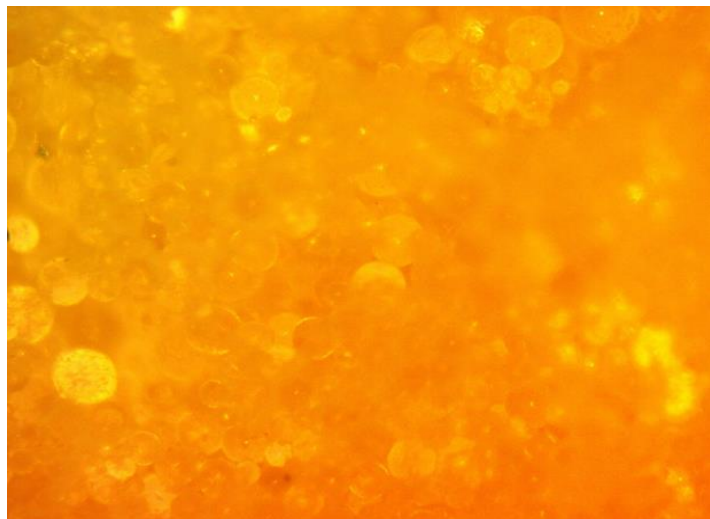


**Figure 4.28:** Pure PMMA.

The distribution of nSiO<sub>2</sub> and mSiO<sub>2</sub> particles in semi-continuous morphology is depicted by the aforementioned figures, which are contingent upon the constituents of the PMMA composite. The micrographs indicate that the distribution of mSiO<sub>2</sub> particles within the PMMA matrix was notably homogeneous and well-dispersed. The inadequate dispersion of nSiO<sub>2</sub> particles in the PMMA matrix, as depicted in Figures (nano), could be attributed to the large surface energy of the nanoparticles, leading to their aggregation and formation of clusters. Hence, it is plausible that the distribution of nSiO<sub>2</sub> particles may exert an impact on the mechanical characteristics of composites composed of PMMA and nSiO<sub>2</sub>.

Conversely, the micro SiO<sub>2</sub> particles exhibit homogeneous dispersion within the PMMA matrix, as depicted in Figure (micro). The strong interaction and interfacial between the polymer matrix and other phases can be attributed to the existence of SiO<sub>2</sub> particles on the PMMA.

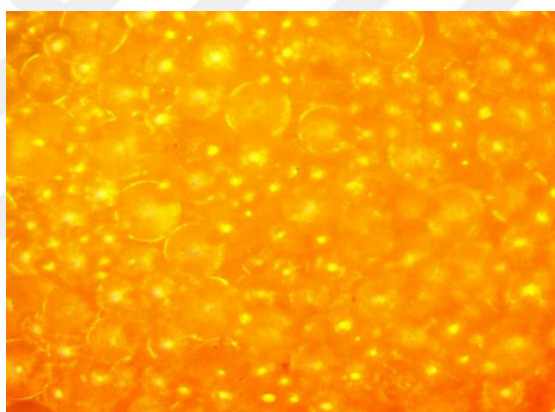


**Figure 4.29:** (PMMA-1% Micro- Silicon Oxide) Composite.



**Figure 4.30:** (PMMA-1% Nano-Silicon Oxide) Composite.

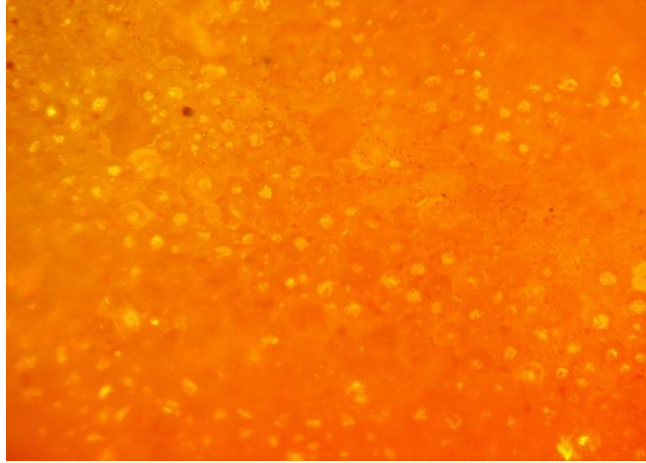


**Figure 4.31:** (PMMA-2% Micro-Silicon Oxide) Composite.

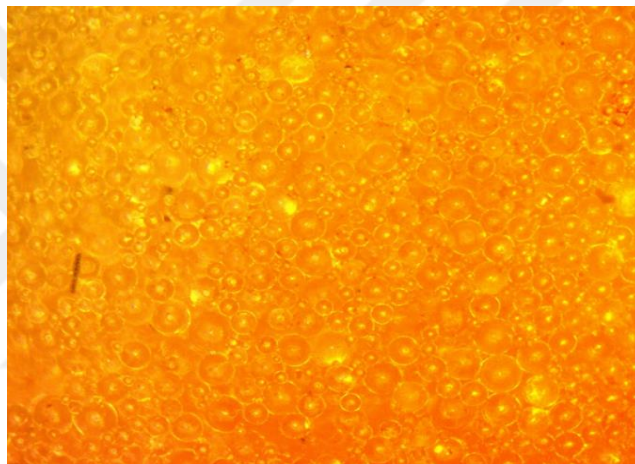


**Figure 4.32:** (PMMA-2% Nano-Silicon Oxide) Composite.



**Figure 4.33:** (PMMA-3% Micro-Silicon Oxide) Composite.



**Figure 4.34:** (PMMA-3% Nano-Silicon Oxide) Composite.

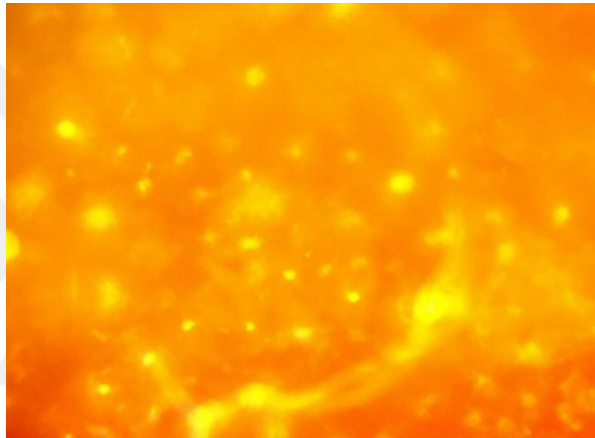


**Figure 4.35:** (PMMA-4% Micro-Silicon Oxide) Composite.



**Figure 4.36:** (PMMA-4% Nano-Silicon Oxide) Composite.

## 5. CONCLUSION AND RECOMMENDATION

### 5.1 INTRODUCTION

Based experimental findings of this study on composite prosthetic complete denture base materials, the following statements can be inferred as conclusions:

- a. The present study explored the effect of volume fractions of micro-SiO<sub>2</sub> and nano-SiO<sub>2</sub> particles on the mechanical features of PMMA composite prosthetic dentures, specifically hardness. The findings indicated that an increase in volume fractions of both micro-SiO<sub>2</sub> and nano-SiO<sub>2</sub> particles led to an increase in the PMMA composite's hardness.
- b. Concerning the impact strength and fracture toughness of PMMA composite prosthetic dentures, especially those with PMMA-nano- SiO<sub>2</sub> and PMMA-micro- SiO<sub>2</sub>, a consistent trend of SiO<sub>2</sub> decreasing mechanical property values was seen as the volume fraction of micro- SiO<sub>2</sub> and nano- SiO<sub>2</sub> particles increased. Importantly, using nano-SiO<sub>2</sub> consistently gave better results in terms of hardness, impact strength, and fracture toughness than using the same amount of micro-SiO<sub>2</sub> particles for instance samples (NA4 and Mc4) contains same amount of SiO<sub>2</sub>, but the hardness value was 88.4 and 83.6, respectively.
- c. The fracture toughness and impact strength of PMMA composite prosthetic dentures, specifically those containing PMMA-nano-SiO<sub>2</sub> and PMMA-micro-SiO<sub>2</sub>, exhibited a decrease in mechanical property magnitudes as the volume fraction of micro-SiO<sub>2</sub> and nano-SiO<sub>2</sub> particles increased.
- d. Based on the obtained results sample NA4 considers the best sample in terms of mechanical properties, with the highest hardness, good impact, perfect fracture toughness, best Modulus of elasticity, maximum Compressive strength, and upmost Tensile Strength results.
- e. Using nano-SiO<sub>2</sub> gives better magnitudes for hardness, impact strength and fracture toughness comparison with using a similar ratio of micr-SiO<sub>2</sub>.

## 5.2 RECOMMENDATIONS

- a. A comparative analysis can be conducted to evaluate various kinds and systems of reinforcing materials, including fibers and particles, at varying weight fractions.
- b. This study aims to assess the impact of a chemical coupling agent on the bonding strength between fibers and particles in PMMA-based composites. It will be better if another studies make evaluation analyzes through a pullout test, and its influence on the mechanical and physical features of the composites will be analyzed.
- c. This investigation aims to explore the biological and biocompatibility characteristics of a PMMA-based composite material and its response to the oral environment so it's better if more in-depth studies were conducted in this field.
- d. This statement discusses studying fluid interaction with a heat exchanger's structure using different materials. Thus, a lot off sectors in it can be utilize.
- e. For future studies, the author suggested that additional investigation on characteristics such as dynamic fracture toughness resulting from dynamic loads, wear, creep, residual monomer, dimensional stability, and color stability of the PMMA-based composite material be conducted. This approach aims to deepen knowledge, exploring the material's behavior in dynamic and complex scenarios for a more comprehensive understanding.

## REFERENCES

- [1] H. Fabritius, C. Sachs, P. R. Triguero, and D. Raabe, “Influence of structural principles on the mechanics of a biological fiber-based composite material with hierarchical organization: the exoskeleton of the lobster *Homarus americanus*,” *Adv. Mater.*, vol. 21, no. 4, pp. 391–400, 2009.
- [2] C.-L. Zhang and S.-H. Yu, “Nanoparticles meet electrospinning: recent advances and future prospects,” *Chem. Soc. Rev.*, vol. 43, no. 13, pp. 4423–4448, 2014.
- [3] R. Talreja and A. M. Waas, “Concepts and definitions related to mechanical behavior of fiber reinforced composite materials,” *Compos. Sci. Technol.*, vol. 217, p. 109081, 2022.
- [4] E. N. Goncharova, M. S. Lebedev, M. I. Vasilenko, and N. I. Kozhukhova, “Study of toxic impact of fly ash bearing construction materials on aquatic organisms,” in *IOP Conference Series: Materials Science and Engineering*, 2021, vol. 1089, no. 1, p. 12029.
- [5] R. R. Nagavally, “Composite materials-history, types, fabrication techniques, advantages, and applications,” *Int. J. Mech. Prod. Eng.*, vol. 5, no. 9, pp. 82–87, 2017.
- [6] D. Lukkassen and A. Meidell, “Advanced materials and structures and their fabrication processes,” *Narrik Univ. Coll. Hin*, 2003.
- [7] J. Hu, *3-D fibrous assemblies: Properties, applications and modelling of three-dimensional textile structures*. Elsevier, 2008.
- [8] S. Singh, M. Uddin, and C. Prakash, “Introduction, history, and origin of composite materials,” in *Fabrication and Machining of Advanced Materials and Composites*, CRC Press, 2022, pp. 1–18.
- [9] E. S. E. ABdalla, “Viscoelasticity- plastic behavior of fiber- reinforced polymer composites.” Sudan University of Science and Technology, 2016.
- [10] C. Ferguson, “Historical Introduction to the Development of Material Science and Engineering as a teaching discipline,” *available from UKCME [http://www. Mater. ac](http://www.Mater.ac)*.

*uk/pub/Materials-History-Intro. pdf*, 2006.

- [11] R. Burford, “Polymers: A historical perspective,” in *Journal and Proceedings of the Royal Society of New South Wales*, 2019, vol. 152, no. 473/474, pp. 242–250.
- [12] L. C. Bank, *Composites for construction: structural design with FRP materials*. John Wiley & Sons, 2006.
- [13] T. Hanninen and M. Hughes, “Historical, contemporary and future applications,” *Ind. Appl. Nat. Fibers*, J. Müssig, Ed. Wiley, pp. 385–395, 2010.
- [14] D. Brigante, “New composite materials,” *Nature*, vol. 442, pp. 282–286, 2014.
- [15] C. Defonseka, *Introduction to polymeric composites with rice hulls*. Smithers Rapra, 2014.
- [16] A. Jangizehi, F. Schmid, P. Besenius, K. Kremer, and S. Seiffert, “Defects and defect engineering in Soft Matter,” *Soft Matter*, vol. 16, no. 48, pp. 10809–10859, 2020.
- [17] K. J. Saunders, *Organic polymer chemistry: an introduction to the organic chemistry of adhesives, fibres, paints, plastics and rubbers*. Springer Science & Business Media, 2012.
- [18] K. Landis, “The Chemistry of Group X Transitions Metels and their reactivity with C60 and Maleonitriledithiolates,” 1998.
- [19] J. Chen, E. S. Garcia, and S. C. Zimmerman, “Intramolecularly cross-linked polymers: from structure to function with applications as artificial antibodies and artificial enzymes,” *Acc. Chem. Res.*, vol. 53, no. 6, pp. 1244–1256, 2020.
- [20] G. M. Whitesides, “Nanoscience, nanotechnology, and chemistry,” *Small*, vol. 1, no. 2, pp. 172–179, 2005.
- [21] W. J. Rogers, “Sterilisation techniques for polymers,” in *Sterilisation of Biomaterials and Medical Devices*, Elsevier, 2012, pp. 151–211.
- [22] M. C. Domínguez López, “Preparation and characterization of composite materials for medical applications,” 2018.

- [23] Y.-Y. Tai, S.-H. Hsu, R.-S. Chen, W.-F. Su, and M.-H. Chen, "Liquid crystalline epoxy nanocomposite material for dental application," *J. Formos. Med. Assoc.*, vol. 114, no. 1, pp. 46–51, 2015.
- [24] B. Al-Zubaidy, N. S. Radhi, and Z. S. Al-Khafaji, "Study the effect of thermal impact on the modelling of (titanium-titania) functionally graded materials by using finite element analysis," *Int. J. Mech. Eng. Technol.*, vol. 1, 2019.
- [25] K. Y. Nam, "Characterization and antifungal activity of the modified PMMA denture base acrylic: Nanocomposites impregnated with gold, platinum, and silver nanoparticles," in *Nanobiomaterials in Dentistry*, Elsevier, 2016, pp. 309–336.
- [26] A. Jain, L. S. Duvvuri, S. Farah, N. Beyth, A. J. Domb, and W. Khan, "Antimicrobial polymers," *Adv. Healthc. Mater.*, vol. 3, no. 12, pp. 1969–1985, 2014.
- [27] D. B. Hazer, M. Mut, N. Dinçer, Z. Saribas, B. Hazer, and T. Özgen, "The efficacy of silver-embedded polypropylene-grafted polyethylene glycol-coated ventricular catheters on prevention of shunt catheter infection in rats," *Child's Nerv. Syst.*, vol. 28, no. 6, pp. 839–846, 2012.
- [28] M. S. Salit, "Tropical natural fibre composites," *Trop. Nat. fibers their Prop.*, vol. 15, 2014.
- [29] T. Coan, G. S. Barroso, R. A. F. Machado, F. S. De Souza, A. Spinelli, and G. Motz, "A novel organic-inorganic PMMA/polysilazane hybrid polymer for corrosion protection," *Prog. Org. Coatings*, vol. 89, pp. 220–230, 2015.
- [30] A. K. Sharma, R. Bhandari, A. Aherwar, and R. Rimašauskienė, "Matrix materials used in composites: A comprehensive study," *Mater. Today Proc.*, vol. 21, pp. 1559–1562, 2020.
- [31] K. K. Chawla, *Ceramic matrix composites*. Springer Science & Business Media, 2013.
- [32] M. Rosso, "Ceramic and metal matrix composites: Routes and properties," *J. Mater. Process. Technol.*, vol. 175, no. 1–3, pp. 364–375, 2006.

- [33] F. N. Cogswell, *Thermoplastic aromatic polymer composites: a study of the structure, processing and properties of carbon fibre reinforced polyetheretherketone and related materials*. Elsevier, 2013.
- [34] P. K. Bal, “Thermal conductivity of cement kiln dust filled epoxy composites.” 2014.
- [35] S. Nayak and J. R. Mohanty, “Influence of chemical treatment on tensile strength, water absorption, surface morphology, and thermal analysis of areca sheath fibers,” *J. Nat. Fibers*, vol. 16, no. 4, pp. 589–599, 2019.
- [36] J. Qiu, Q. Gu, Y. Sha, Y. Huang, M. Zhang, and Z. Luo, “Preparation and application of dielectric polymers with high permittivity and low energy loss: A mini review,” *J. Appl. Polym. Sci.*, vol. 139, no. 24, p. 52367, 2022.
- [37] M. A. Masuelli, “Introduction of fibre-reinforced polymers– polymers and composites: concepts, properties and processes,” in *Fiber reinforced polymers-the technology applied for concrete repair*, IntechOpen, 2013.
- [38] R.-M. Wang, S.-R. Zheng, and Y.-P. G. Zheng, *Polymer matrix composites and technology*. Elsevier, 2011.
- [39] R. Hsissou, R. Seghiri, Z. Benzekri, M. Hilali, M. Rafik, and A. Elharfi, “Polymer composite materials: A comprehensive review,” *Compos. Struct.*, vol. 262, p. 113640, 2021.
- [40] O. Kehinde, O. J. Ramonu, K. O. Babaremu, and L. D. Justin, “Plastic wastes: environmental hazard and instrument for wealth creation in Nigeria,” *Heliyon*, vol. 6, no. 10, p. e05131, 2020.
- [41] S. Dai, Z. C. Deng, Y. J. Yu, K. Zhang, S. H. Wang, and J. Ye, “Orthotropic elastic behaviors and yield strength of fused deposition modeling materials: Theory and experiments,” *Polym. Test.*, vol. 87, p. 106520, 2020.
- [42] B. Sadeghi and P. D. Cavaliere, “Reviewing the Integrated Design Approach for Augmenting Strength and Toughness at Macro-and Micro-Scale in High-Performance Advanced Composites,” *Materials (Basel)*, vol. 16, no. 17, p. 5745, 2023.

- [43] A. Salas Ordóñez, “Damage and failure modelling of composite materials for the automotive industry.” Universitat Politècnica de Catalunya, 2017.
- [44] G. W. Milton, *The theory of composites*. SIAM, 2022.
- [45] T.-D. Ngo, “Introduction to composite materials,” *Compos. Nanocomposite Mater. Knowl. to Ind. Appl.*, 2020.
- [46] M. Elkington, D. Bloom, C. Ward, A. Chatzimichali, and K. Potter, “Hand layup: understanding the manual process,” *Adv. Manuf. Polym. Compos. Sci.*, vol. 1, no. 3, pp. 138–151, 2015.
- [47] A. T. Marques, “Fibrous materials reinforced composites production techniques,” in *Fibrous and composite materials for civil engineering applications*, Elsevier, 2011, pp. 191–215.
- [48] S. Mahato, “Fabrication of Decorative Fluorescent Composite Material.” 2011.
- [49] G. Archambault, B. Jodoin, S. Gaydos, and M. Yandouzi, “Metallization of carbon fiber reinforced polymer composite by cold spray and lay-up molding processes,” *Surf. Coatings Technol.*, vol. 300, pp. 78–86, 2016.
- [50] R. M. Mayer, *Design with reinforced plastics: a guide for engineers and designers*. Springer Science & Business Media, 2012.
- [51] M. Schwartz, “Resin transfer molding and associated closed molding and infusion processes,” *Innov. Mater. Manuf. Fabr. Environ. Saf.*, pp. 503–529, 2010.
- [52] D. K. Rajak, P. H. Wagh, and E. Linul, “Manufacturing technologies of carbon/glass fiber-reinforced polymer composites and their properties: A review,” *Polymers (Basel)*, vol. 13, no. 21, p. 3721, 2021.
- [53] C. L. Tan, A. I. Azmi, and N. Muhammad, “Delamination and surface roughness analyses in drilling hybrid carbon/glass composite,” *Mater. Manuf. Process.*, vol. 31, no. 10, pp. 1366–1376, 2016.
- [54] M. R. Abusrea, S.-W. Han, K. Arakawa, and N.-S. Choi, “Bending strength of CFRP laminated adhesive joints fabricated by vacuum-assisted resin transfer molding,”

*Compos. Part B Eng.*, vol. 156, pp. 8–16, 2019.

- [55] D. Mulkerrins, “An investigation of cost-effective rapid tooling for fibre reinforced polymer parts using low-cost 3D printing,” 2021.
- [56] C. Garschke, C. Weimer, P. P. Parlevliet, and B. L. Fox, “Out-of-autoclave cure cycle study of a resin film infusion process using in situ process monitoring,” *Compos. Part A Appl. Sci. Manuf.*, vol. 43, no. 6, pp. 935–944, 2012.
- [57] P. Dumont, F. Martoia, and L. Orgéas, “Compression moulding,” in *Design and Manufacture of Structural Composites*, Elsevier, 2023, pp. 273–300.
- [58] P. Mitschang and K. Hildebrandt, “Polymer and composite moulding technologies for automotive applications,” in *Advanced materials in automotive engineering*, Elsevier, 2012, pp. 210–229.
- [59] R. A. Tataara, “Compression molding,” in *Applied plastics engineering handbook*, Elsevier, 2017, pp. 291–320.
- [60] W. G. Frizelle, “Injection molding technology,” in *Applied Plastics Engineering Handbook*, Elsevier, 2011, pp. 205–214.
- [61] M. Azeem *et al.*, “Application of filament winding technology in composite pressure vessels and challenges: a review,” *J. Energy Storage*, vol. 49, p. 103468, 2022.
- [62] N. Minsch, F. H. Herrmann, T. Gereke, A. Nocke, and C. Cherif, “Analysis of filament winding processes and potential equipment technologies,” *Procedia CIRP*, vol. 66, pp. 125–130, 2017.
- [63] S. C. Joshi, “The pultrusion process for polymer matrix composites,” in *Manufacturing techniques for polymer matrix composites (PMCs)*, Elsevier, 2012, pp. 381–413.
- [64] G. Marsh, “Composites lift off in primary aerostructures,” *Reinf. Plast.*, vol. 48, no. 4, pp. 22–27, 2004.
- [65] E. Oromiehie, B. G. Prusty, P. Compston, and G. Rajan, “Automated fibre placement based composite structures: Review on the defects, impacts and inspections

- techniques,” *Compos. Struct.*, vol. 224, p. 110987, 2019.
- [66] K. Yassin and M. Hojjati, “Processing of thermoplastic matrix composites through automated fiber placement and tape laying methods: A review,” *J. Thermoplast. Compos. Mater.*, vol. 31, no. 12, pp. 1676–1725, 2018.
  - [67] O. Baho, G. Ausias, Y. Grohens, M. Barile, L. Lecce, and J. Férec, “Automated fibre placement process for a new hybrid material: a numerical tool for predicting an efficient heating law,” *Compos. Part A Appl. Sci. Manuf.*, vol. 144, p. 106360, 2021.
  - [68] P. Dudek, “FDM 3D printing technology in manufacturing composite elements,” *Arch. Metall. Mater.*, vol. 58, no. 4, pp. 1415–1418, 2013.
  - [69] G. Sumithra, R. N. Reddy, G. D. Kumar, S. Ojha, G. Jayachandra, and G. Raghavendra, “Review on composite classification, manufacturing, and applications,” *Mater. Today Proc.*, 2023.
  - [70] K. Chua, I. Khan, R. Malhotra, and D. Zhu, “Additive manufacturing and 3D printing of metallic biomaterials,” *Eng. Regen.*, vol. 2, pp. 288–299, 2021.
  - [71] M. V. S. Narnaware, “Metallic biomaterials for human body implant: a review study,” *Int J Sci Dev Res*, vol. 2, pp. 220–229, 2017.
  - [72] P. Parida, A. Behera, and S. C. Mishra, “Classification of Biomaterials used in Medicine,” 2012.
  - [73] F. Isidor and K. Brøndum, “Intermittent loading of teeth with tapered, individually cast or prefabricated, parallel-sided posts,” *Int. J. Prosthodont.*, vol. 5, no. 3, 1992.
  - [74] M. Nagabushanam *et al.*, “Advance biomedical engineering—A fundamental review of composite materials and its applications,” *Mater. Today Proc.*, 2023.
  - [75] E. Araujo and J. Perdigão, “Anterior Veneer Restorations-An Evidence-based Minimal-Intervention Perspective,” *J. Adhes. Dent.*, vol. 23, no. 2, 2021.
  - [76] E. Habib, “Methods and physical chemistry of resin-based dental composites,” 2018.
  - [77] A. N. Hadi and J. K. Oleiwi, “Improving tensile strength of polymer blends as

- prosthetic foot material reinforcement by carbon fiber,” *J. Mater. Sci. Eng.*, vol. 4, no. 2, pp. 22–2169, 2015.
- [78] S. H. Ahmed and W. M. Salih, “Enhancement of the characteristics for polymeric blend (PMMA/UP) used in socket prosthetic,” in *AIP Conference Proceedings*, 2022, vol. 2437, no. 1.
- [79] R. Pugliese, B. Beltrami, S. Regondi, and C. Lunetta, “Polymeric biomaterials for 3D printing in medicine: An overview,” *Ann. 3D Print. Med.*, vol. 2, p. 100011, 2021.
- [80] S.-J. Estermann, “Replicating liver tissue in terms of mechanical properties for anatomical models.” Wien, 2021.
- [81] P. M. Visakh, G. Markovic, and D. Pasquini, “Recent Developments in Polymer Macro, Micro and Nano Blends: Preparation and Characterisation,” 2016.
- [82] H. J. Maria *et al.*, “Gas barrier, rheological and mechanical properties of immiscible natural rubber/acrylonitrile butadiene rubber/organoclay (NR/NBR/organoclay) blend nanocomposites,” *Materials (Basel)*, vol. 13, no. 11, p. 2654, 2020.
- [83] M. De Sarkar, W. Nishino, Y. Ishigaki, and T. Sunada, “Introduction to the New Copolymer of Chloroprene and Acrylonitrile with Differentiated Properties,” *Adv. Polym. Technol.*, vol. 2021, pp. 1–17, 2021.
- [84] J. Schneider, “Circular economy in the automotive industry: the case of polymethylmethacrylate (PMMA),” 2020.
- [85] F. B. Gul and N. Baydogan, “Synthesis of Poly (methyl methacrylate) with Borax Decahydrate Addition for Energy Applications,” in *ICSEEC: Sustainable Energy and Energy Calculations Proceedings of International Conference on Sustainable Energy and Energy Calculations Organized by Turkish-German University, Beykoz, Istanbul, Turkey*, 2020, p. 38.
- [86] R. L. Clough, “High-energy radiation and polymers: A review of commercial processes and emerging applications,” *Nucl. Instruments Methods Phys. Res. Sect. B Beam Interact. with Mater. Atoms*, vol. 185, no. 1–4, pp. 8–33, 2001.

- [87] HaHasmile, “multilayer and acetal pmma material dental products.,” 2023. <https://www.hahasmiledental.com/news-why-pmma-materials-are-used-in-dentistry.html>.
- [88] G. Uzun and N. Hersek, “Comparison of the fracture resistance of six denture base acrylic resins,” *J. Biomater. Appl.*, vol. 17, no. 1, pp. 19–28, 2002.
- [89] D. C. Jagger and A. Harrison, “The fractured denture-solving the problem,” *J Prim. Dent Care*, vol. 5, pp. 159–162, 1998.
- [90] M. M. Gad *et al.*, “Impact of different surface treatments and repair material reinforcement on the flexural strength of repaired PMMA denture base material,” *Dent. Mater. J.*, vol. 39, no. 3, pp. 471–482, 2020.
- [91] T. Nejatian, A. Johnson, and R. Van Noort, “Reinforcement of denture base resin,” in *Advances in Science and Technology*, 2006, vol. 49, pp. 124–129.
- [92] G. A. Zarb and C. O. Boucher, “Boucher’s prosthodontic treatment for edentulous patients,” (*No Title*), 1997.
- [93] S. Choudhary, “Complete denture fracture—A proposed classification system and its incidence in National Capital Region population: A survey,” *J. Indian Prosthodont. Soc.*, vol. 19, no. 4, p. 307, 2019.
- [94] A. A. Adeyemi, *Bonding of Acrylic Resin Denture Teeth to Acrylic Resin Denture Base Materials*. University of Glasgow (United Kingdom), 2003.
- [95] S. Yannikakis, A. Zissis, G. Polyzois, and A. Andreopoulos, “Evaluation of porosity in microwave-processed acrylic resin using a photographic method,” *J. Prosthet. Dent.*, vol. 87, no. 6, pp. 613–619, 2002.
- [96] J. J. Manappallil, *Basic dental materials*. JP Medical Ltd, 2015.
- [97] W. Babeer, “Microtensile bond strength of IvoBase resins and two commercially available denture teeth.” State University of New York at Buffalo, 2017.
- [98] C. A. Price, “A history of dental polymers,” *Aust. Prosthodont. J.*, vol. 8, pp. 47–54, 1994.

- [99] V. Greig, "Craig's restorative dental materials." Nature Publishing Group UK London, 2012.
- [100] C. Shen, H. R. Rawls, and J. F. Esquivel-Upshaw, *Phillips' Science of Dental Materials E-Book*. Elsevier Health Sciences, 2021.
- [101] C.-J. Lee, S.-B. Bok, J.-Y. Bae, and H.-H. Lee, "Comparative adaptation accuracy of acrylic denture bases evaluated by two different methods," *Dent. Mater. J.*, vol. 29, no. 4, pp. 411–417, 2010.
- [102] W. F. E. Yau, Y. Y. Cheng, R. K. F. Clark, and T. W. Chow, "Pressure and temperature changes in heat-cured acrylic resin during processing," *Dent. Mater.*, vol. 18, no. 8, pp. 622–629, 2002.
- [103] L. Liu, B.-M. Zhang, D.-F. Wang, and Z.-J. Wu, "Effects of cure cycles on void content and mechanical properties of composite laminates," *Compos. Struct.*, vol. 73, no. 3, pp. 303–309, 2006.
- [104] M. F. M. Basso, E. T. Giampaolo, A. L. Machado, A. C. Pavarina, and C. E. Vergani, "Evaluation of the occlusion vertical dimension of complete dentures after microwave disinfection," *Gerodontology*, vol. 29, no. 2, pp. e815–e821, 2012.
- [105] F. J. Welch, "Polymerization of methyl methacrylate by triethylboron–oxygen mixtures," *J. Polym. Sci.*, vol. 61, no. 171, pp. 243–252, 1962.
- [106] S. El Bahra, "Dimensional precision and volumetric shrinkage of PMMA denture bases polymerized with different methods." 2016.
- [107] A. T. Sidambe, "Biocompatibility of advanced manufactured titanium implants—A review," *Materials (Basel)*, vol. 7, no. 12, pp. 8168–8188, 2014.
- [108] M. W. Hahn, U. Koll, and J. Schmidt, "Isolation and cultivation of bacteria," *Struct. Funct. Aquat. Microb. communities*, pp. 313–351, 2019.
- [109] F. Ronkay, "Impact of fiber reinforced on polymer blend properties," *Soc. Plast. Eng.*, 2011.
- [110] D. Raviteja, K. H. N. S. Kumar, A. Murali, R. Hemanth, P. Manikanta, and T. S. S.

V. Prasad, “FABRICATION AND EXPERIMENTAL INVESTIGATION ON THE MECHANICAL & SURFACE CHARACTERIZATION OF HYBRID COMPOSITES INTEGRATED WITH EPOXY.”

- [111] R. Van Noort and M. Barbour, *introduction to dental materials-E-book*. Elsevier Health Sciences, 2014.
- [112] A. N. S. D. Association, “ANSI/ADA Specification no. 12-1975 Denture Base Polimers,” *Counc. Sci. Aff. ADA, Chicago*, 1999.
- [113] A. S. for T. and Materials, *Standard Test Method for Tensile Properties of Plastics by Use of Microtensile Specimens*. ASTM international, 2015.
- [114] J. K. Oleiwi and Q. A. Hamad, “Studying the mechanical properties of denture base materials fabricated from polymer composite materials,” *Al-Khwarizmi Eng. J.*, vol. 14, no. 3, pp. 100–111, 2018.
- [115] S. Feih, A. P. Mouritz, Z. Mathys, and A. G. Gibson, “Tensile strength modeling of glass fiber—polymer composites in fire,” *J. Compos. Mater.*, vol. 41, no. 19, pp. 2387–2410, 2007.
- [116] J. S. Berg, *An evaluation of composite material compression test methods*. University of Wyoming, 1988.
- [117] D. R. Askeland, P. P. Fulay, and D. K. Bhattacharya, “Essentials of Material Science and Engineering, Cengage Learning,” *Inc., FL, USA*, pp. 358–364, 2010.
- [118] M. Chanda, *Plastics technology handbook*. CRC press, 2017.
- [119] D. R. Askeland and W. J. Wright, *Essentials of materials science and engineering*. Cengage Learning, 2018.
- [120] P. K. Mallick, *Fiber-reinforced composites: materials, manufacturing, and design*. CRC press, 2007.
- [121] T. Kanie, H. Arikawa, K. Fujii, and S. Ban, “Light-curing reinforcement for denture base resin using a glass fiber cloth pre-impregnated with various urethane oligomers,” *Dent. Mater. J.*, vol. 23, no. 3, pp. 291–296, 2004.

- [122] A. C.-T. Sun, “Material Science & Engineering,,” Sandia National Lab.(SNL-NM), Albuquerque, NM (United States), 2012.
- [123] A. B. of I. S. O. Standard, “Standard Test Method for Unnotched Izod Impact Testing of Plastics,” *ISO-180*, pp. 1–2, 2006.
- [124] L. Lan, Z. Yang, W. Wang, Z. Cui, and X. Hao, “Effect of initial powder particle size on densification behavior and mechanical properties of laser additive manufacturing of AlCoCrFeNi<sub>2</sub>. 1 eutectic high-entropy alloy,” *Powder Technol.*, vol. 420, p. 118379, 2023.
- [125] K. Nam, C. Lee, and C. Lee, “Antifungal and physical characteristics of modified denture base acrylic incorporated with silver nanoparticles,” *Gerodontology*, vol. 29, no. 2, pp. e413–e419, 2012.
- [126] N. S. Radhi, K. F. Morad, M. H. Hafiz, A. A. Atiyah, and A. Bouaissi, “OPTIMIZATION OF NICKEL CONTENT ON SOME PROPERTIES OF ( NITI ) SHAPE MEMORY ALLOY,” pp. 4–11, 2020.
- [127] W. Bolton, *Engineering materials technology*. Elsevier, 2013.
- [128] C. T. Herakovich and Y. M. Tarnopolskii, “Hand book on Composites.” Elsevier Science Publishers, AMSTERDAM, 1988.
- [129] I. H. Hilal, M. R. Mohammed, and W. A. Shakir, “Effect of silver (Ag) nanoparticles on structural and mechanical properties of (PMMA) blend and its application for denture base,” *Int. J. Med. Res. Heal. Sci.*, vol. 8, no. 1, pp. 154–159, 2019.
- [130] M. Busuioc, K. Mackiewicz, B. A. Buttaro, and P. J. Piggot, “Role of intracellular polysaccharide in persistence of *Streptococcus mutans*,” *J. Bacteriol.*, vol. 191, no. 23, pp. 7315–7322, 2009.
- [131] B.-Y. Wang and H. K. Kuramitsu, “Interactions between oral bacteria: inhibition of *Streptococcus mutans* bacteriocin production by *Streptococcus gordonii*,” *Appl. Environ. Microbiol.*, vol. 71, no. 1, pp. 354–362, 2005.
- [132] W. Winn Jr, “Konemann’s color atlas and diagnostic text of microbiology,”

*Lippencott Williams Wilkins Publ. Philadelphia, PA*, pp. 945–1021, 2006.

- [133] A. Pegoretti, J. Kolarik, and M. Slouf, “Phase structure and tensile creep of recycled poly (ethylene terephthalate)/short glass fibers/impact modifier ternary composites,” *Express Polym. Lett.*, vol. 3, no. 4, pp. 235–244, 2009.
- [134] S. I. Salih, J. K. Oleiwi, and Q. A. Hamad, “Comparative study the flexural properties and impact strength for PMMA reinforced by particles and fibers for prosthetic complete denture base,” *Iraqi J. Mech. Mater. Eng.*, vol. 15, no. 4, pp. 288–307, 2015.
- [135] H. K. Hameed and H. A. Rahman, “The effect of addition nano particle ZrO<sub>2</sub> on some properties of autoclave processed heat cure acrylic denture base material,” *J. baghdad Coll. Dent.*, vol. 27, no. 1, pp. 32–39, 2015.