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Spécialité : génie des matériaux

CARACTÉRISATION DES PROPRIÉTÉS MÉCANIQUES D’UNE NOUVELLE CLASSE DE MATÉRIAUX COMPOSITES A PARTIR DE DECHETS DE PLASTIQUE

Thèse soumise au Département de Génie Mécanique en vue de l'obtention du diplôme de Doctorat en Génie des Matériaux

Présentée par: MOULAI ARBI Youcef Seif Eddine
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MUSTAPHA STAMBOULI UNIVERSITY
Mascara

جامعة مصطفى اسطمبولي
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University of Mascara, Algeria
Faculty of Science and Technology
Department of Mechanical Engineering

DOCTORAL THESIS

Specialty of materials engineering

MECHANICAL CHARACTERIZATION OF A NEW COMPOSITE MATERIAL FROM PLASTIC WASTE

Thesis submitted to the Department of Mechanical Engineering in fulfillment of the requirements for the degree of Doctorate in Materials engineering

Presented by: MOULAI ARBI Youcef Seif Eddine
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ABSTRACT

Composite materials are utilized in a wide range of applications, such as the automotive sector, aerospace, aeronautics, and civil construction, among others. A composite material is composed of two or more different constituents in terms of their nature and form, and it possesses enhanced mechanical properties compared to each of its individual components. Composite materials offer valuable performance advantages, including high strength, lightweight, extended lifespan, high resistance to corrosion, heat, and environmental influences.

This study contributes to achieving an in-depth and accurate idea about the possibility of producing a new composite material in the field of materials development in order to integrate it into living life. This research presents us a new usable material after an in-depth study in the previous researches, this new material is a composite material, which is composed of plastic waste and brick powder. After producing this compound material, it passed through a series of tests and it provided us with satisfactory results compared to old researches, also it provided some new data that were not studied in previous researches.

Manufacturing this material can create a new field of work in the industry and facilitate the reduction of the percentage of plastic waste thrown into the ground. Brick dust is also a ground product of tile waste produced by tile factories.

Key words: composite material, polymers, ceramics, polyethylene terephthalate, brick powder, masonry wall.

الملخص

تُستخدم المواد المركبة في مجموعة واسعة من التطبيقات، مثل قطاع السيارات والفضاء وعلم الطيران والبناء المدني، وغيرها من التطبيقات. المادة المركبة تتألف من جزأين أو أكثر مختلفين من حيث طبيعتهما وشكلهما، وتمتلك خصائص ميكانيكية محسَّنة مقارنة بكل من مكوِّناتها الفردية. تقدم المواد المركبة مزايا أداء قيمة، بما في ذلك مقاومة عالية، وخفة الوزن، وعمر طويل، ومقاومة عالية للتآكل والحرارة وتأثيرات البيئة.

تسهم هذه الدراسة في تحقيق فهم عميق ودقيق حول إمكانية إنتاج مادة مركبة جديدة في ميدان تطوير المواد بهدف دمجها في الحياة اليومية. يقدم هذا البحث لنا مادة جديدة قابلة للاستخدام بعد دراسة مستفيضة في الأبحاث السابقة، وهذه المادة المركبة الجديدة مكونة من نفايات البلاستيك ومسحوق الطوب. بعد إنتاج هذه المادة المركبة، تمت خضوعها لسلسلة من الاختبارات وقدمت لنا نتائج مرضية مقارنة بالأبحاث القديمة، وأيضًا قدمت بعض البيانات الجديدة التي لم تتم دراستها في الأبحاث السابقة.

إن تصنيع هذه المادة يمكن أن يخلق مجال عمل جديد في صناعة المواد ويسهم في تقليل نسبة النفايات البلاستيكية التي يتم التخلص منها في المحيط. مسحوق الطوب هو أيضًا منتج أرضي يتم الحصول عليه من البلاط الذي يتم إنتاجه من مصانع البلاط

كلمات مفتاحية: مواد مركبة، بوليمرات، سيراميك، بولي إيثيلين تيريفثالات، مسحوق الطوب، جدار البناء

RÉSUMÉ

Les matériaux composites sont utilisés dans une large variété d'applications, telles que le secteur automobile, l'aérospatiale, l'aéronautique et la construction civile, entre autres. Un matériau composite est composé de deux ou plusieurs constituants différents en termes de leur nature et de leur forme, et il possède des propriétés mécaniques améliorées par rapport à chacun de ses composants individuels. Les matériaux composites offrent des avantages de performance précieux, notamment une grande résistance, une légèreté, une durée de vie prolongée, une grande résistance à la corrosion, à la chaleur et aux influences environnementales.

Cette étude contribue à obtenir une idée approfondie et précise de la possibilité de produire un nouveau matériau composite dans le domaine du développement des matériaux afin de l'intégrer dans la vie quotidienne. Cette recherche nous présente un nouveau matériau utilisable après une étude approfondie des recherches précédentes, ce nouveau matériau étant un matériau composite composé de déchets plastiques et de poudre de brique. Après la production de ce matériau composite, il a été soumis à une série de tests et nous a fourni des résultats satisfaisants par rapport aux anciennes recherches, fournissant également de nouvelles données qui n'avaient pas été étudiées dans les recherches précédentes.

La fabrication de ce matériau peut créer un nouveau domaine de travail dans l'industrie et faciliter la réduction du pourcentage de déchets plastiques jetés dans la nature. La poussière de brique est également un produit résultant des déchets de carreaux produits par les usines de carreaux.

Mots-clés : matériau composite, polymères, céramiques, polyéthylène téréphtalate, poudre de brique, mur de maçonnerie.

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LIST OF ABBREVIATIONS

µm micrometer
°C Celsius degree
UV Ultraviolet
MPa Megapascal
GPa Gigapascal
Kg kilogram
m^3 cubic meters
% percent
Glass R reinforcement glass
Carbon HM High Modulus Carbon
SiC Silicon Carbide
Al_2O_3 Aluminum Oxide
ZRO_2 Zirconium Dioxide
TiO_2 Titanium Dioxide
WC Tungsten Carbide
BCE Before Common Era
CE Common Era
K_2O Potassium Oxide
SiO_2 silicon dioxide
AlN aluminum nitride
B boron
C carbon
Fe_2O_3 Iron Oxide
MgO Magnesium Oxide
CaO Calcium Oxide
Na_2O Sodium Oxide
K_2O Potassium Oxide
Li_2O Lithium Oxide
WC tungsten carbide
VC vanadium carbide
TaC tantalum carbide
TiC titanium carbide
B_4C boron carbide
FeO, **Fe_2O3**, **Fe_2O_4** graphit
Si_3N_4 silicon nitride
BN boron nitride
PET polyethylene terephthalate
PE polyethylene
PP polypropylene
PMMA polymethyl methacrylate
Tm melting temperature
g/mol grams per mole
∞ Infinity
σ stress
Ksi kilo pounds per square inch
ZrN Zirconium nitride
E young's modulus
Bi bismuth
Ru ruthenium
ITO Indium tin oxide
Y yttrium
Ba barium
Cu copper
O oxygen
SnO_2 tin oxide
Pb lead
Zr zirconium
Ti titanium
PZT piezoelectric ceramic
Sr strontium
PMN Lead magnesium niobate
Gd gadolinium
Zn zinc
Cd cadmium
La lanthanum
PLZT Lead Lanthanum Zirconate Titanate
$Y_3AL_5O_{12}$ yttrium aluminum garnet
TiN Titanium Nitride
H hydrogen
n number of repeating units
DP degree of polymerization
N nitrogen
F fluorine
Cl chlorine
Br bromine
I iodine
S sulfur
P phosphorus
Si silicon
PS polystyrene
PVC polyvinyl chloride
PTFE polytetrafluoroethylene
PC polycarbonate
PA polyamide
CFD Computational Fluid Dynamics
AEM applied element method
DEM discrete element method
FEM finite element method
CDP concrete damaged plasticity
t traction force

HALS Hindered Amine Light Stabilizers
H_2O water
FDA Food and Drug Administration
EFSA European Food Safety Authority
HW household waste
NHIW non-hazardous industrial waste
OECD Organisation for Economic Co-operation and Development
RIC Resin Identification Code
SPI Society of the Plastics Industry
HDPE high-density polyethylene
TGA thermogravimetric analysis
DSC differential scanning calorimetry
SEM scanning electron microscope
N/mm^2 Newton's per square millimeter
LDPE Low-Density Polyethylene
CO_2 carbon dioxide
ASTM American Society for Testing and Materials
SO_3 sulfur trioxide
P.F Percentage of Formula
g/cm^3 grams per cubic centimeter
cm^2/g square centimeters per gram
L Length
W Width
T Thickness
Mg milligrams
mm/min millimeters per minute
ρ density
M mass
V volume
Td degradation temperature
w/g weight to grams
j/g joules per gram
KJ/m^2 kilojoules per square meter
3D three-dimensional
CAE Computer-Aided Engineering.
FEA finite element analysis
δ separation vector
Knn normaldirection
Kss shear direction
Ktt second shear direction
BK Benzeggagh-Kenane
Gt transverse fracture energy
Gs shear fracture energy
ε strain
Dt damage parameter for tension
Ut displacement
KN kilonewtons
β Angle of friction
R Flow stress ratio
Ψ Dilation angle
Sec seconds
AVG average

GENERAL INTRODUCTION

GENERAL INTRODUCTION

Composite materials play a significant role in production today, and their usage continues to experience widespread applications in everyday life. This importance has captured the attention of many researchers over recent decades. Furthermore, it is essential to study their mechanical behavior to best adapt them to various service conditions.

In a broad sense, the term "composite" means "made up of two or more different parts." A composite material consists of one or more discontinuous phases distributed within a continuous phase. The discontinuous phase, known as the reinforcement or reinforcing material, is typically harder and possesses superior mechanical properties compared to the continuous phase, which is referred to as the matrix.

Composite materials are materials that exhibit mechanical behavior distinct from that of their individual constituents. In this regard, it is crucial to study the mechanical behavior of these materials.

This manuscript is dedicated to investigating the potential for producing a composite material utilizing plastic waste and brick powder. It is structured into four chapters.

The four chapters of the manuscript lay out an integrated plan that explains all the steps for manufacturing this material from beginning to end, and it consists of:

The first chapter discusses overall properties of composite materials. It begins with a detailed definition and then elaborates on the fundamental components of any composite material, which are composed of a matrix and reinforcements. It also emphasizes the significance of interfacial interactions and, of course, enumerates the various types of composite materials. Additionally, this chapter explores the numerous methods for manufacturing composite materials, with a particular focus on the approach that will be employed in our research.

The second chapter focuses on the two main components of the material intended for production in this study, namely ceramics and polymers, dividing the chapter into two sections.

The first part provides a comprehensive definition of ceramics and highlights its historical significance across various fields. It also delves into the partial structure of ceramics, discussing the available types of ceramics and their respective applications based on their characteristics. This section includes details about the manufacturing methods for ceramics available from various manufacturing companies.

The second part introduces polymers, emphasizing the diversity of polymer types that dominate the production market. It outlines the unique features of each type and addresses the polymer manufacturing process. This section places particular emphasis on polyethylene terephthalate, which is the second component of the manufactured material. It also addresses the environmental issues caused by the extensive production of polymers, making them environmentally harmful materials. Additionally, it discusses recycling methods and presents recent statistics on polymer consumption and recycling rates worldwide in recent years.

The third chapter initially presents a study of previous researches in this field. This chapter is based on the fact that previous researches did not address the idea of combining brick powder specifically with polyethylene terephthalate. Thus, this chapter explains the detailed method for combining these two materials, taking into account the mixture ratio between them, to produce them in the form of test tubes according to the standards for testing, and finally applying the tests to this material.

This chapter also explores the possibility of integrating this new composite material into the construction industry, specifically in building walls. The substitution involves replacing traditional brick with plastic brick tiles. In this study, a numerical analysis is conducted, and comparisons are made with other numerical and experimental studies. This chapter also discusses the software program used for this study and explain the model employed, detailing its characteristics. The model is subjected to both in-plane loads, and in-plane cyclic loads to simulate seismic conditions.

The fourth chapter provides us the experimental results, which are thermal results mechanical results and morphological results; this study also enables us the numerical results to determine the load-bearing capacity of this material when used in wall construction under the applied stresses.

This thesis serves two goals:

Primary objective: researching the possibility of producing a new composite material based on plastic waste and brick powder, with high mechanical characteristics.

Secondary objective: Research the possibility of incorporating the new material into building materials.

CHAPTER I

COMPOSITE MATERIALS

1 INTRODUCTION

Materials have shaped our lives and society significantly throughout human history. In order to emphasize the significance of the time's dominating materials, entire historical eras have been named after them [1]. With their volume and applications constantly rising over the past fifty years, composite materials, plastics, and ceramics have recently emerged as dominant materials. Particularly in the fields of fiberglass boats, graphite, sports, goods, and aerospace, composite materials have significantly expanded into new markets and uses. The only restriction on the applications of composite materials is the individual's creativity [2].

2 DEFINITION

A composite material is distinct from a typical macroscopically homogenous substance, as the term suggests.

When two or more materials are combined on a macroscopic scale to produce a useful third substance, it is referred to as a composite material; Figure 1 explains the process to composite material [3].

Now, composite materials are substances that have durable fibers (continuous or not) incorporated into a matrix or weaker substance. The matrix transfers the load imposed on the composite component to these fibers while maintaining the geometric configuration of the fibers [4].

The final composite product has a mechanical performance that is intermediate, meaning that it is better than the matrix, but not as good as the fibrous reinforcement. In general, this material also exhibits certain unique features than individual components [5].

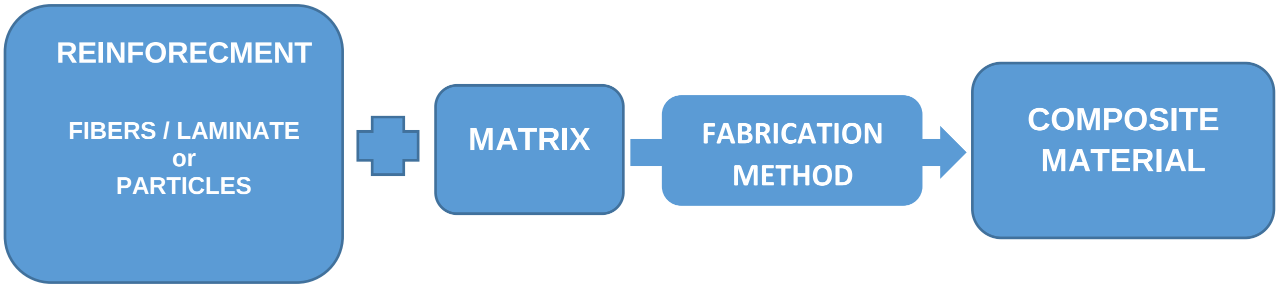


Figure 1. Composite material

Although contemporary composite materials have received a lot of attention recently, they are not a recent creation. In reality, composite materials have been in use since antiquity; examples include wood, straw, and mud. In the past, composites were used to improve the performance of even conventional weaponry. For instance, stronger and more potent weapons were made by fusing wood with materials like animal hide and bone [4].

Using composite materials has the advantage that, when well developed, they frequently display the best characteristics of both constituents and frequently some characteristics that neither part possesses. The following properties are some of the qualities that may be enhanced by creating a composite material [6]:

- Strength
- rigidity
- endurance to fatigue
- dependent on response to temp
- design
- weight
- resistance to corrosion
- durability against wear
- heat insulation
- thermal efficiency
- acoustical insulation

3 COMPOSITE COMPONENTS

Composite components consist of two essential elements: the matrix and the reinforcement. These components work together to create a synergistic material with enhanced properties. Additives and fillers also used to provide specific properties.

3.1 Matrix

The matrix is the element that binds and holds the fibers together. It distributes the forces (resistance to compression or bending) and ensures the chemical protection of the fibers.

The classification of the types of matrices commonly encountered is given in Figure 2.

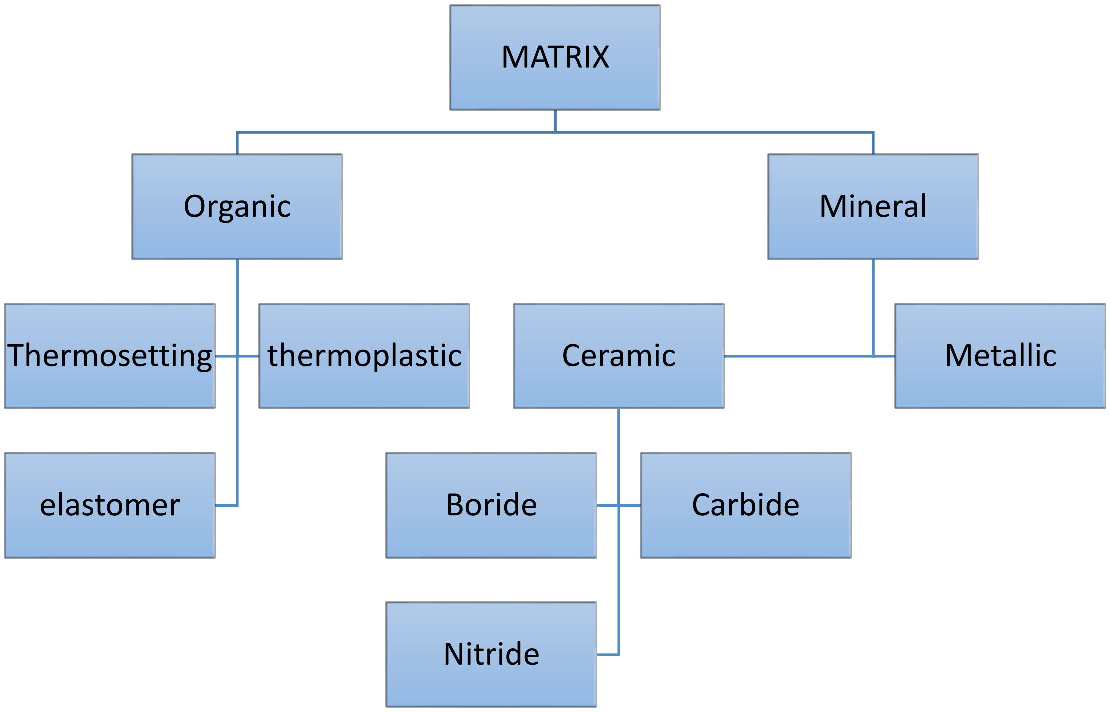


Figure 2. Different matrix families [7]

The primary types of resins utilized in composite materials are thermoset resins, thermoplastic resins and thermostable resins.

3.1.1 Thermosetting resin

Thermosetting resins have high mechanical properties (thermal or physico-chemical treatment). These resins therefore have the particularity of being able to be shaped only once [5]. The main thermosetting resins used in the implementation of composite materials are in decreasing order in tonnage: unsaturated polyester resins, condensation resins, epoxy resins [8].

3.1.2 Thermoplastic resin

Thermoplastic resins are polymers that, within a certain temperature range, can be repeatedly softened by heating and toughened by chilling [5]. Thermoplastic resins have the ability, in the softened state, to mold easily by plasticity [9].

Figure 3 shows a thermoplastic resin with glass fibers.

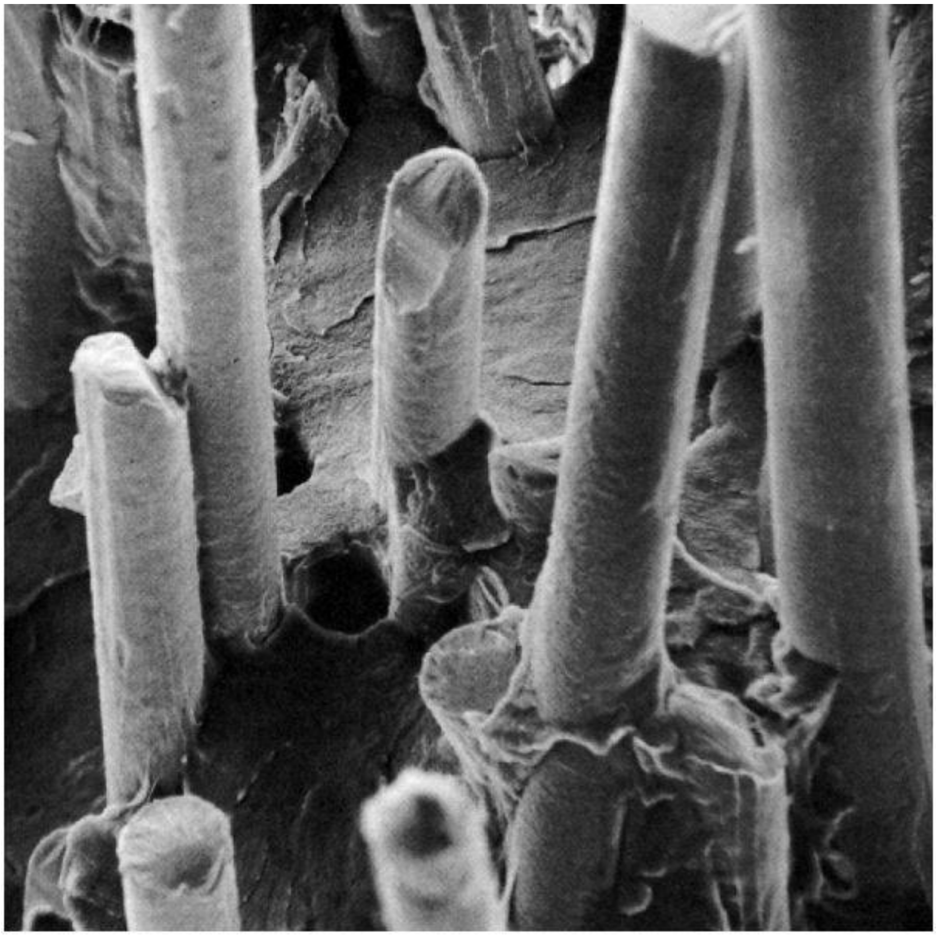


Figure 3. Thermoplastic resin with glass fibers, fiber dimeter 5 µm [10]

3.1.3 Thermostable resin

These are polymers with stable mechanical characteristics under high pressures and temperatures (>200°C) applied continuously [5]. This property is measured by determining the temperature that the resin can withstand for 2000 hours without losing half of its mechanical characteristics [8, 9].

3.2 Reinforcement

The addition of reinforcement in composites can lead to significant improvements in strength, stiffness, fatigue resistance, impact resistance, and other mechanical properties compared to the matrix material alone. The selection and arrangement of the reinforcement phase are crucial factors in achieving the desired performance characteristics of the composite material for various applications, ranging from aerospace and automotive industries to construction and sporting goods [9].

The classification of commonly encountered types of reinforcements is shown in Figure 4.

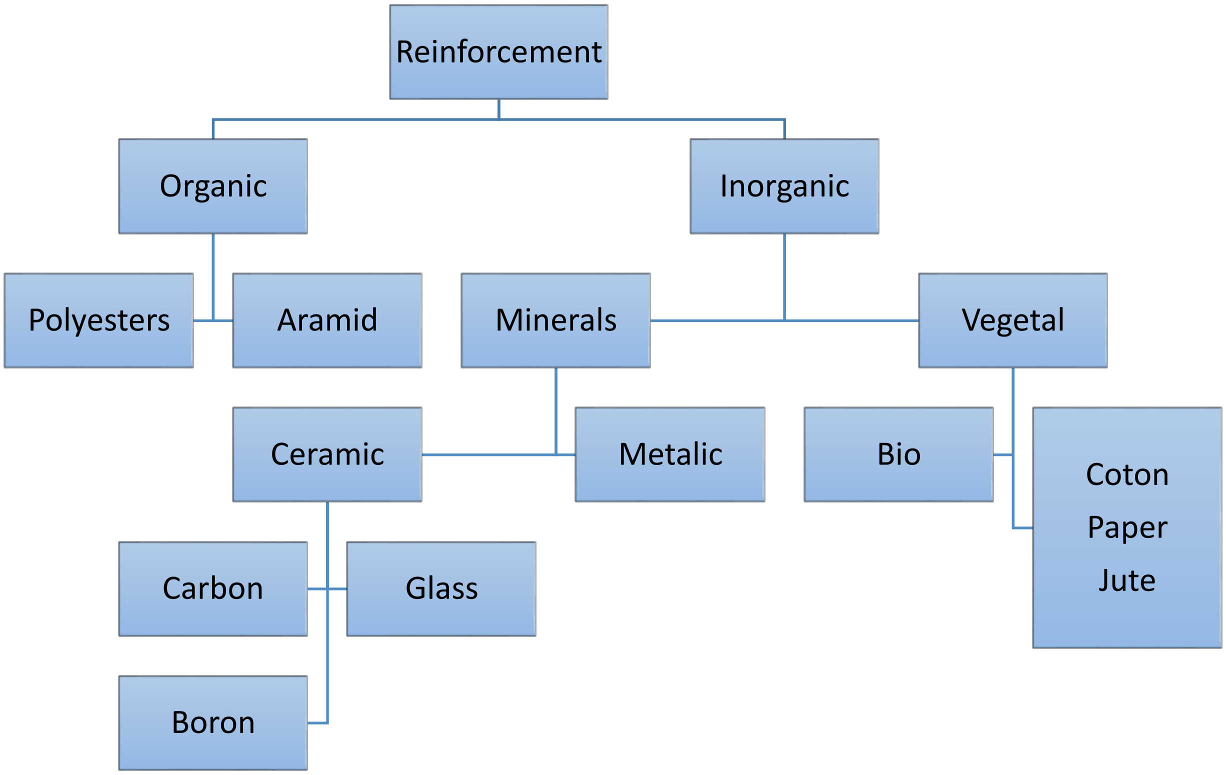


Figure 4. Reinforcement types [7]

Figure 5 represent deferent shapes of reinforcement, the types below are more described in classification of composite materials [11].

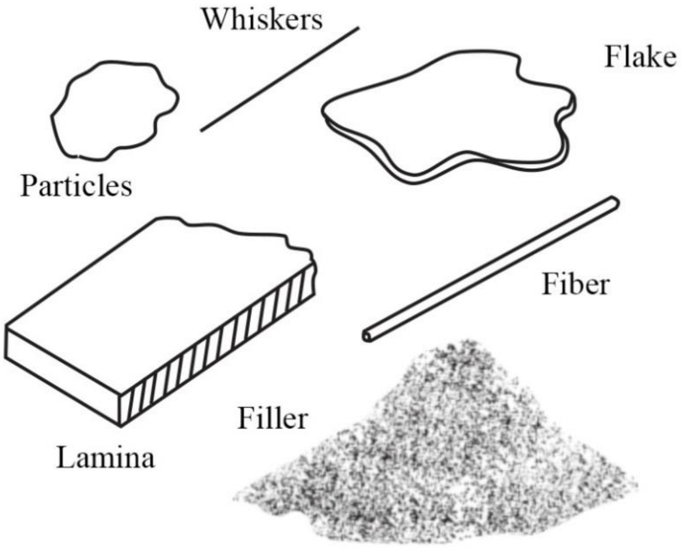


Figure 5. Different shapes of reinforcement used in composite materials [11]

3.3 Fillers and additives

3.3.1 Filers

To increase the resin's mechanical qualities, reinforcing fillers are applied. These fillers can be categorized based on their shape as spherical or non-spherical. On the other hand, non-reinforcing fillers are used either to reduce the cost of resins while maintaining their performance or to enhance specific resin properties. Examples of non-reinforcing fillers include low-cost fillers, flame-retardant fillers, and conductive or antistatic fillers [9].

3.3.2 Additives

Additives are found in small amounts, typically a few percent or less, and they serve different functions, including acting as lubricants and release agents, providing pigmentation and coloring, acting as anti-shrinkage agents, and serving as UV stabilizers.

4 INTERFACE AND INTERPHASE

An interface refers to the boundary or surface between two phases, such as the boundary between the fiber and the matrix in a composite material. On the other hand, an interphase is a thin film or layer that is bonded to both the fiber and the matrix in Figure 6. The interphase typically consists of multiple layers when it is a multilayer structure. In summary, an interphase involves the presence of at least two interfaces: one between the interphase and the matrix, and another between the interphase and the fiber [12-14].

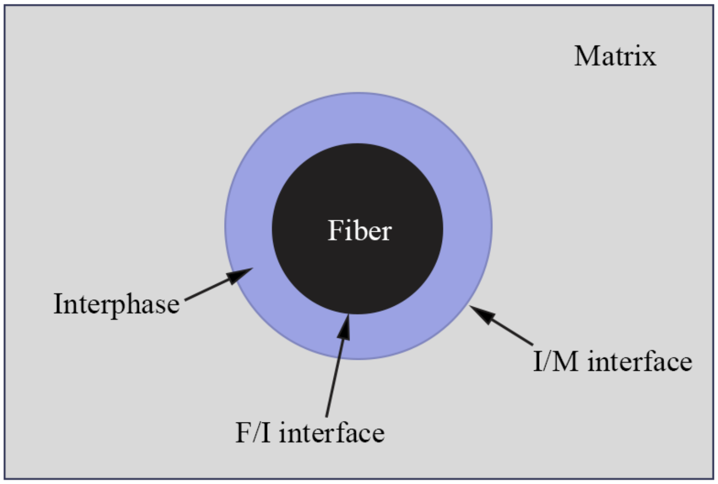


Figure 6. Interface and interface [15]

The interface and interphase in composite materials play important roles in determining the overall performance and properties of the material [13, 15]:

4.1 Interface

Interface serves four properties:

- **Load transfer:** The interface facilitates the transfer of mechanical loads between the different components of the composite, such as the reinforcement and the matrix [13]. A strong interface ensures efficient stress transfer, leading to improved mechanical properties [14].
- **Adhesion:** The interface provides adhesion between the components, promoting bonding and cohesion. A good bond at the interface enhances the overall strength and integrity of the composite.
- **Energy dissipation:** The interface can help in dissipating energy during mechanical deformation or impact events, improving the material's ability to withstand and absorb forces.
- **Prevention of delamination**: A well-bonded interface resists delamination or separation between layers, preventing the propagation of cracks and enhancing the material's fracture toughness.

4.2 Interphase

- **Compatibility:** The interphase acts as a transitional region between the reinforcement and the matrix, providing improved compatibility between the two components. It can help to minimize the occurrence of stress concentration and promote better load transfer [14].
- **Stress relaxation:** The interphase can help to relieve stress concentrations at the interface by providing a gradual transition in properties, thereby preventing localized failure and improving the material's overall durability.
- **Chemical protection:** In certain cases, the interphase can act as a barrier, protecting the reinforcement from chemical attack or degradation by the matrix or the surrounding environment.
- **Improved bonding:** The interphase can enhance the adhesion and bonding between the matrix and the reinforcement, promoting better load transfer and mechanical properties.

5 COMPOSITE MATERIAL CLASSIFICATION

There are four common varieties of composite materials:

- Fibrous composite, which comprise fibers embedded in a matrix.
- Laminated composites, comprising numerous layers made up of various materials.
- Particulate composites composed of particles dispersed within a matrix.
- Combinations of one or more of the aforementioned types, where multiple types are incorporated into a single composite material.

The following subsections include descriptions and discussions of these different forms of composite materials [6, 16].

5.1 Fibrous composite materials

Long fibers, in their various configurations, possess significantly higher stiffness and strength in comparison to the same substance in bulk. For instance, when ordinary plate glass breaks at 20 MPa of pressure [6], glass fibers commercially available can have strengths ranging from 2800 to 4800 MPa, and laboratory-prepared forms can reach approximately 7000 MPa. This demonstrates that the geometry and physical characteristics of a fiber play a critical role in determining its strength and must be carefully considered in structural applications [6].

There are several types of fiber [1]:

- **Carbon fiber**
- **Fiberglass**
- **Aramid fiber**
- **Boron fiber**
- **silica fiber (quartz)**
- **High modulus polyethylene fibers**

Whiskers are also considered as fibers, but they are small in diameter and length as compared to fibers. Table 1 introduces mechanical properties of some fiber reinforcement.

Table 1. Mechanical properties of fiber reinforcement [5]

material	Young's modulus (GPa)	Tensile strength (MPa)	Density (Kg/m^3)	Maximum operating temperature(°C)	Elongation at break (%)
R Glass	80	2500	2500	650	3
Kevlar 49	130	3600	1450	200	
HM Carbon	400	2000	1900	2500	2
Boron	400	3500	2650	700	0.8
SiC (fiber)	480	2300	3200	900	0.5
SiC (whisker)	840	21000	3200	1600	2.5

5.2 Laminated composite materials

Composite materials that have been laminated together consist of several layers of different materials. The purpose of lamination is to combine the advantageous properties of each layer and bonding material, resulting in a more functional composite material. By utilizing lamination, specific qualities like rigidity and strength, light weight, corrosion resistance, wear resistance, aesthetics, thermal insulation, and acoustic insulation can be emphasized and optimized [17].

Examples of laminated composite material as described in texts below:

- **Bimetals**
- **Clad metals**
- **Laminated Glass**
- **Plastic based laminate**

5.3 Particulate composite materials

The components of particulate composite materials are suspended within a matrix substance [18]. Flakes are considered as a category within the particulate composite materials as shown in figure 7, they are particulate in nature because they are discrete particles that are incorporated into a matrix material [19].

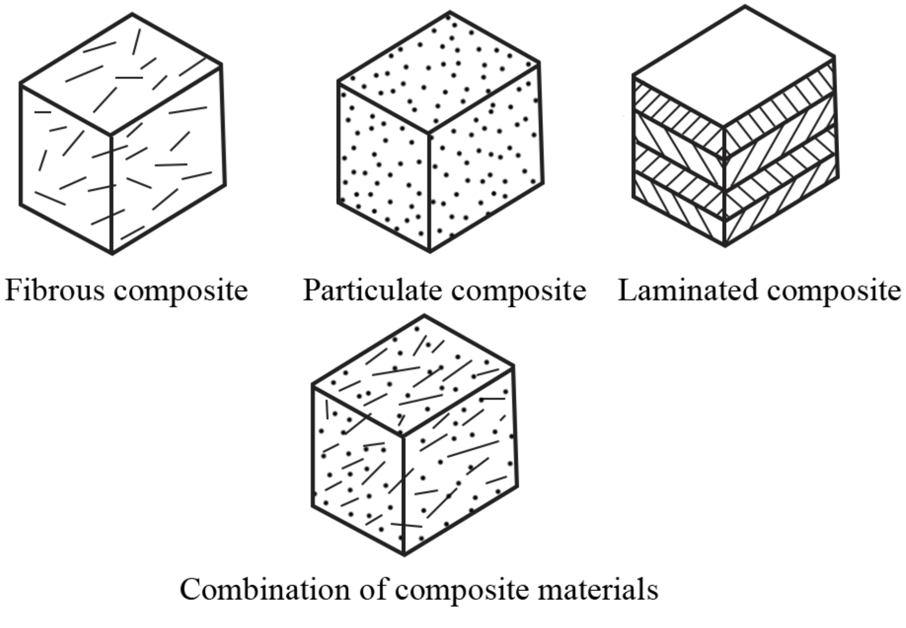
Both the matrix material and the particles might be metallic or nonmetallic. There are now four possible ingredient combinations as a result [20]:

- **Nonmetallic Particles in Nonmetallic Matrix Composite Materials**
- **Metallic Particles in Nonmetallic Matrix Composite Materials**
- **Metallic Particles in Metallic Matrix Composite Materials**
- **Nonmetallic Particles in Metallic Matrix Composite Materials**

5.4 Combination of composite materials

A combination of fibrous, laminated, or particulate composite material display more than one property of the different classifications. As an illustration, reinforced concrete demonstrates characteristics of both particulate composite materials (due to the presence of gravel within a cement-paste binder) and fibrous composite materials (because of steel reinforcement). Laminated fiber-reinforced composites are a hybrid type of composite materials that combine fibrous composite materials and lamination processes, such as those seen in tennis rackets, golf clubs, rocket motor cases, boat hulls, and airplane wings [9-12].

Figure 7. Represents a classification of composite materials.



Fibrous composite

Particulate composite

Laminated composite

Combination of composite materials

Figure 7. Classification of composite materials [10]

6 MANUFACTURING PROCESS

Once the reinforcement and resin are mixed and the matrix is hardened, a composite part is formed. At this stage, the material undergoes a curing process, during which the resin undergoes a chemical reaction and solidifies, permanently bonding the reinforcement [4]. Once the matrix has hardened, it becomes a rigid and stable structure, and it is not possible to modify the material without undergoing significant processes such as melting or decomposition. Therefore, it is crucial to carefully design and manufacture composite parts, as any desired modifications or adjustments need to be made before the curing phase [21].

The subsequent sections will provide an overview of the main procedures involved in the production of composite parts:

6.1 Contact molding

Contact molding, as depicted in figure 8, is a type of open molding process that utilizes a single mold, either male or female. In this procedure, layers of fibers impregnated with accelerator and resin are applied to the mold. Utilizing a roller or vacuum to remove any air pockets allows for compaction. Depending on variables like the temperature and the amount of accelerator used, the time needed for the resin to solidify might range from a few minutes to a few hours. Depending on their complexity during the lay-up stage, this technique enables the manufacturing of large-sized parts with an average of two to four components per day per mold. [22].

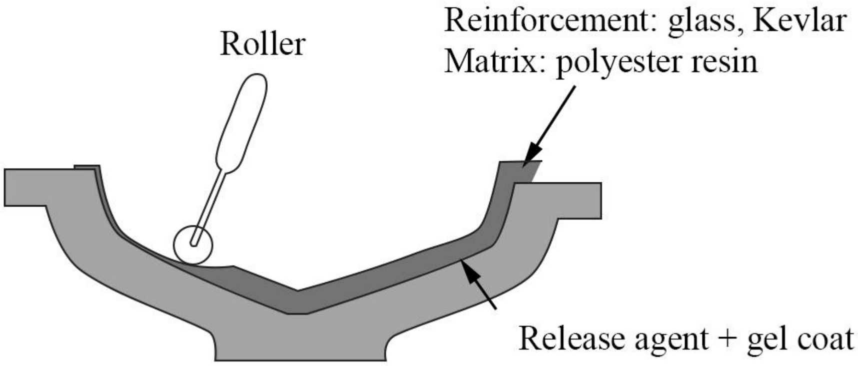


Figure 8. Contact molding method [4]

6.2 Compression and vacum molding

A counter mold will shut the mold in compression molding (see figure 9), which is done after the injected reinforcements are completed added. The entire assembly is put into a press that has a one- to two-bar pressure capacity. Either ambient temperature or a higher temperature is used for the polymerization [23].

The vacuum molding is similar to compression molding, but it requires the use of a vacuum pump. During this process, the part is placed in a mold and vacuum pressure is applied, causing the part to be compressed under atmospheric pressure and eliminating any air bubbles. Porous felt is utilized to absorb any extra resin. The entire material is then polymerized by subjecting it to heat and pressure in an oven or an autoclave.

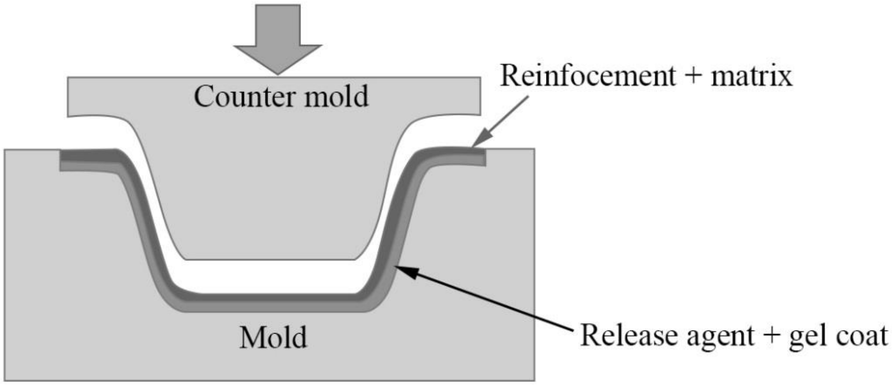


Figure 9. Compression-molding method [4]

6.3 Resin injection molding

Resin injection molding, as depicted in figure 10, involves placing the reinforcements (such as mats or fabrics) between the mold and counter mold [24]. The resin, which can be polyester or phenolic, is then injected into the mold. The molding pressure used in this process is relatively low. Mostly used in automobile bodies [25].

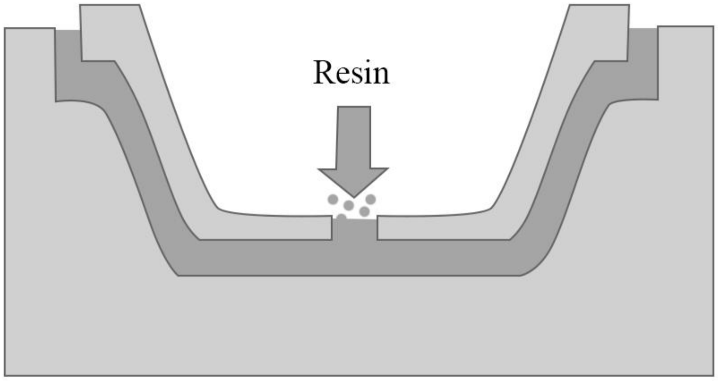


Figure 10. Resin injection method [4]

6.4 Injection molding with extruder

Extruder injection molding enables for automation of the manufacturing cycle. Composites with high temperature resistance can be created using thermoplastic and thermosetting resins [4, 26], as shown in figure 11.

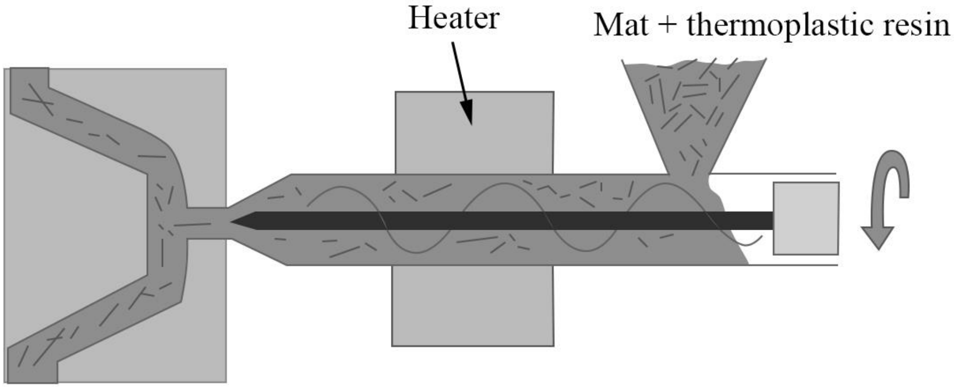


Figure 11. Extrusion molding method [4]

6.5 Molding of Hollow Axisymmetric Components

The creation of tubes and pipes uses the centrifugal molding technique (see Figure 12). It enables the inside surface of the tube as well as the homogenous resin dispersion with a high-quality surface finish. The length of the mold determines the tube's length [4].

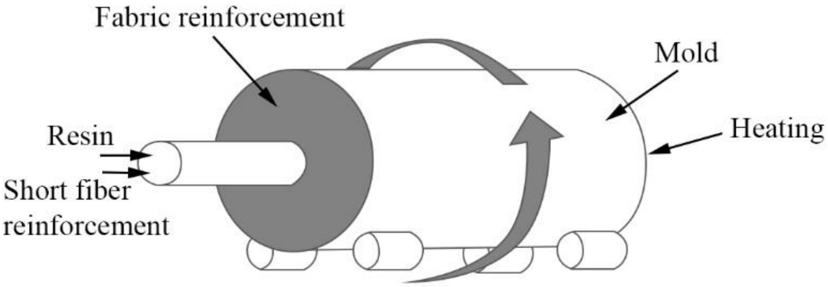


Figure 12. Centrifugal molding method [4]

6.6 Filament winding

The filament winding process, illustrated in figure 13, can be seamlessly integrated into a continuous production chain, allowing for the fabrication of long-length tubes. This process has a high production rate, capable of producing 500 kg or more of composite material per day [4]. It is well suited for manufacturing various types of tubes, including those used for petroleum transportation, as well as cylindrical shells for missiles, rockets, torpedoes, and containers [26].

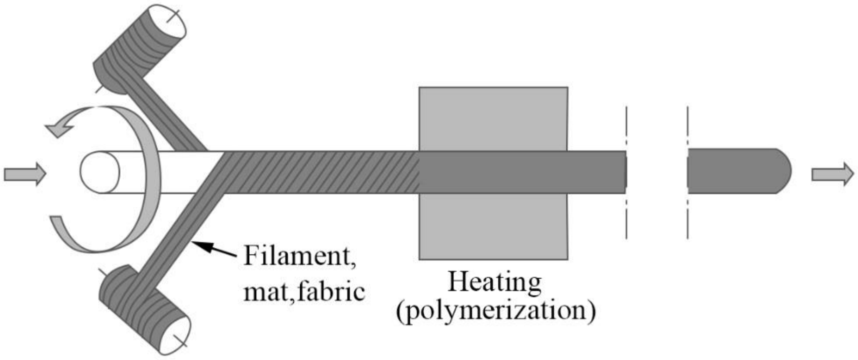


Figure 13. Filament winding method [4]

7 CONCLUSION

In conclusion, composite materials have grown to be an impressive class of materials with a wide range of applications due to their exceptional properties. Their unique combination of strength, lightweight nature, and resistance to various environmental factors has made them increasingly popular across industries, leading to their extensive use worldwide. Moreover, the existence of relatively simple manufacturing processes has empowered individuals to create their own composite materials.

The superior properties of composite materials have revolutionized numerous sectors, including aerospace, automotive, construction, and sports equipment. The remarkable strength-to-weight ratio of composites has enabled the evolution of lighter, more fuel-efficient aircraft, stronger and more durable automotive components, and structurally sound buildings. These materials have also played a crucial role in enhancing the safety and performance of protective gear, such as helmets and body armor.

As the world continues to seek innovative solutions that combine strength, durability, and lightness, composite materials are poised to play an increasingly vital role. Their versatility, coupled with the ability for individuals to contribute to their development, ensures that composite materials will remain at the forefront of material science and continue to shape our technologically advanced society.

CHAPTER II

CERAMICS AND POLYMERS

1 INTRODUCTION

In the materials science field, the categorization of solid materials is commonly done by dividing them into distinct classes. These classes primarily include ceramics, metals, and polymers, they are categorized according to the particular atom kinds that are found in the materials, and the nature of bonding that exists between these atoms. In addition to ceramics, metals, and polymers, there are two other well-known classes of materials: semiconductors like silicon and gallium and composites. Semiconductors and composites are also widely recognized categories within the study of materials.

However, this chapter in particular, we will be focusing on ceramics and polymers. The chapter will be divided into two parts:

Part one will delve into ceramics, where we will explore their general properties, various types, and their characteristics.

The second part of the chapter is dedicated to polymers, providing an in-depth description of these materials.

PART 1

2 CERAMICS

The term "ceramics" essentially refers to pottery, porcelain, and bricks. Currently, it encompasses all non-metallic inorganic materials [27].

Ceramics are composed of oxides such as Al_2O_3, ZrO_2, CaO, TiO_2, and other chemical compounds like SiC, WC, and so on. These materials have the ability to form a homogeneous macroscopic solid at temperatures exceeding 900°C [28].

The structure and microstructure of ceramics are determined during the fabrication process, which involves transforming powdered raw materials into a dense material, ideally free from pores [29].

Ceramics are polycrystalline materials manufactured through the sintering process of an oxide mixture. Their fabrication process can be adjusted, along with their composition, to tailor their dielectric, mechanical, and piezoelectric properties. The properties of ceramics depend on their microstructure, which includes factors such as morphology, the types of phases present, and surface quality [30].

Etymologically, the word "ceramic" (originating with the Greek term "keramikos" meaning "baked clay" and "keramos" meaning "clay") refers to a material obtained through the thermal treatment of certain natural minerals, such as clay. The starting product is a fine-grained powder mixed with a liquid binder, often simply water. Shaping is achieved by molding a plastic paste, such as the mixture of clay and water used by potters, or by pouring a slurry into a plaster mold. The firing process, preceded by drying and dehydration stages, requires varying temperatures depending on the chemical composition of the initial material and the desired densification. At high temperatures, atomic diffusion occurs, causing the grains to fuse together. This operation, known as sintering, is sometimes facilitated by a liquid phase's presence [31].

3 HISTORICAL

The history of ceramics can be traced back to ancient times. In the Stone Age, flint, a variety of chart, was used as a ceramic material (figure 1). The Stone Age also witnessed the emergence of various types of ceramic tools and artifacts. Oldowan pebble tools, Acheulean handaxes, Clactonian chopping tools, and Mousterian flake tools are some examples of early ceramic implements. Figure 1 shows a sharp flint for hunting purposes.

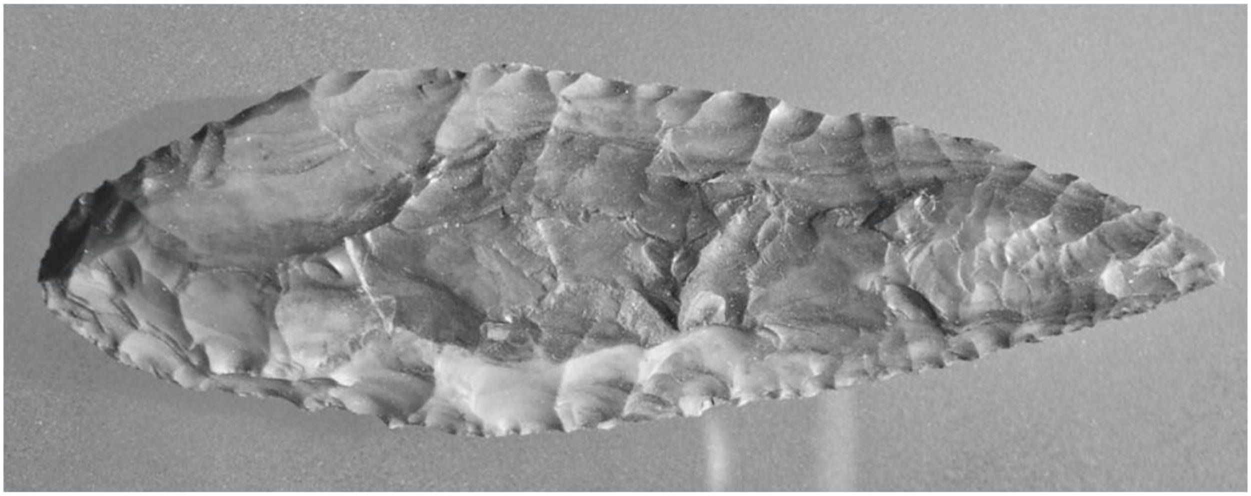


Figure 1. Sharp flint from Stone Age [32]

As civilizations developed, pottery became a ubiquitous craft, found in cultures worldwide. Pottery was produced in ancient civilizations ranging from pre-Columbian America to the Orient. Greeks, known for their expertise in clay purification, created finely crafted pottery with remarkable surface quality. They introduced kilns constructed with walls, departing from earlier pit firing techniques [33].

Over time, the invention of glazes further enhanced the aesthetics and functionality of ceramics. Ancient Egyptians utilized copper to add green and turquoise hues to their pottery. Obsidian, a volcanic glass, served as a tool material during the Paleolithic period [33]. Obsidian and other glasses exhibit conchoidal baked clay figurines and statuettes have also been discovered, such as the Venus of Vestonice, a well-preserved fertility charm dating back to 23,000 BCE. The absence of facial features on these figures has led anthropologists to rethink their significance in prehistoric societies [34].

The development of faience, a type of pottery with a porous body covered in glaze, remains uncertain in terms of its origins. However, it is believed to have been introduced in China, Persia, Armenia, and later by Arabs in Spain during the 12th century. Its production subsequently spread to Italy, France (notably with Bernard Palissy in the 16th century), Germany, and England [34].

Around 200 BCE, the invention of stoneware, an impermeable and unglazed ceramic, revolutionized pottery making. This advancement was made possible by the discovery of vitrifiable clay and improved firing techniques [35].

The Chinese, during the Tang dynasty (618-907 CE), achieved a breakthrough with the creation of white and translucent porcelain, possibly using kaolin as one of its key components. Marco Polo introduced porcelain to Europe in 1298, and its popularity surged after the opening of the maritime route to the East Indies in 1498 [36].

European attempts to replicate Chinese porcelain led to the establishment of porcelain factories, including Meissen in 1709. These factories held the monopoly on porcelain production for several decades [34].

In the 18th and 19th centuries, the porcelain industry continued to thrive, and the discovery of kaolin near Limoges, France, facilitated the production of hard-paste porcelain. This discovery led to the growth of the Limoges porcelain industry [37].

The industrialization of ceramics in the 19th and 20th centuries brought diversification and technological advancements. Ceramic materials, such as refractory ceramics and high-tech ceramics, found applications in various industries, including electronics, aerospace, medical, biotechnology, and automotive sectors.

The 21st century holds great potential for further advancements in ceramic materials and their applications. Ceramics, from their humble beginnings as simple pottery, have evolved into sophisticated and versatile materials that have made lasting contributions to human culture, art, and technological progress [37].

4 MICROSTRUCTURE

Single crystals and polycrystalline solids are two different types of crystalline solids. A single crystal is a perfect solid with an uninterrupted pattern of properly organized atoms running across the entire specimen [32]. On the other hand, a polycrystalline solid consists of multiple individual crystals called grains, separated by areas of disorder called grain boundaries as seen in figure 2. In ceramics, these grains are typically 1 to 50 micrometers in size and require a microscope to be visible. The microstructure of ceramics, which includes the shape, size, distribution of grains, as well as the presence of porosity and other phases, significantly influences their properties. Hence, the properties of ceramics are closely tied to their microstructure [38, 39]

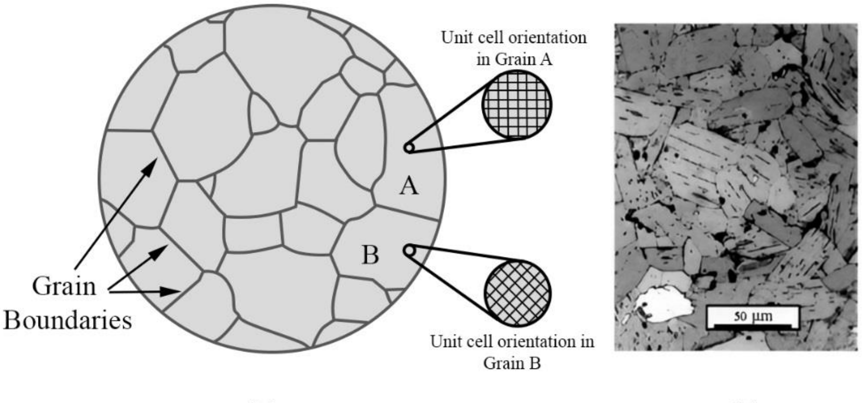


Figure 2. (a) Polycrystalline sample schematic. The multiple grains that make up a polycrystal are divided from one another by areas of disorder called grain borders. (b) An optical microscope image of a typical microstructure [38]

Solids, including ceramics, can display either long-range order, short-range order, or both in their atomic arrangement. When a solid exhibits long-range order, it is referred to as a crystalline solid. In contrast, solids that lack this periodicity and do not possess a regular arrangement of atoms are referred to as noncrystalline, glassy, or amorphous solids. The distinction between the two can be best visualized in a diagram, as depicted in figure 3 [38]. The figure clearly demonstrates that a solid exhibits long-range order when the atoms repeat in a pattern that extends well beyond the individual bond lengths. With the exception of glasses and glass-ceramics, the majority of metals and ceramics, belong to the category of crystalline solids [40].

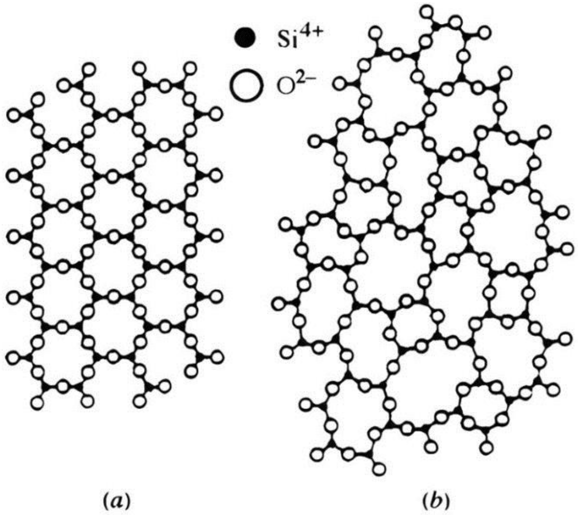


Figure 3. (a) Long range order, (b) short range order [38]

Monolithic ceramics can be classified into two main categories: "crystalline solids" and "amorphous solids,"(see figure 4) as described earlier. Within crystalline solids, there are further subdivisions: "single crystals" and "polycrystals." [41].

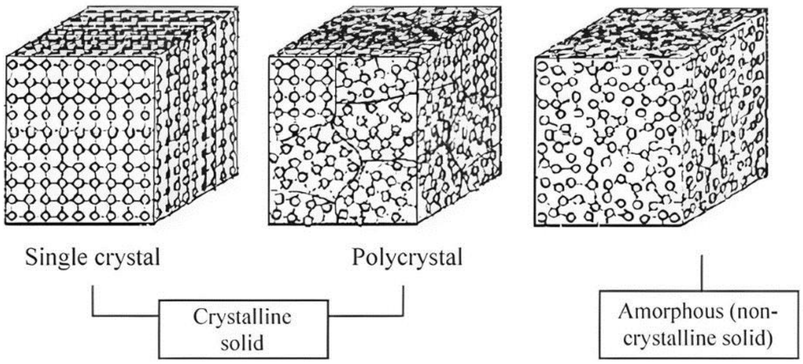


Figure 4. Structure of ceramics (schematic) [41]

5 TYPE OF CERAMICS

In the types of ceramics, there are traditional ceramics and technical ceramics.

5.1 Traditional ceramics

Traditional ceramics are made from natural raw materials such as clay, kaolin, and quartz. They are typically processed using methods like casting. And are fired at relatively low temperatures. Examples of traditional ceramics include faience, terracotta (construction bricks), and porcelain (tableware, decorative objects). Traditional ceramics are obtained from minerals such as feldspar ($K_2O.Al_2O_3.6SiO_2$), kaolin (Al_2O_3, $2SiO_2$, $2H_2O$), and silica sand (SiO_2) [42].

These ceramics are commonly found in our everyday environment, such as tableware and sanitaryware (handcrafted items). They are ceramics made from clay and have been continuously improving in terms of processes, products, and materials [32].

5.2 Technical ceramics

Technical ceramics encompass materials that have been recently developed in research laboratories due to their exceptional chemical or physical properties. They are typically produced through processes such as sintering (thermomechanical treatment) in specialized furnaces, which causes the cohesion of powder granules with a prepared cold agglomerate, or by electrofusion (direct casting of oxides into a mold). The high cost associated with these ceramics has greatly contributed to the development of new materials [42].

The mechanical strength of a modern ceramic depends on factors such as increased toughness and a less dispersed distribution of micro cracks. Technical ceramics differ from traditional ceramics in terms of higher shaping temperatures, strict control of constituent elements, and specific forming processes [43].

5.2.1 Technical ceramics families

The most important families of ceramics include oxides such as zirconium dioxide (ZrO_2), nitrides such as aluminum nitride (AlN), carbides such as silicon carbide (SiC), and mixtures between metals and metalloids were created. Ceramics can also be based on a single chemical element, such as boron (B) or carbon (C) in the form of graphite or diamond.

Technical ceramics can be classified into several families:

A. metal oxides

Metal oxides refer to compounds formed when a metal element combines with oxygen. Among binary ceramic compounds, metal oxides are the most significant [42]. This primary family of ceramics finds applications in various fields. In the list below, we have provided an overview of the key metal oxides [43].

Iron Oxide (Fe_2O_3)

Titanium Dioxide (TiO_2)

Aluminum Oxide (Al_2O_3)

Zirconium Dioxide (ZrO_2)

Silicon Dioxide (SiO_2)

Magnesium Oxide (MgO)

Calcium Oxide (CaO)

Sodium Oxide (Na_2O)

Potassium Oxide (K_2O)

Lithium Oxide (Li_2O)

B. carbides

Carbides have a high melting point, excellent stability, great hardness, and very good thermal and electrical conductivity, but they are also highly brittle. Additionally, many refractory carbides are prone to attack by the atmosphere. Metal carbides, especially WC (tungsten carbide), VC (vanadium carbide), TaC (tantalum carbide), and TiC (titanium carbide), are commonly used as cutting tools and for manufacturing high-temperature components in the aerospace and nuclear industries [42]. The high neutron capture cross-section of B_4C (boron carbide) has made it suitable for use in nuclear reactor shielding. The list below presents the key carbides [43].

Tungsten Carbide (WC)

Carbon (C)

Silicon Carbide (SiC)

Boron Carbide (B_4C)

Graphit (FeO, Fe_2O_3, Fe_3O_4)

C. nitrides

transition elements from the third, fourth, and fifth groups of the periodic table, as well as the actinide and lanthanide series, boron, silicon, and aluminum, form high-melting nitrides. In the structure of nitrides, nitrogen atoms occupy interstitial positions in the metallic lattice. Refractory nitrides have a higher melting point than their corresponding oxides and sulfides, but they tend to dissociate more easily. Consequently, they are less commonly used. However, there is growing interest in silicon nitride (Si_3N_4) and boron nitride (BN). They are stable in air and exhibit good resistance to chemical attacks. BN is used as an abrasive or component in high-temperature oxidizing environments [42].

Si3N4 is used for manufacturing static and dynamic components for applications up to 1200°C in oxidizing environments. It is also utilized as an accessory in gas turbines. The list below presents the key nitrides [43].

Silicon Nitride (Si_3N_4)

Boron Nitride (BN)

Aluminum Nitride (AlN)

Zirconium nitride (ZrN)

D. borides

Borides have a very high melting point, ranging from 1900 to 3000°C, and they are not very volatile. Additionally, they exhibit low electrical resistivity, high stability, and high hardness. However, they are not highly resistant to oxidation at temperatures exceeding 1200°C. The most common application of borides is in the manufacturing of crucibles for vacuum metallization processes.

Borides possess desirable high melting points and excellent electrical conductivity, making them suitable for specific applications that require extreme temperatures and vacuum conditions [43].

6 PROPERTIES AND APPLICATIONS

Ceramics possess distinct properties that are typically attributed to them:

6.1 Brittleness

The primary cause of brittleness in ceramics is the ionic and covalent bonding that works together to keep the atoms together. However, when ceramics are heated above their glass transition temperature, such as in the case of glass, they exhibit a transition from a brittle state to a viscous liquid-like behavior. This transition allows glass to be easily molded into complex shapes. Therefore, despite the fact that ceramics are typically brittle at room temperature, their behavior at a high temperature can vary, and they may exhibit less brittleness under those conditions [32].

6.2 Electrical insulation

Ceramics are generally poor electrical conductors due to their inherent properties and atomic structure. The low electrical conductivity of ceramics can be attributed to several factors [38, 44]:

Band gap: Ceramics often have wide band gaps, which means there is a significant energy barrier for electrons to move freely. This obstructs the movement of the electrical current.

Insulating nature: Ceramics are typically insulating materials, meaning they have a high barrier to electric current flow. This is because the valence electrons are tightly bound to the atoms and do not move easily [44].

Lack of free charge carriers: Ceramics lack free charge carriers, such as electrons or ions, that can readily move and carry electric charge. This is in contrast to metals, which have delocalized electrons that can move freely throughout the material.

Ionic bonding: Many ceramics contain ionic bonds, where electrons are transferred between atoms, resulting in a fixed lattice structure. These bonds restrict the movement of electrons, limiting their ability to conduct electricity [38].

6.3 Thermal insulation

Ceramics are known for their excellent thermal insulation properties. They are effective at reducing heat transfer due to several factors:

Low thermal conductivity: Ceramics have a low thermal conductivity, meaning they are not efficient at conducting heat. This is since there are little voids or air pockets within the material, which act as thermal insulators [45].

High porosity: Many ceramics have a high porosity, which creates a network of air pockets or trapped gases. By lessening the solid-to-solid contact between ceramic particles, these gaps aid in preventing the transfer of heat.

Low thermal expansion: When compared to other materials, ceramics frequently have low coefficients of thermal expansion, which means they expand and contract less with temperature changes. This property helps to minimize thermal stress and maintain the integrity of the insulation over a range of temperatures.

Refractory nature: Certain ceramics, known as refractory ceramics, have high melting points and excellent resistance to heat. They can withstand extremely high temperatures without deforming or degrading, making them suitable for thermal insulation in applications such as furnaces and high-temperature environments [46].

6.4 Mechanical properties

Ceramics exhibit higher strength in compression compared to tension, unlike metals which have comparable strengths in both modes. This characteristic is particularly significant when utilizing ceramic components in load-bearing applications. Care must be taken to ensure that the stress distribution in ceramics remains compressive. Designing concrete bridges is one notable instance, where the ceramic-based concrete (a type of ceramic matrix composite) needs to be maintained under compression. Generally, ceramics have lower toughness; however, the incorporation of ceramics into composites can significantly enhance this property [47].

Ceramics exhibit a high level of hardness, with a relatively low elastic limit. In addition, as the temperature rises, the Young's modulus of ceramics drops, Table 1 displays the mechanical properties of ceramics [48, 49].

Table 1. Ceramics mechanical properties [49].

Material	Hardness	E (GPa)	Compressive strength (Mpa)	Melting temperature °C
Diamaond (C)	**8000**	**930**	**7000**	**3500**
Boron Nitride	**5000**	**860**	**7000**	**1540**
boron carbide (B_4C)	**3500**	**450**	**2900**	**2425**
titanium carbide (TiC)	**3100**	**350**	**2800**	**3100**
Silicon carbide (SiC)	**3000**	**400**	**1000**	**2400**
Tungsten carbonate (WC)	**2700**	**600**	**5000**	**2780**
Alumina (Al_2O_3)	**2100**	**350**	**3000**	**2050**
Quartz (SiO_2)	**1000**	**54**	**700**	**1600**

6.5 Chemical insensitivity

Ceramics exhibit a remarkable resistance to harsh chemical and thermal conditions. Many ceramics, including Pyrex glass, are widely employed in chemistry laboratories due to their exceptional chemical inertness. Pyrex glass is known for its resistance to corrosive chemicals, ability to withstand high temperatures, and its resistance to thermal shock, due to its low thermal expansion coefficient. These qualities also make Pyrex glass a popular choice for bakeware applications [32].

6.6 Transparent

Transparency in ceramics refers to the property of allowing light to pass through without significant absorption or scattering. It means that ceramics can transmit light, similar to materials like glass [32].

The transparency of ceramics is achieved through careful control of their composition and structure. It typically requires ceramics to have a high degree of crystallinity and uniformity in their microstructure. The absence of defects, impurities, or scattering centers within the material is crucial for maintaining transparency [50].

Ceramics encompass a broad range of materials with diverse applications (see table 2). They are utilized in various industries, including construction (bricks, tiles), electronics, and magnetism. Ceramics offer a wide range of properties, which make them suitable for different uses and functionalities in these applications in table below:

Table 2. Properties and Applications for Ceramics [32]

property	**Example**	**applications**
Electrical	Bi2Ru_2O_7	Conductive element in thick-film resistors
	Doped ZrO_2	Solid-oxide fuel cell electrolyte
	Indium tin oxide (ITO)	Transparent electrode
	SiC	components for furnaces used in resistive heating
	$YBaCuO_7$	Superconducting quantum interference devices (SQUIDs)
	SnO_2	Electric glass melting furnace electrodes
dielectric	α-Al_2O_3	Spark plug insulator
	PbZr0.5Ti0.5O3 (PZT)	Micropumps
	SiO_2	Furnace bricks
	$(Ba,Sr)TiO_3$	Dynamic random access memories (DRAMs)

	Lead magnesium niobate (PMN)	capacitor chips
Magnetic	γ-Fe_2O_3	tape recordings
	$Mn0.4Zn0.6Fe_2O_4$	Touch tone telephone transformer cores
	$BaFe_{12}O_{19}$	speakers' permanent magnets
	$Y2.66Gd0.34Fe4.22Al0.68Mn0.09O_{12}$	phase-shifting radars
optical	Doped SiO_2	Laser fibers
	α-Al_2O_3	envelopes in transparent street lights
	Doped $ZrSiO_4$	Ceramic colors
	Doped (Zn,Cd)S	microscopes with fluorescent screens
	$Pb1-xLax(ZrzTi1-z)1-x/4O_3$ (PLZT)	optical thin-film switches
	Nd doped $Y3Al_5O_{12}$	crystalline lasers
Mechanical	TiN	abrasion-resistant finishes
	SiC	polishing abrasives
	Diamond	Cutting tools
	Si_3N_4	components of engines
	Al_2O_3	Artificial tooth roots, bone, and joints, hip implants
Thermal	SiO_2	insulating tiles for spaceships

Al_2O_3 and AlN	Integrated circuit packages
Lithium-aluminosilicate glass ceramics	mirror supports for telescopes
Pyrex glass	Cookware and glassware for laboratories

7 CERAMIC PREPARATION

There are several preparation methods for ceramics, depending on the desired composition, structure, and properties of the final product. Ceramics typically share a common manufacturing process, see organizational diagram in figure 5:

Figure 5. General diagram for the manufacture of a ceramic

7.1 Powder

The solid raw material of ceramics is reduced into fine particles (with a diameter of 1µm) to react with each other in the solid state and bond together through sintering. The manufacturing of ceramics involves natural raw materials composed of minerals. This mixture of raw materials is a complex combination of minerals with varying particle size and morphology. Several methods are used for powder preparation, including mechanical, physical, and chemical methods. Mechanical methods commonly used include grinding and mechano-synthesis. Physical methods often involve atomization techniques, while chemical methods involve the use of chemical species called reactants and reagents in powder preparation [51].

7.2 Pretreatment

After the powder preparation stage, the particles can easily separate from each other. To address this issue, the powder is typically dispersed in a liquid medium, creating a colloidal suspension. Other additive elements such as dispersants, binders, and plasticizers may also be added to the suspension to improve its homogeneity. These additives, which are usually organic, will be removed during the debinding stage [52].

7.3 Shaping

The primary goal of this stage is to achieve the desired shape of the final ceramic piece using powder. It typically involves compacting the powder at room temperature through techniques like isostatic compression, uniaxial compression, injection molding, or extrusion. The resulting piece, known as the "green part," has a specific density but is mechanically fragile, held together by mechanical interlocking. To enhance its mechanical strength, the green part undergoes the sintering process [53].

7.3.1 Compaction mechanism

Compaction mechanisms are divided to four types:

A. Uniaxial pressing

In the uniaxial pressing mechanism, the raw material is compressed within a metallic die along a specific direction [54].

B. Isostatic pressing

The creation of components, such as elongated pieces (tubes) or complex-shaped and/or large-volume sections, that are challenging to acquire through uniaxial pressing is accomplished by isostatic pressing. The benefit of using this pressing technique is that the component will receive an even distribution of pressure. Additionally, it is used in the production of parts with a high, consistent green density, such as grinding and bearing balls, as well as medical prostheses. In isostatic pressing, the powder mixture is placed in a mold submerged in a liquid subjected to pressure [54].

C. Slip casting

Slip casting is a process that involves a suspension of powder in a liquid, typically with a high solids content, ranging from 60% to 75%. This technique is commonly employed in the production of complex-shaped objects, such as decorative pieces or tableware, as well as large-sized components like sanitary ware. Slip casting utilizes porous molds and can also involve pressure casting methods to achieve the desired shape and structure [54].

D. Injection molding

Injection molding is a technique in which an organic resin is added to the ceramic powder to create a plastic paste that can be molded into complex shapes at room temperature. This method relies on the application of pressure to shape the material [54].

7.4 Drying

At this stage, the goal is to remove the organic additives that were added during the powder mixing process. This is achieved through a relatively low-temperature heat treatment, typically around 500°C [54].

7.5 Sintering

The sintering process involves the consolidation of the "green part" through a heat treatment. This step is crucial for imparting the desired mechanical properties to the ceramic component by controlling the evolution of its microstructure and densification. The thermal cycle typically consists of three phases: a heating phase to the sintering temperature, followed by an isothermal phase, and finally a cooling phase [53].

During the high-temperature isothermal phase, the necks between particles develop and the piece densifies, sometimes leading to grain growth. Sintering can occur without mechanical constraints (heating in air or controlled atmosphere), which is known as natural sintering. Alternatively, pressure can be applied during the heating process, known as pressure-assisted sintering (see figure 6). The microstructure of the compacted powders undergoes changes throughout this operation [54].

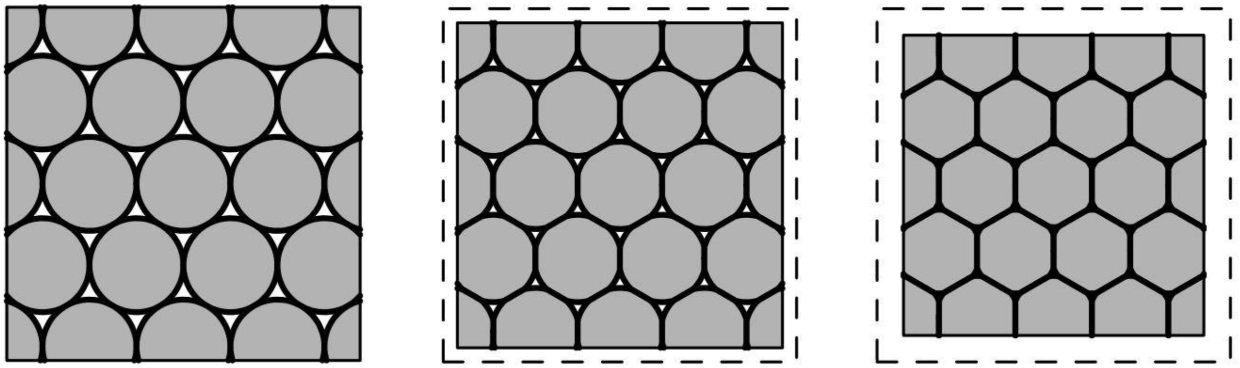


Figure 6. Variation of the microstructure of powders during the sintering operation [53].

Pressure-assisted sintering is employed to achieve higher densification or lower sintering temperatures compared to natural sintering. The application of pressure activates diffusion at particle contacts at lower temperatures than conventional sintering, leading to enhanced bonding and densification. In the case of metal sintering, it can even induce plastic deformation. From a physico-chemical standpoint, at least two types of sintering can be distinguished:

7.5.1 Solid-state sintering

Solid-state sintering is a process in which the heat treatment does not cause the melting of any of the constituents. Interparticle bonding primarily occurs through atomic rearrangement, known as solid-state diffusion. Densification during solid-state sintering occurs in three stages, as observed in figure 7:

- Formation of bridges between grains, which typically completes at a relative density of around 0.65.

- Elimination of open porosity, occurring within the relative density range of 0.65 to 0.92,

The elimination of closed porosity continues until the end of the sintering process, and this final stage is the most challenging.

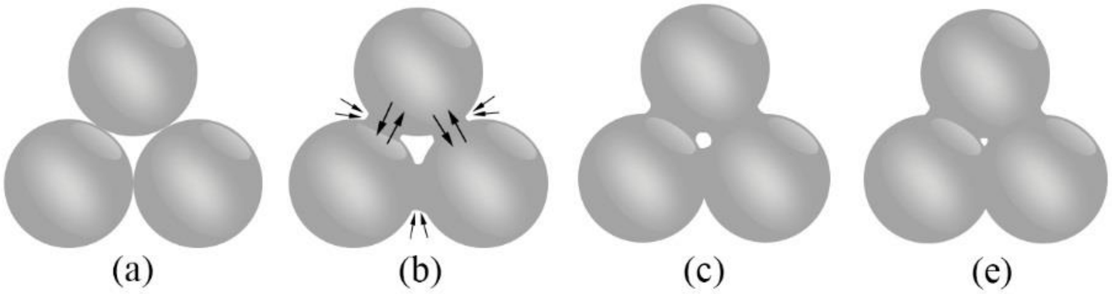


Figure 7. Solid phase sintering steps: (a) bridge formation, (b) porosity removal, (c) and (e) end of sintering

7.5.2 Liquid phase sintering

During liquid-phase sintering, a certain amount of liquid is present, which facilitates the rearrangement of particles, species diffusion, and the formation of liquid bridges between the grains, among other effects.

7.6 Finishing

Finishing is an additional step that depends on the intended application and can involve machining, surface treatment, and other processes [54].

PART 2

8 INTRODUCTION TO POLYMERS

Polymeric materials are frequently employed because of their unique mechanical characteristics and processing versatility. These characteristics are strongly related to their structure, and it is easy to imagine the resulting morphology and the accompanying attributes based on a specific molecular structure [55].

When we mention polymers, our initial association is often with plastics. However, it is important to differentiate between natural and synthetic polymers. Throughout human history, natural polymeric materials like amber and natural rubber have found various applications. Biopolymers, such as proteins and nucleic acids, play vital roles in biological processes. On the other hand, synthetic polymers, which have been studied since 1832, are commonly referred to as plastics, and their variety is seemingly limitless [56].

In the 1920s that the concept of macromolecules began to be widely accepted within the scientific community. Herman Staudinger, a chemistry professor at the Federal Institute of Technology in Zurich from 1912 to 1926, and later a professor in Freiburg Im Breisgau, was one of the main advocates of this idea. Staudinger, who won the Nobel Prize for Chemistry in 1953, demonstrated that polymeric materials such as cellulose, silk, and rubber were composed of long molecular chains referred to as macromolecules. This groundbreaking notion paved the way for more systematic chemical and physical research on the synthesis, structure, and behavior of solid polymers [57-59].

9 DEFINITION

The term "polymer" (the word "polus" in Greek means "many", several" and "mêros" meaning "unit, part") ,referring to a substance composed of multiple repeating units or parts (see figure 8). A polymer is a high-molecular-weight macromolecule, whether organic or inorganic, formed by the covalent bonding of a vast number of repeating units (also known as motifs or monomers) derived from one or more monomers [60].

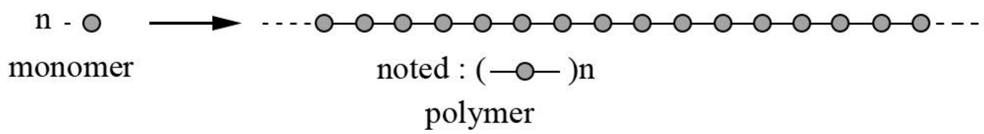


Figure 8. Schematic model of polymer synthesis [60]

For example, ethylene (CH_2=CH_2) leads to polyethylene, which is equivalent to -[CH_2-CH_2]n-, where n represents the quantity of units that repeat.

The number n of repeating units is referred to as the degree of polymerization (Dp). It represents the average value for a given sample. The molar mass is then expressed as Mn = n M_0, where M_0 denotes the molar mass of the monomer [61].

Organic polymers are formed from monomers consisting of atoms commonly used in organic chemistry, mainly nitrogen (N), oxygen (O), hydrogen (H), and carbon (C), as well as other elements such as halogens (fluorine (F), chlorine (Cl), bromine (Br), iodine (I)), sulfur (S), and phosphorus (P). Additionally, there are other polymers where the carbon atom is replaced by silicon (Si) [61].

The Macromolecule is a substantial molecule made up of repeating units derived from monomers. **Monomer** is the initial, simple molecule (from the Greek words "monos" meaning "alone or single" and "meros" meaning "part"). **Repeating motif** is a small, periodic structure that repeats along the chain, consisting of one or more basic units (monomers), and **Polymerization** is the reaction that joins monomers together to form macromolecules [62, 63].

10 POLYMERS CLASSIFICATION

Polymers can be classified in several ways based on different criteria. Here are the most common classification methods:

10.1 Based on source

we distinguish:

10.1.1 Natural polymers

Natural polymers originate from plant or animal sources and often exist in the form of fibers. Examples of plant-based fibers include wood, paper, cotton, and latex (extracted from the Hevea tree). Animal-based fibers include leather, silk, and wool [64].

10.1.2 Artificial polymers

Artificial (regenerated) polymers are obtained by chemically modifying natural polymers to alter certain properties. While the basic constituent is of natural origin, they result from a chemical transformation of the functional groups carried by the monomer units. For example, cellulose derivatives such as cellulose esters, rubber, artificial silk, crosslinked collagen, etc., are examples of artificial polymers derived from the base molecule cellulose [65].

10.1.3 Synthetic polymers

Synthetic polymers are entirely manufactured by humans using monomer molecules that do not exist in nature. The structures created through synthesis (polymerization) often resemble those of natural polymers. Examples include polystyrene (PS), polyvinyl chloride (PVC), polyethylene terephthalate (PET), and polyethylene (PE) [66].

10.2 Based on patterns number

According to this type of classification, we find:

10.2.1 Homopolymers

A homopolymer as seen in figure 9 is a type of polymer composed of a single type of repeating unit or monomer. In other words, all the units in the polymer chain are identical. Homopolymers exhibit a uniform chemical composition and structure throughout their entire chain. Examples of homopolymers include polyethylene (PE), polypropylene (PP), and polyvinyl chloride (PVC), where the repeating units consist of ethylene, propylene, and vinyl chloride, respectively [66].

–A–A–A–A–A–A–A–A–A–A–

Figure 9. Linear homopolymer [66]

10.2.2 Copolymers

Copolymers are polymers that contain multiple types of repeating units. Similar to homopolymers, copolymers can be classified into various families, including statistical, alternating, and block copolymers [67].

A. Statistical polymers

These copolymers have randomly distributed repeating units along the polymer chain, without any specific arrangement or sequence (figure 10) [67].

–A–A–B–A–B–B–A–B–A–A–B–B–B–A–

Figure 10. statistic copolymer [67]

B. Alternating Copolymers

Alternating copolymers have a regular and alternating sequence of two different types of repeating units along the polymer chain (figure 11).

−A−B−A−B−A−B−A−B−A−B−A−B−A−B−A−B−

Figure 11. Alternating copolymer [67]

C. Block Copolymers

Block copolymers consist of long blocks or segments of two or more different types of repeating units that are connected together (figure 12).

−A−A−A−A−A−A−A−B−B−B−B−B−B−B−

Figure 12. Block copolymer [67]

10.3 Based on the architecture of molecular chains

Many polymers are constructed in such a way that their molecules consist of thousands of atoms arranged in a linear chain, resulting in a preference for elongation in a straight line. However, this is not the case for all polymers, as there are numerous other arrangements. Therefore, Based on how they are arranged, polymers are divided into two types: linear and non-linear [67].

10.3.1 Linear arrangement

A linear polymer is a polymer in which the molecules consist of more or less long chains of atoms, known as the main chain. Typically, small chains, referred to as side chains, are attached to certain atoms of the main chain see figure 13. These side chains are much shorter than the main chain and usually contain only a few atoms, while the main chain may have hundreds or thousands of atoms [67].

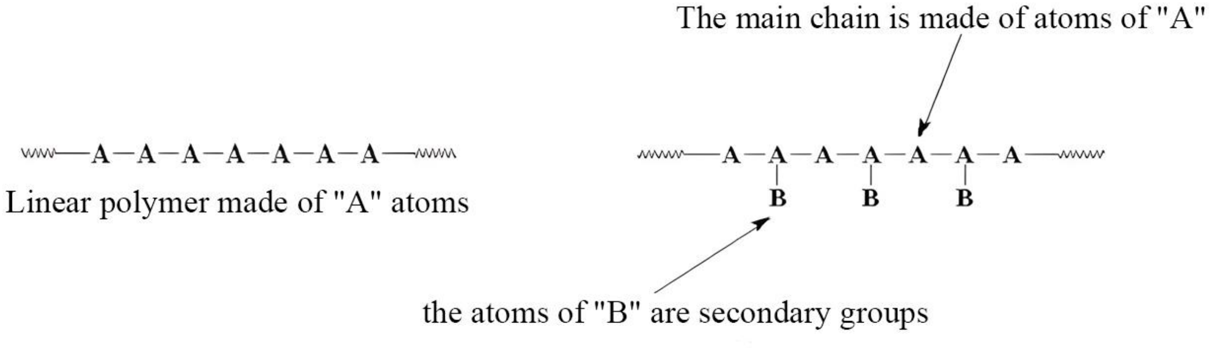


Figure 13. Linear polymer [67]

10.3.2 Non-linear arrangement

In this type of arrangement, we mainly encounter:

A. Branched polymer

A branched polymer is a polymer that has at least one branching point. During polymerization, homopolymeric or copolymeric chains can graft onto the main chain as seen in figure 14. The branched chain is referred to as a graft when its composition differs from that of the main chain [68].

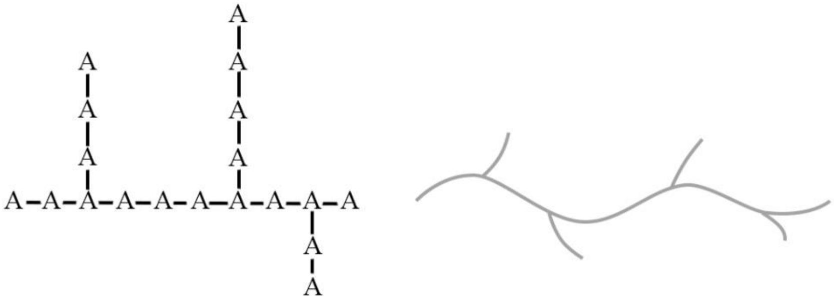


Figure 14. Branched polymer [65]

B. Cross-linked polymer

A cross-linked polymer as shown in figure 15 is a type of polymer in which all the polymer molecules are linked together, making them difficult to separate. When a cross-linked polymer such as Charles Goodyear's vulcanized rubber is heated, the molecules cannot flow or slide past each other, which is why the polymer does not melt and does not become brittle when cooled [68].

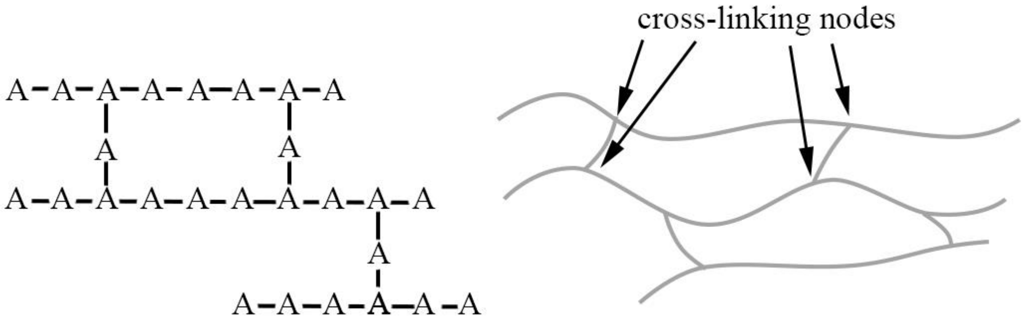


Figure 15. Cross-linked polymer [65]

C. Star polymer

A star polymer is a form of polymer in which several polymer chains' ends are joined at a single location (figure 16) [68].

Figure 16. Star polymer [65]

D. Dendritic polymer:

Dendritic polymers, also known as dendrimers, are polymers in which branches grow on branches, and additional branches grow on those branches, see figure 17.

Figure 17. Dendritic polymer [65]

10.4 Based on dimensionality

Based on their dimensionality, polymers can be categorized as follows:

10.4.1 Monodimensional polymers

Monodimensional polymers (linear polymers) are polymers in which each macromolecular chain is composed of a high and finite number of units [69].

10.4.2 Bidimensional polymers

Bidimensional polymers, (figure 18), some of which can be produced by nature (such as graphite carbon and keratin), exist in the form of two-dimensional sheets or layers (lamellar structure) [70].

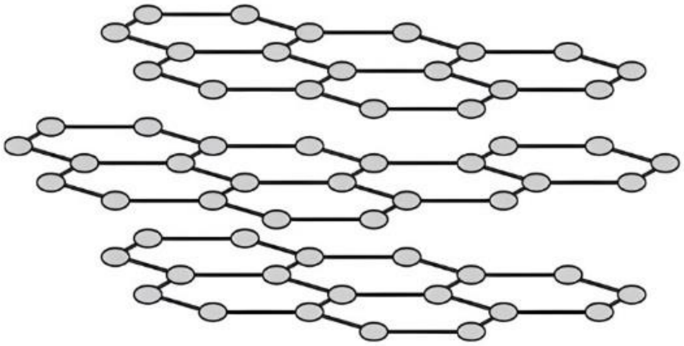


Figure 18. Schematic representation of a bidimensional polymer example of graphite carbon [71]

10.4.3 Three-dimensional polymers

Three-dimensional polymers are polymers that possess a highly interconnected and extended structure in three dimensions [69]. Unlike linear polymers, which have a linear chain arrangement, three-dimensional polymers have branches, crosslinking points, or a network structure that expands in all directions see figure 19.

These polymers can be naturally occurring, such as lignin, or they can be synthesized through the crosslinking of linear polymers or the polymerization of monomers with higher valences. The crosslinking can occur through physical or chemical means, resulting in the formation of a three-dimensional network [69].

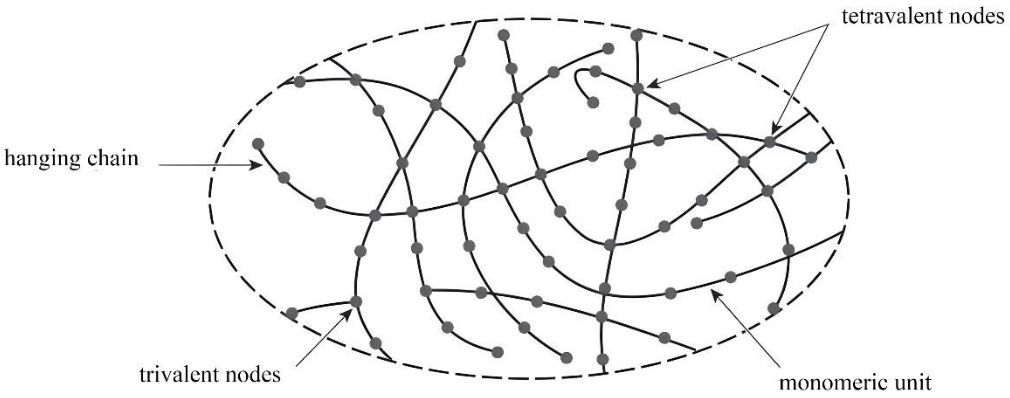


Figure 19. schematic representation of the three-dimensional polymer[71]

10.5 Classification based on thermal behavior

The properties of polymers enable a wide range of applications, which can be grouped into four main categories:

- Thermoplastics.
- Thermosetting polymers.
- Elastomers.
- Thermoplastic elastomers.

10.5.1 Thermoplastics

Thermoplastics soften when exposed to heat, becoming flexible and malleable, and then harden again when cooled. These materials are easily recyclable and maintain their characteristics. The base polymers of thermoplastics consist of weakly bonded linear macromolecules that can rupture when exposed to heat or strong pressures. This allows the polymer chains to slide past each other and assume a different shape. The thermoplastics maintain their new shape as the material cools because the bonds rebuild. Thermoplastics include various types of polymers such as polyethylene (PE), polypropylene (PP), polystyrene (PS), polyvinyl chloride (PVC), polymethyl methacrylate (PMMA), polytetrafluoroethylene (PTFE), polyesters (PET), polycarbonates (PC), and polyamides (PA) [72].

10.5.2 Thermosets

Thermosetting polymers, unlike thermoplastics, cannot be recycled because their shape, set through a chemical process during molding, is permanent. They are harder and more rigid than thermoplastic polymers. The main types of thermosetting polymers include epoxies, phenolics, and polyamides [73].

10.5.3 Elastomers

These polymers exhibit similar elastic qualities as rubber. At rest, an elastomer is composed of long, coiled molecular chains. When subjected to stress or strain, the molecules can slide past one another and deform, allowing the elastomer to exhibit its elastic behavior [74].

Elastomers are distinguished from thermosetting polymers by their characteristic rubber-like elasticity, which refers to their ability to undergo significant reversible deformations under mechanical stress. They can achieve extremely large elongations (up to 500%) while still being capable of returning to their original shape by releasing the energy that was applied during deformation back into the environment [75].

The most commonly used elastomers include silicone and polyurethane.

10.5.4 Thermoplastic elastomers

Thermoplastic elastomers belong to a new category of polymers that combine the deformability of elastomers with the recyclability of thermoplastics [74].

11 PROPERTIES

Polymers exhibit a wide range of properties that make them versatile and suitable for various applications. Some key properties of polymers include:

11.1 Crystallinity

Polymers can be categorized as either amorphous or semi-crystalline. Amorphous polymers have disordered and random chains, lacking the ability to undergo crystallization and melting. Instead, they experience a glass transition. On the other hand, Regularly repeating units in semi-crystalline polymers enable the chains to fold orderly to produce crystalline regions known as crystallites. These polymers exhibit a crystallization temperature (Tc) and a melting temperature (Tm). However, even in semi-crystalline polymers, complete crystallization is not achieved, and amorphous areas still exist [76].

The crystallinity of polymers can be induced by factors such as using homogeneous chain lengths, cooling molten polymer, evaporating polymer solutions, or annealing the polymer at a specified temperature in a vacuum or inert environment to avoid oxidation. Additionally, the degree of crystallinity can be altered by incorporating co-monomers during synthesis. Co-crystallization is typically limited among monomers with different structures, and increasing the proportion of amorphous monomers reduces crystallinity [76].

Semi-crystalline polymers tend to be stiffer, higher density and greater solvent resistance than their amorphous equivalents [77].

11.2 Thermal properties

The glass transition temperature (Tg) is a property of a polymer's amorphous regions, indicating the temperature at which it transitions from a stiff, glassy condition to a flexible, rubbery state. Under (Tg), the polymer behaves as a glass, being brittle and stiff, while above Tg, it exhibits rubber-like flexibility. The increase in temperature leads to higher molecular motion, with greater vibrational and rotational freedom of the polymer chains. This increased motion requires an expansion of the free volume, the space between the atoms. The Tg value is influenced by the level of rotational freedom and segmental motion within the polymer [56].

Several factors affect Tg. Generally, polymers with higher molecular weights have less free space and few chain ends, resulting in higher (Tg). Bulky substituents on the polymer backbone, such as branching, decrease flexibility (i.e., freedom of rotation) and raise (Tg). The polarity of the monomeric units also influences (Tg), as increased dipole-dipole interactions lead to a higher Tg [56].

In contrast, the melting temperature (Tm) applies to crystalline polymers and denotes the temperature at which the chains become fully movable due to thermal energy, resulting in the polymer's flow. Table 3 lists some popular polymers' approximative equilibrium melting points. Semi-crystalline polymers melt over a relatively small temperature range, in contrast to amorphous polymers, which progressively liquefy over a wide temperature range above (Tg). Similar factors that affect Tg, such as the polymer's rigidity, branching, and composition, can also influence Tm. A flexible and linear polymer would have a lower (Tm) than a rigid and branched polymer containing cyclic units. [78].

Table 3. Polymers melting point [67]

Polymer	Melting point (°C)
Polyisoprene (cis form)	28
Poly(ethylene oxide)	66
Polyisoprene (trans form)	80
1,2-Polybutadiene (isotactic form)	120
Polyethylene (linear)	135
1,2-Polybutadiene (syndiotactic form)	154
Polypropylene (syndiotactic form)	163
Polyoxymethylene	183
Polypropylene (isotactic form)	187
Poly(vinyl chloride)	212
Polystyrene (isotactic form)	240
Poly(vinyl alcohol)	250
Nylon-6	260
Poly(ethylene terephthalate)	260
Nylon-6,6	270
Polytetrafluoroethylene	332
Polyacrylonitrile (syndiotactic)	341

11.3 Mechanical properties

Having a good understanding of fundamental mechanical properties of a material is crucial prior to its utilization in any field. These properties include the material's ability to stretch, bend, hardness or softness, and its response to repeated loading, among others. Familiarity with these properties is essential for making informed decisions regarding the material's suitability for specific applications [79].

11.3.1 Strength

Strength refers to a material's capacity to withstand stress before it breaks. Various types of strength include tensile strength (resistance to stretching), compressional strength (resistance to compression), flexural strength (resistance to bending), torsional strength (resistance to twisting), and impact strength (resistance to hammering) [79]. When it comes to polymers, their strength can be categorized in the following order from lowest to highest: network polymers, cross-linked polymers, branching polymers, and linear polymers [80].

Several factors influence the strength of polymers. These factors can affect the mechanical properties of the material and determine its overall strength. Some of the key factors include:

A. Molecular Weight

The tensile strength of the polymer rises along with its molecular weight until it reaches a point where it levels out. (Figure 20).

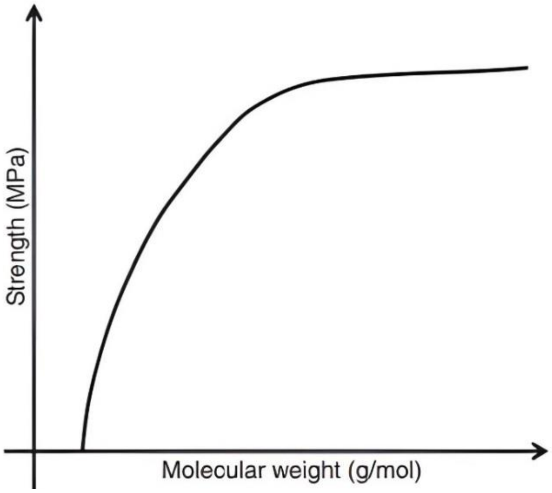


Figure 20. Polymer's molecular weight [81]

The equation relating tensile strength to molecular weight is expressed as:

$$\sigma = \sigma_{\infty} - \frac{A}{M} \qquad (1)$$

σ represents the tensile strength of the polymer, $\sigma\infty$ represents the limiting tensile strength at infinite molecular weight, A is a constant, and M represents the molecular weight of the polymer. The constant A is specific to the particular polymer system and is determined experimentally. It represents the contribution of molecular weight to the tensile strength of the polymer.

At lower molecular weights, the polymer chains are held together by weak van der Waals forces, resulting in loose bonding and easy movement of the chains. This leads to lower strength, despite the presence of crystallinity. On the other hand, in polymers with larger molecular weights, the chains become longer and more entangled, which contributes to the overall strength of the polymer [82].

B. Crosslinking

Cross-linking limits the mobility of polymer chains and enhances the strength of the material [81].

C. Crystallinity

The strength of the polymer is enhanced by its crystallinity, as the intermolecular bonds become more prominent in the crystalline phase. This allows for higher strength and the alignment of polymer chains during deformation [81].

11.3.2 Percent Elongation to Break

Elongation at break is a measure of the strain or percentage change in length of a material before it fractures, as depicted in Figure 21. It provides an indication of the material's ductility. Ceramics exhibit very low elongation (<1%), metals have moderate elongation (1-50%), while thermoplastic materials demonstrate high elongation (>100%) and thermosets have low elongation (<5%) [80].

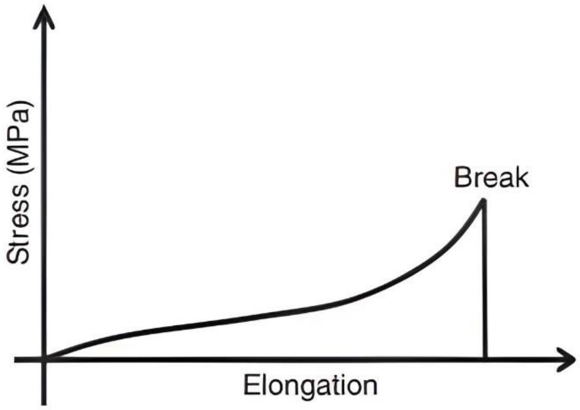


Figure 21. Elongation to break of the polymer [80]

11.3.3 Young’s Modulus

A measurement of a material's stiffness or rigidity is its Young's modulus. It measures the ratio of stress to strain in the material's linearly elastic area [80].

Elastic modulus is a measure of the stiffness of the material:

$$E = \frac{\sigma}{\varepsilon} \qquad (2)$$

Tensile Stress (σ)

Tensile Strain (ε)

11.3.4 Toughness

Toughness is known as the capacity of a material to absorb energy and undergo plastic deformation prior to fracture. It is calculated by integrating the stress (σ) with respect to strain (dε) over the entire deformation process [80].

$$Toughness = \int \sigma \, d\varepsilon \qquad (3)$$

Figure 22 depicts a stress-strain curve illustrating the behavior of various materials. Rigid materials, including brittle polymers, exhibit a high Young's modulus, indicating their stiffness. Ductile polymers, on the other hand, exhibit a similar elastic modulus but with greater fracture toughness, meaning they can deform significantly before fracturing. Elastomers, characterized by their rubbery nature, have low Young's modulus values, indicating their high flexibility [80].

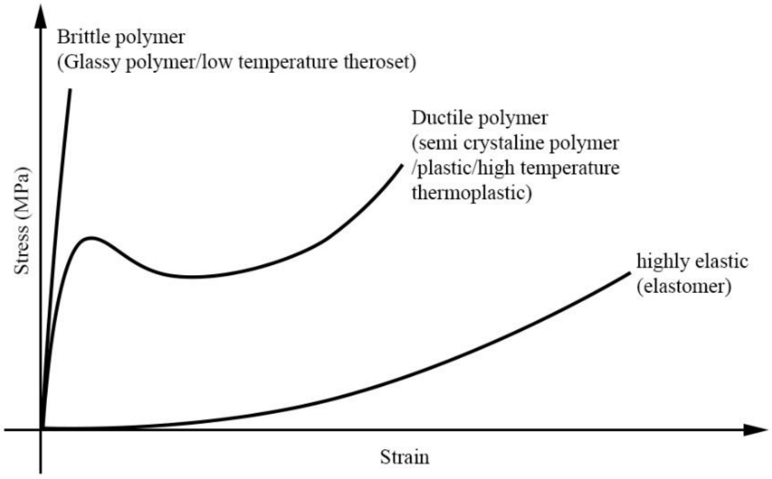


Figure 22. Stress-starin behavior of different types of polymers [83]

The stress at which the linear elastic section of the stress-strain curve ends is referred to as a plastic polymer's yield strength (as depicted in Figure 23). It marks the point where the material transitions from elastic deformation to plastic deformation. On the other hand, the tensile strength represents the stress at which the polymer fractures. It should be noted that the tensile strength might be either superior to or inferior to the yield strength, as shown in Figure23. [83].

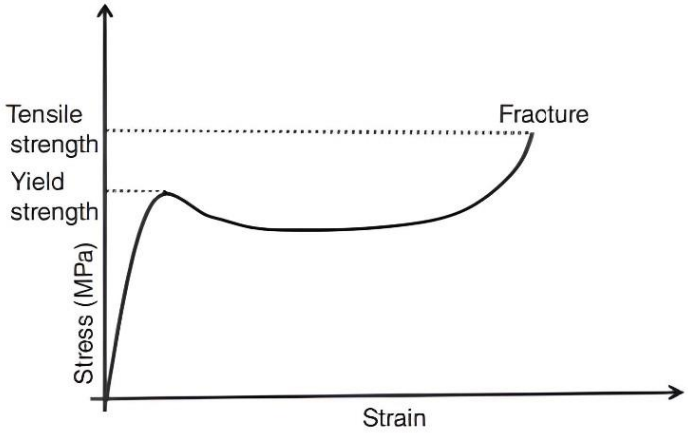


Figure 23. yield strength and tensile strength of polymer [83]

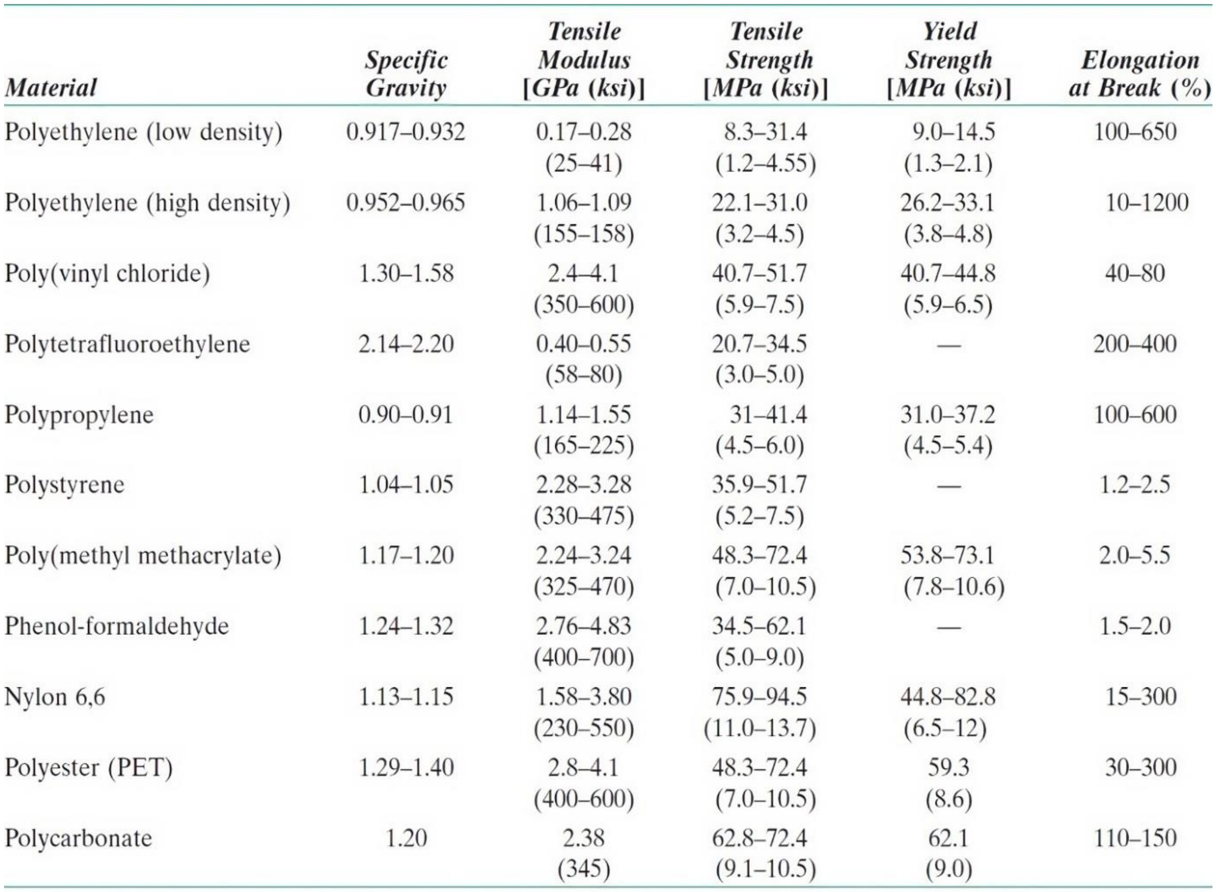
11.3.5 Viscoelasticity

Polymers are known for their viscoelastic behavior. When polymers are subjected to external forces, they exhibit both elastic and viscous responses that depend on the time scale of deformation. This behavior arises from the molecular structure and dynamics of polymers.

In the viscous regime, polymers exhibit time-dependent flow and deformation. When subjected to a constant force or strain, polymers gradually deform over time, leading to a permanent change in shape. This viscous behavior is associated with the movement and rearrangement of polymer chains, which occurs due to the relaxation of molecular entanglements and the slipping of polymer segments [81].

Table 4 represents some mechanical properties of some polymers. [84]

Table 4. Polymers mechanical properties



Material	*Specific Gravity*	*Tensile Modulus [GPa (ksi)]*	*Tensile Strength [MPa (ksi)]*	*Yield Strength [MPa (ksi)]*	*Elongation at Break (%)*
Polyethylene (low density)	0.917–0.932	0.17–0.28 (25–41)	8.3–31.4 (1.2–4.55)	9.0–14.5 (1.3–2.1)	100–650
Polyethylene (high density)	0.952–0.965	1.06–1.09 (155–158)	22.1–31.0 (3.2–4.5)	26.2–33.1 (3.8–4.8)	10–1200
Poly(vinyl chloride)	1.30–1.58	2.4–4.1 (350–600)	40.7–51.7 (5.9–7.5)	40.7–44.8 (5.9–6.5)	40–80
Polytetrafluoroethylene	2.14–2.20	0.40–0.55 (58–80)	20.7–34.5 (3.0–5.0)	—	200–400
Polypropylene	0.90–0.91	1.14–1.55 (165–225)	31–41.4 (4.5–6.0)	31.0–37.2 (4.5–5.4)	100–600
Polystyrene	1.04–1.05	2.28–3.28 (330–475)	35.9–51.7 (5.2–7.5)	—	1.2–2.5
Poly(methyl methacrylate)	1.17–1.20	2.24–3.24 (325–470)	48.3–72.4 (7.0–10.5)	53.8–73.1 (7.8–10.6)	2.0–5.5
Phenol-formaldehyde	1.24–1.32	2.76–4.83 (400–700)	34.5–62.1 (5.0–9.0)	—	1.5–2.0
Nylon 6,6	1.13–1.15	1.58–3.80 (230–550)	75.9–94.5 (11.0–13.7)	44.8–82.8 (6.5–12)	15–300
Polyester (PET)	1.29–1.40	2.8–4.1 (400–600)	48.3–72.4 (7.0–10.5)	59.3 (8.6)	30–300
Polycarbonate	1.20	2.38 (345)	62.8–72.4 (9.1–10.5)	62.1 (9.0)	110–150

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11.4 Chemical Resistance

Polymers can exhibit different levels of resistance to various chemicals, solvents, acids, and bases. Some polymers are highly resistant, making them suitable for corrosive environments or chemical processing applications [84].

11.5 Electrical Properties

Polymers can be insulating or conductive, depending on their molecular structure. They can possess electrical conductivity, dielectric strength, and dielectric constant, making them useful in applications such as insulation, electronics, and electrical components [85].

11.6 Optical Properties

Polymers can have different optical characteristics, including transparency, refractive index, and light transmission properties. These properties make them suitable for applications in optics, displays, and packaging [85].

11.7 Barrier Properties

Certain polymers exhibit excellent barrier properties against gases, moisture, and other substances. This property is crucial in packaging materials to preserve the quality and shelf life of products [85].

12 POLYMERIZATION AND CONDESATION

Polymerization is a fundamental process used to fabricate polymers it involves the chemical reaction of monomer molecules to form long chains or networks known as polymers. During polymerization, monomers undergo a bonding process, through either addition reactions (addition polymerization) or condensation reactions (condensation polymerization) [86].

Figure 24 depicts the steps for polymer fabrication using either polymerization or condensation

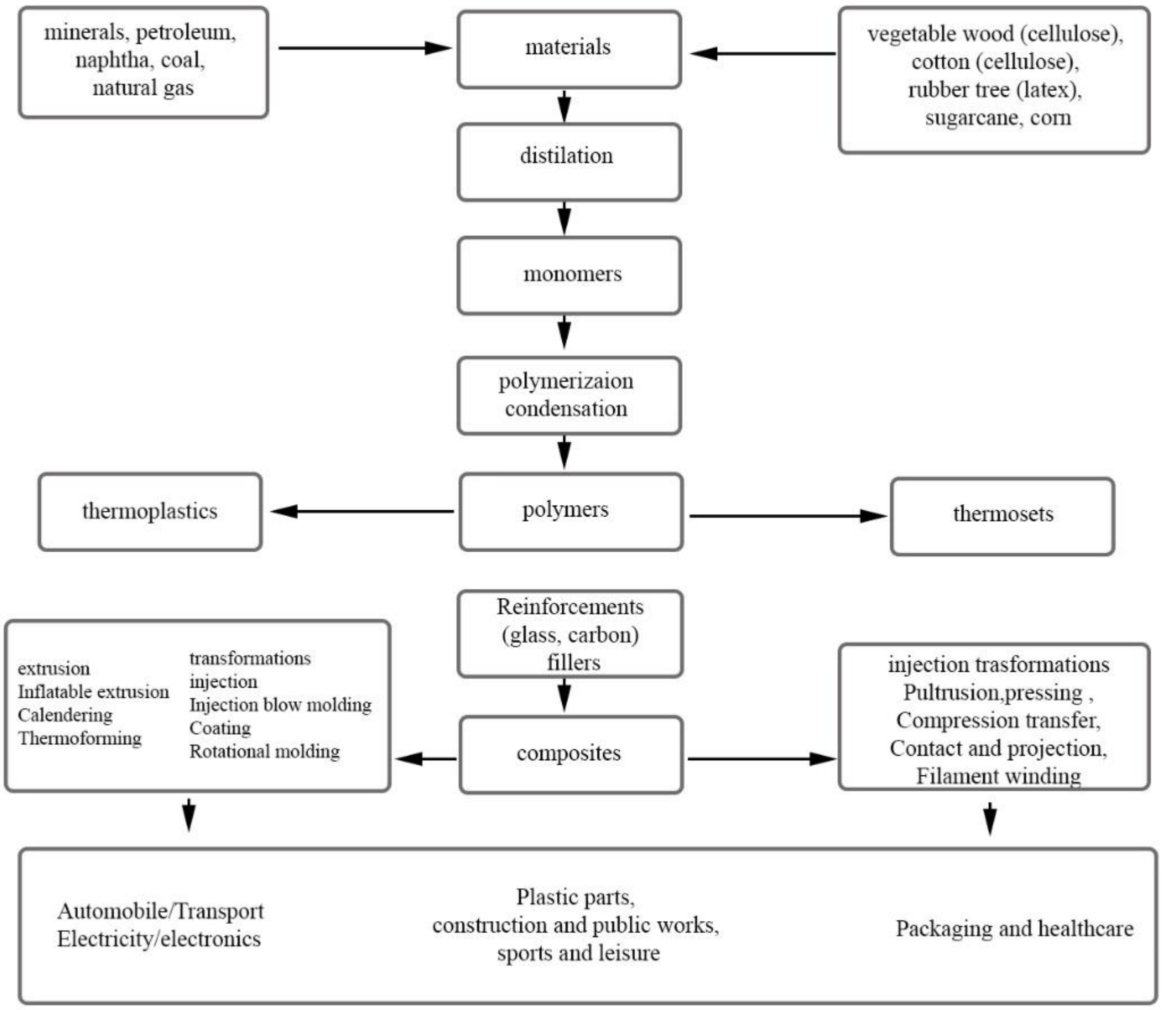


Figure 24. Polymer fabrication route [87]

Along with polymerization, unsaturated-bond monomers (such vinyl monomers) go through a chain reaction in which the double bond is broken and the monomers link together to form a polymer chain. This process typically requires the use of initiators, such as heat, light, or catalysts, to initiate and propagate the polymerization reaction [88].

The reaction between two distinct monomers, frequently with two functional groups (such as carboxyl and hydroxyl groups), is what happens in condensation polymerization, on the other hand, which combine and release a small molecule (such as water or alcohol) as a byproduct. The reaction proceeds through repeated condensation steps until a polymer is formed. Polycodensation is another term used to describe this type of polymerization [64].

The main difference between addition polymerization and condensation polymerization (polycodensation) lies in the nature of the chemical reactions and the byproducts formed. Addition polymerization only involves the monomers themselves, with no byproducts produced during the reaction. In contrast, condensation polymerization (polycodensation) involves the elimination of small molecules (such as water or alcohol) as byproducts during the formation of the polymer chain [67].

Both addition and condensation polymerizations have their advantages and applications. Addition polymerization is commonly used for the fabrication of thermoplastics, where the resulting polymers can be melted and reshaped multiple times without significant degradation. Condensation polymerization, on the other hand, is often employed to produce thermosetting polymers or materials with specific properties, such as high temperature resistance or chemical resistance [67].

Overall, polymerization, whether through addition or condensation reactions, is a key process in the fabrication of polymers, enabling the production of a wide range of materials with diverse properties for various industrial and consumer applications [88].

13 POLYMER DEGRADATION

Polymer degradation refers to the process of deterioration that occurs in polymers as a result of a variety of environmental conditions including heat, light, chemicals, and mechanical stress. It leads to changes in the physical, chemical, and mechanical properties of the polymers, which are often undesirable. However, degradation can also be deliberately induced for specific purposes such as recycling [89].

The changes in properties resulting from degradation are commonly referred to as "ageing." These changes can include color fading, shape distortion, chemical breakdown, and reduced mechanical strength. Polymer degradation can lead to cracking, disintegration, and loss of functionality in polymer-based products [89].

The six main polymers used in various applications are polyethylene, polypropylene, polyvinyl chloride (PVC), polyethylene terephthalate (PET), polystyrene, and polycarbonate. Each of these polymers exhibits distinct modes of breakdown and degrees of heat, light, and chemical resistance. Factors such as oxidation, hydrolysis, photodissociation, and oxidation can contribute to polymer degradation [90].

Oxidation occurs when polymers react with atmospheric oxygen, especially at elevated temperatures during processing. It can lead to the weakening of the polymer's molecular structure and the formation of cracks. Hindered-amine light stabilizers (HALS), UV-absorbers, and antioxidants are used to mitigate the effects of oxidation and protect the polymer from degradation [91].

Hydrolysis refers to the degradation of polymers by acids, which can cause cracking and deterioration, particularly in nylon-based materials. Photodissociation, or the breaking down of chemical compounds by photons, can occur when polymers are exposed to light with sufficient energy, such as ultraviolet light. This can result in the degradation of the polymer's chemical bonds and subsequent weakening of its structure [92].

Polymer degradation can have detrimental effects on the performance and lifespan of polymer-based products. However, understanding the degradation mechanisms and implementing strategies to prevent or delay degradation can help improve the durability and reliability of polymers in various applications. Additionally, controlled degradation processes can be utilized for recycling and reusing polymer waste, reducing environmental pollution [92].

14 POLYETHYLENE TEREPHTALATE

Polyethylene terephthalate (PET) is a polyester polymer that was first produced in the 1930s as a synthetic fiber. It is commonly used today to manufacture fibers for various industrial and clothing applications. PET fibers are often blended with natural fibers like cotton and wool, and they are commonly found in fleece sweaters [92].

In the 1950s, PET found its application in packaging films and as a carrier for film and magnetic tape. It became widely used for packaging films due to its excellent properties. Additionally, PET bottles were developed in the 1970s and initially used for soft drinks. Over time, their use expanded to include bottled water [92].

PET is produced by reacting terephthalic acid, a dicarboxylic acid, with ethylene glycol, a dialcohol (see figure 25). This chemical reaction forms long polymer chains, with water being produced as a by-product. As with most polymerization processes, a catalyst is used to accelerate the reaction kinetics [93].

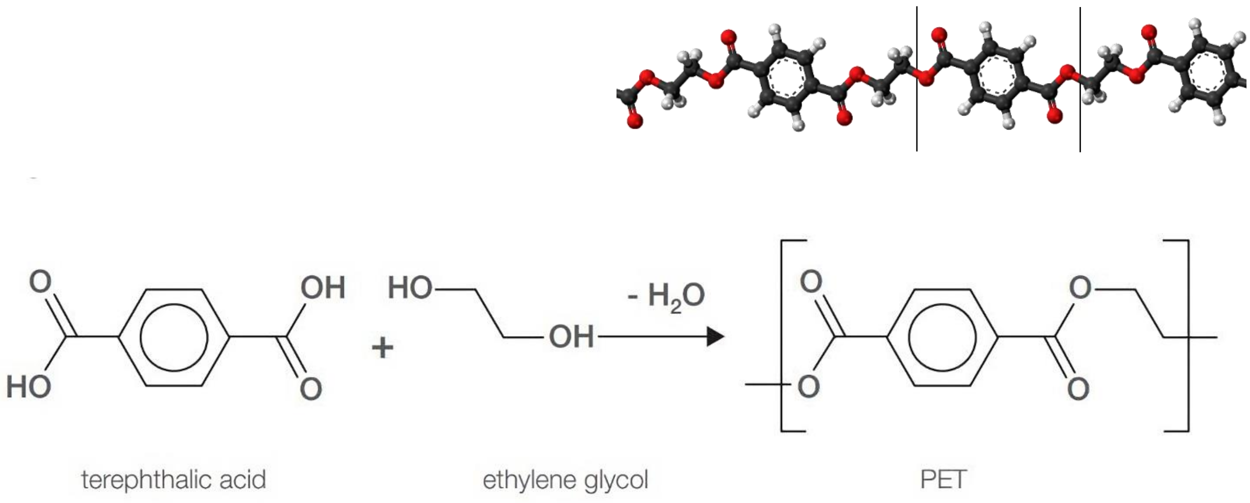


Figure 25. Structure of polyethylene terephthalate [94]

Polyethylene Terephthalate (PET) is a very flexible, colorless, semi-crystalline resin that, depending on processing, can be either semi-rigid or rigid. It exhibits excellent dimensional stability, impact resistance, and resistance to moisture, alcohols, and solvents. PET is known for its high strength-to-weight ratio, making it lightweight and easy to transport. Additionally, it has great electrical insulating capabilities, superior gas and moisture barrier properties, and other qualities. PET has a low gas permeability and a wide temperature range of -60 to 130 °C, especially with carbon dioxide [95].

PET is appropriate for transparent applications and, in some circumstances, can replace glass because it is shatter-resistant. It has been given the go-ahead for safe contact with food and beverages by regulatory agencies like the FDA, Health Canada, and EFSA. It is also recyclable and transparent to microwave radiation. When it comes to chemical resistance, PET shows great resistance to alcohols, aliphatic hydrocarbons, oils, grease, and diluted acids, while displaying only moderate resistance to diluted alkalis, aromatic, and halogenated hydrocarbons [92].

The glass transition temperature (Tg) of PET ranges from 65 to 80°C, depending on the degree of crystallinity. Its melting temperature falls between 240 and 270°C [96]. Crystallization occurs within a specific temperature range, reaching a crystallinity of 40-50%. PET can also be polymerized into a co-polymer that cannot crystallize [97].

PET is easily processed through injection molding and extrusion. Extrusion is commonly used to produce films and sheets, which can later be thermoformed. Blow molding is the preferred method for manufacturing transparent bottles. PET filaments are widely used for 3D printing due to their high flexibility and toughness [98].

PET is the most recycled plastic in the planet and is 100% recyclable. Recycling code #1 can be used to recognize it. The fabrication of carpet, fleece coats, tote bags, as well as the manufacture of containers for food, drink, and non-food goods, all use recycled PET flakes. Recycled PET is also used in the production of automotive components, films and sheets, strapping, and industrial end products like geotextiles and roof insulation. [99].

15 RECYCLING

After use, polymers are included in household waste (HW) and non-hazardous industrial waste (NHIW). Packaging constitutes a significant portion of plastic waste materials. These waste items can be disposed of in landfills, reused after cleaning (in the case of certain containers or drums), incinerated without energy recovery, or recycled. There are three main avenues for valorization: landfilling, reuse, and recycling [100, 101]:

- Thermal valorization involves incineration with energy recovery, as polymers can be considered as hydrocarbons with a certain level of energy content [100].

- Chemical valorization aims to convert polymers into smaller molecules, or even back into their original monomers (such as PET), which can be utilized as raw materials for various chemical processes [102].
- Material valorization: The concept of material valorization in plastic recycling closely resembles the manufacturing process of thermoplastic products. The key distinction lies in substituting virgin materials with recovered materials. Factories carry out this practice on a daily basis by reintegrating scraps and trimmings into the production cycle through simple grinding. When it comes to household waste (HW) or non-hazardous industrial waste (NHIW), material valorization involves selective collection, treatment (including grinding, cleaning, washing, separation, and granulation), and the creation of new finished products. However, the recycled materials often exhibit inferior properties due to impurities.Ongoing efforts focus on enhancing the processes of separation and purification, incorporating virgin materials, and introducing additives to overcome these limitations.

According to the latest forecasts from the OECD's Global Plastics Outlook (Organisation for Economic Co-operation and Development), By 2060, plastic waste is anticipated to quadruple. The amount of waste is expected to increase from 353 million tonnes to 1 billion tonnes during the following four decades from 2019. Two-thirds of this waste will likely consist of packaging, consumer products, textiles, as well as significant amounts from construction and transport sectors [103].

During this period, recycling rates are anticipated to improve, increasing from 9 percent in 2019 (as shown in figure 26) to 17 percent by 2060. However, recycling will still represent a smaller proportion compared to landfilling at 50 percent and incineration at 19 percent. The other 22% of plastic garbage, was either burned in open pits, dumped in unregulated landfills, or spilled into the environment. [103].

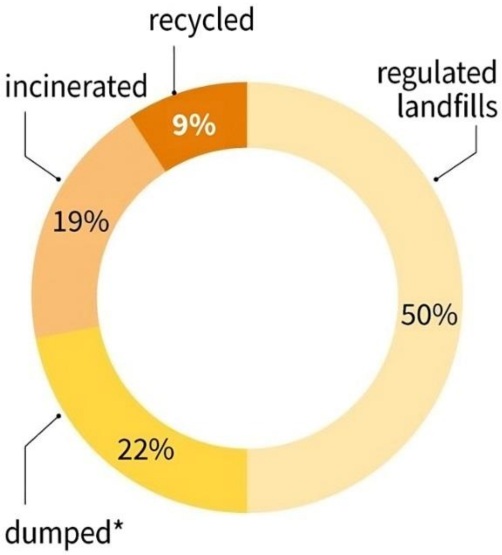


Figure 26. Proportions of plastic waste in fields [104]

The Resin Identification Code (RIC), which is a numbering system used to identify different types of plastics for recycling purposes. The RIC was developed by the Society of the Plastics Industry (SPI) in 1988 to assist with sorting and recycling efforts [105].

Each type of plastic, or polymer, is assigned a specific number within the RIC. These numbers range from 1 to 7 and are typically found inside a triangle of arrows, known as the recycling symbol (see figure 27). The purpose of these numbers is to help recyclers, consumers identify, and classify various polymers according to their chemical composition [106].

Figure 27. Plastic recycling symbols [107]

Plastic recycling faces various challenges and problems. Contamination from mixed plastics and non-recyclable materials is a significant issue, affecting the quality of recycled plastic. Limited recycling infrastructure and inconsistent guidelines for plastic recycling further complicate the process. Downcycling, where recycled plastic is turned into lower-grade products, reduces the overall value and sustainability of recycling. Economic viability is another concern, as the cost of collection and processing can outweigh the value of recycled plastic. Additionally, some plastics are difficult to recycle due to their composition, and single-use plastics pose particular challenges. Overcoming these obstacles requires improved infrastructure, consumer education, technological advancements, and sustainable policies [106].

16 CONCLUSION

In conclusion, this chapter explored the fascinating world of ceramics and polymers, two diverse classes of materials with distinct properties and applications. Ceramics, They are widely used in a variety of industries, including construction, electronics, and healthcare, thanks to their extraordinary hardness, high melting points, and resilience to heat and wear. From traditional pottery to advanced ceramics like superconductors and bioceramics, their versatility and durability make them indispensable in modern society. On the other hand, polymers, characterized by their lightweight nature, flexibility, and wide range of mechanical properties, have revolutionized countless aspects of our daily lives. Whether it is the packaging materials we use, the textiles we wear, or the medical devices we rely on, polymers provide unique solutions. This chapter highlighted the different types of polymers, their recycling challenges, and the importance of resin identification codes. As we continue to explore the ever-evolving world of materials science, the synergistic combination of ceramics and polymers holds great promise for future innovations, pushing the boundaries of what is possible in fields ranging from electronics and energy storage to medicine and beyond.

CHAPTER III

EXPERIMENTAL AND NUMERICAL STUDY

1 INTRODUCTION

The objective of this chapter is to methodically create a novel composite material through experimental methods and then carry out a series of thorough tests, including mechanical tests like tensile and Charpy impact tests, pressure measurements, and flexural tests, as well as thermodynamic evaluations like Thermogravimetric Analysis (TGA) and Differential Scanning Calorimetry (DSC). Along with morphological investigations, density assessments will also be carried out. Parallel to this, numerical simulations will provide a thorough investigation of the behavior of the composite material when incorporated into brick wall systems.

2 EXPERIMENTATION

We were able to improve the accuracy and depth of our knowledge of the essential characteristics of the material under research, which had first been uncovered during our thorough experimental investigation, by a number of follow-up experimental experiments. We were able to explore further into the material's behavior and properties thanks to these additional experiments. Not only were we able to confirm and match our initial findings, but we also discovered details and variations that are crucial for a complete understanding of the material's applicability and performance in real-world applications.

3 LITERATURE REVIEW

Today's world faces significant waste management challenges, particularly with regard to plastic garbage. Since plastic cannot decompose, a dangerous substance pollutes the environment by contaminating soil and water [108]. Plastic is a resource that has changed people's lives since it was first manufactured in 1907. It is composed of a range of high molecular weight synthetic or semi-synthetic organic chemicals as well as other malleable materials that can be shaped into solid shapes. Natural substances including Salt, natural gas, coal, cellulose, crude oil, minerals, and plants are polymerized or polycondensed to create them. Due to its flexibility and capacity to be used in a variety of ways, it offers adaptability and can serve various functions.

In comparison to other materials like wood, rubber, paper, and organic materials such as cotton and wool, plastic has a significant advantage with regard to size, strength, flexibility, diversity, and affordability. It is the least expensive material on the market and is produced on a huge scale [109]. The same characteristics that make it valuable, meanwhile, also contribute to the problem of global waste [110]. It is a resource that individuals misuse [111, 112]. Between the 1950s and 2021, the amount of plastic produced worldwide rose to 8.1±4 billion tons [113, 114]. Only 9±0.8% of the plastic garbage generated was recycled, and 12±0.9% of it was burned instead [113-115]. The remaining 72±6 percent of the waste was thrown away in landfills or released into the environment, endangering aquatic life and the ecosystem severely [113–116]. Plastic garbage production is still growing, which highlights a severe environmental risk [117].

Due to its tendency to contaminate the air, water, and land, plastic has the potential to harm the ecosystem, because it is made up of significant hazardous chemicals [108]. The most pervasive issue that endangers the land, air, and marine environments is plastic pollution. Additionally, it threatens climate change, food safety, quality, and ocean health. A second factor in global warming is plastic. Burning plastic garbage causes carbon emissions to rise because of the atmospheric emissions of carbon dioxide. Plastic waste reduces the aesthetic appeal of tourist destinations, which lowers tourism-related income and increases the cost of cleaning and maintaining locations [118].

Even in wealthy nations, managing plastic trash is a challenge [119]. The disposal of plastic garbage is a significant concern because the substance could become carcinogenic with frequent recycling [120]. Many people are converting their conventional, naturally resource-based homes into contemporary homes that require a large number of traditional bricks due to the population and economy's fast growth. The usage of earth-based clay materials has resulted in resource depletion and environmental deterioration since there is a striking mismatch between the supply and demand for conventional construction materials [121]. Plastic trash can be included into the construction of buildings. The most practical uses are thought to be in these fields [122].

Waste materials have been tried to be used in the brick-making process [123–127]. These blocks might eventually help with plastic control while encouraging long-term growth. Plastic sand brick use is advantageous and would lessen waste. The usage of plastic bricks thus encourages both environmental preservation and sustainable development [128], highlighting the urgent need to increase plastic waste recycling and reuse in sustainable products and thereby lessen its buildup in the surrounding environment.

To overcome these challenges, several investigators have investigated the use of discarded plastics as binders, fillers, or aggregates alternatively to cementitious substances while making bricks [124, 125]. With this technology, the manufacturing of cement in particular might dramatically reduce the road and pavement construction sectors' carbon impact [124, 125]. Studies have looked into the production of plastic sand bricks by combining plastic waste with other basic components. Akinyele et al. [129] studied the usage of (PET) as an addition to lateritic clay in burnt bricks. The bricks were made by combining PET at weights of 0, 5, 10, 15, and 20% with lateritic clay and firing them for 48 hours at 900°C. According to the findings, 15% to 20% of the samples dissolved at high temperatures, Edge deformation occurred in a much lesser percentage of the samples. Bricks having 0, 5, and 10% of weighted PET had respective compressive strengths of 5.15, 2.30, and 0.85 N/mm2, whereas their respective rupture moduli were 13.20, 11.96, and 8.53 N/mm^2. Bhushaiah et al. [130] used a mixture of 0.992 kg cement, 4.04 kg fly ash, and 3.24 kg fine aggregate; the fine aggregate was replaced with 5-20% finely crushed LDPE, and the compressive strength was 19.8 MPa. By substituting the fine aggregate with 100% finely ground sand while maintaining a mixing ratio of 1:6 (cement/fine aggregate) and a water-cement ratio of 0.34, Wahab et al. [131] compared the results to conventional sand bricks made with a mixing ratio of 1:4 and a water-cement ratio of 0.35. The results of the investigation show that the compressive strength peaked at 5% and 15% of the weight of the plastic, or 11.618 N/mm^2 and 20 N/mm^2, respectively. The third research found that the brick has a compressive strength of 5.56 N/mm^2.

Other research substituted plastic (plastic binder) for cement as a binding agent. Gopu Mohan et al. [132] combined molten plastic, thermocol, and sand with varying weight percentages of molten plastic (5%, 15%, 25%, and 35%, respectively). According to the experiment, each sample had 0% water absorption and the compressive strength was highest at 11 N/mm^2 when plastic made up 25% of the weight. Using 4.75 mm sand and molten HDPE in a 1:4 ratio, A material with a compressive strength of 9.141 N/mm^2 and a water absorption of 0.789% was created by Salahuddin and Zambani [117]. In their study on HDPE and sand, Sellakutty and Dinesh used the mix ratios of 1:3, 1:4, and 1:5, and they found that the compressive strengths were 4.78 N/mm^2, 5.12 N/mm^2, and 4.92 N/mm^2 respectively. 3:7 in proportion, By mixing molten LDPE, HDPE, PET, and PP plastic with stone dust, Singhal and Netula [134] were able to ascertain that there was no water absorption and that the compressive strength was 5.6 N/mm^2. The compressive strength was higher than that of conventional clay bricks, according to Chauhan et al.'s [135] examination of mixing ratios of 1:2, 1:3, and 1:4 (PET bottles: sand). The water absorption ranged from 0.95 to 4.5%.

The reuse of demolition materials as mineral additions in the composition of cementitious materials through partial substitution of cement appears to be one of the most effective ways to reduce greenhouse gas emissions (CO_2) from the cement industry, which is the main source of negative environmental effects [136]. However, prior research has not concentrated on investigating materials made of demolition trash, particularly brick waste, and plastic garbage.

With PET being one of the main plastic wastes in the world, the objective is to develop a new material based on plastic and brick waste in order to decrease plastic and brick waste. Given that brick is the most common material used in construction, brick waste was combined with plastic waste to create a low-cost, high-quality composite material. This research uses brick waste to address the issue of construction debris generated as a result of building demolition. In addition, a lot of the defective brick produced by brick firms is discarded. Additionally, brick manufacturers have investigated the clay's qualities beforehand, making it appropriate for use.

Our goal is to characterize this material physically and mechanically. In 5% increments, the weight of the block increases from 30% to 45%. Because they create a composite that is incredibly deformable, the specimens with a mixture of more than 70% PET and 30% brick sand weight are suspended, and the specimens with a mixture of less than 50% PET are also discarded because there is insufficient resin (binder) in them to ensure that the mixture will adhere [137-139].

4 RESOURCES AND EXPERIMENTAL METHODS

This section provides a detailed account of all the materials, tools, equipment, facilities, and procedures used in conducting experiments and investigations.

4.1 Brick sand

The brick scraps were gathered from the El Malah brick factory in Ain Temouchent, Algeria. Since the fineness affects the reactivity of the additives, this trash was ground and crushed to get the 80-µm sieve pass (Figure 1) [140].

Before **After**

Figure.1. Brick before and after scrumbling

Table 1 lists the brick powder's physical features and chemical makeup. The findings of the chemical analysis are listed. It should be mentioned that brick powder complies with ASTM C618 [141] criteria because the components [Al_2O_3 + Fe_2O_3 + SiO_2] total 79.94%. In cementitious materials, the brick powder can therefore be utilized as a pozzolanic additive [142]. Brick powder also has a poor thermal conductivity, which limits the flow of heat through it, and it can withstand temperatures of up to 1500 °C. The particle/polymer matrix interface refers to the forces that interact between the two phases on a short time frame. The interface effect takes over when particle size decreases. A significantly big interfacial air results from uniform particle dispersion.

Table 1: properties of brick powder

Chemical composition (%)										
Components	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	TiO_2	K_2O	Na_2O	SO_3	Loss
Quantity (%)	61.91	14.80	3.23	11.23	2.43	-	2.15	0.19	0.65	3.41
Physical characteristics										
Density (g/cm^3)						2.65				
Blaine-specific surface (cm^2/g)						3140				

Additionally, the closer and more frequent the particles are for a given volume percentage of reinforcement, the greater the reduction in particle size. As a result, when a particle's size reaches a few micrometers, it can either acquire new properties or improve certain mechanical, thermal, and electrical properties [143].

Brick powder's particle size curve is depicted in Figure 2. The grain size analysis produced the size distribution histogram (Figure 2) that you see here. We may get the typical values of the grain size of the brick powder from the statistics given. 50% of the particles are, as can be seen, less than 45 µm.

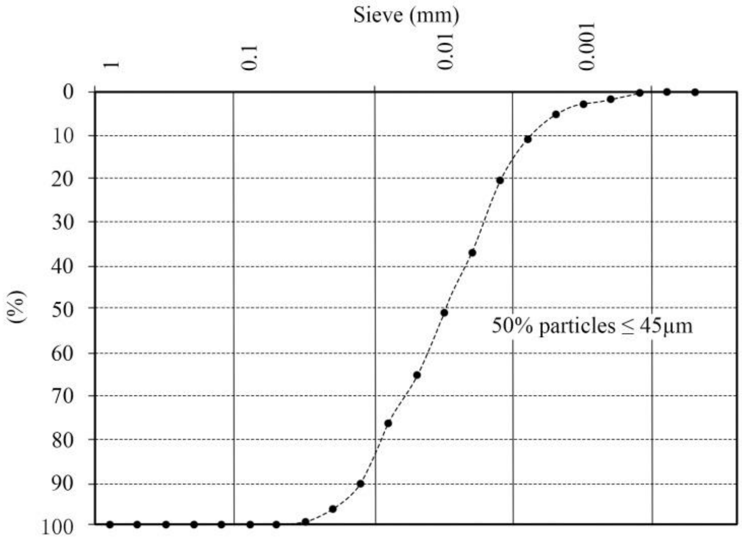


Figure 2. Brick powder's particle size distribution [140]

4.2 Polyethylene terephthalate

PET is a robust, lightweight polymer that is classified as a thermoplastic that is not biodegradable and has a strong moisture barrier. PET is a member of the polymer family. PET melts at 260°C, like all thermoplastics, and may be chilled without significantly losing any of its qualities. PET is frequently utilized in everyday objects because of its outstanding qualities [130, 135].

In this work, PET is employed as a matrix. The crushed plastic debris was made from discarded water and juice bottle plastic garbage. Before being sun dried for at least three days, PET trash was collected and thoroughly washed with tap water to get rid of any impurities or dangerous elements. The garbage was then processed and pulverized into pellets that were between 1 mm and 8 mm in size. The ground materials are shown in Figure 3.

Figure 3. Crushed polyethylene terephthalate sample

5 PREPARATION OF THE TEST TUBES

In the oven, Brick sand and PET pellets were dried at 50°C for at least 12 hours. They went through mechanical pre-mixing after that to create a solid mixture that was as homogenous as feasible.

After passing through a FARREL BRIDGE type two-cylinder mixer (figure 4) at 180°C, the (PET) granules and brick sand are then placed into a 20D single-screw extruder (figure 5) at 260°C. 30 rpm has been set as the spinning speed of the screw.

Figure 4. Two-cylinder FARREL BRIDGE type mixer

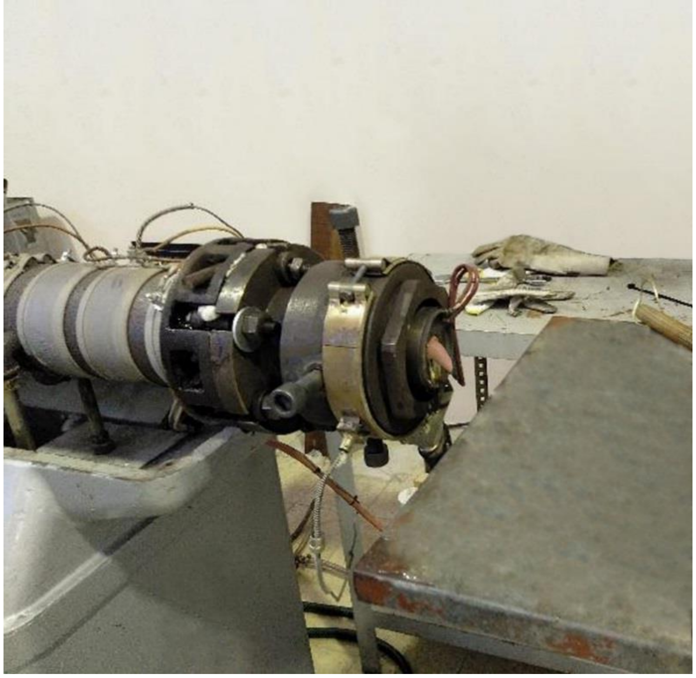


Figure 5. Single-screw 20 D extruder

After 15 minutes of mixing, the extrudate is recovered at the outlet and pulverized in a BRABENDER-style grinder while the load of the extruder is being monitored. Granules produced by extrusion are meant to be injected into an injection device of the BATTENFELD BA 200 CD type (figure 6).

Figure 6. Injection molding machine BATTENFELD BA 200 CD

The combinations including brick sand in varied weight percentages (between 30% and 45%) are shown in Table 2. The various brick mix ratios were evaluated using C_0 specimens as controls. For each test, three samples were collected.

Table 2. Mixtures with varying weight percentages of brick sand

Sample n°	**C_0**	**C_1**	**C_2**	**C_3**	**C_4**
PET weight%	100	70	65	60	55
Brick sand weight%	0	30	35	40	45

An illustration of the production process in simplified form, from raw materials to test specimens, is shown in Figure 7. The thermoplastic material tensile testing mold in accordance with ASTM D638 [144]. The mold (L=150mm, W=20mm, and T=4mm) is made with a detachable central piece for simple specimen removal.

For thermoplastic materials, the Charpy mold triple complies with ISO 179-1 [145]. (for Charpy specimen Length L = 80mm, Width W = 10mm, and Thickness T = 4mm) is used.

According to ASTM C78 [146], a prismatic mold with dimensions of L=160mm, W=40mm, and H=40mm is utilized for flexural testing.

According to ASTM C109 [147], the compression test is conducted using a 50mm cubic test tube.

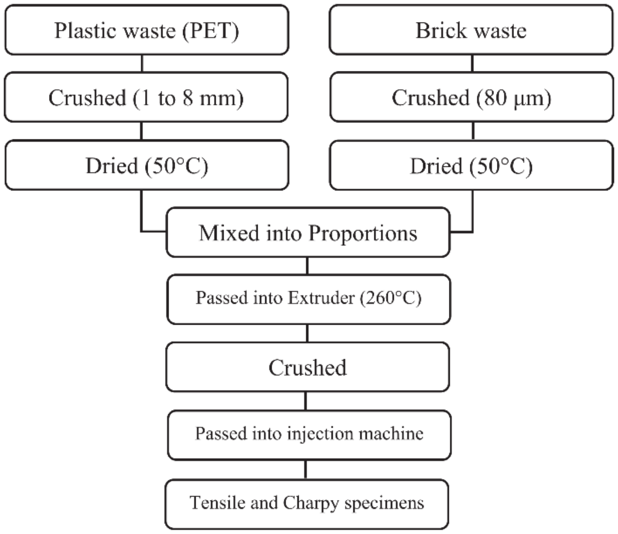


Figure 7. Flowchart for the fabrication process

6 CHARACTERIZATION

6.1 Determination by TGA

In an oxidizing or inert environment, thermogravimetric analysis is typically used to evaluate thermal stability. When a sample is subjected to a linear temperature variation, this analysis method enables the variation of the sample's mass to be recorded [148, 149]. The sample (m_0 = 10 mg) is put into a platinum pod that is connected to an accurate balance. The sample is then placed in an oven where it is heated repeatedly between ambient temperature and a maximum of 1000°C while the weight of the sample is monitored to determine how the product degrades.

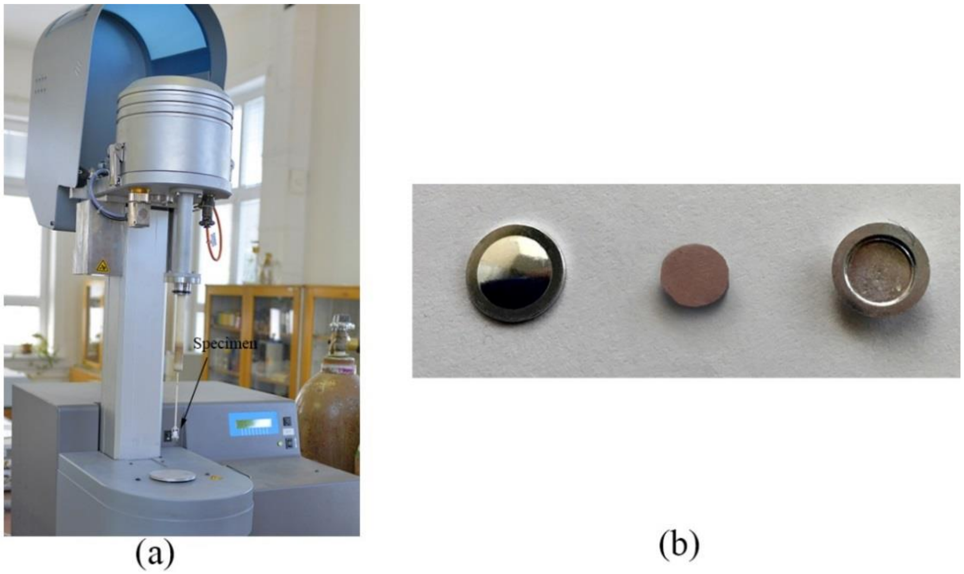
The impact of brick waste rate on PET composites' thermal stability was studied using thermogravimetric analysis (TGA). Thermal Instruments' TA Q-50 analyser is the one in use (Figure 8). The samples were heated to a maximum temperature of 500 °C using an argon flow rate of 40 ml/min and a heating rate of 10 °C/min. The samples chosen for thermogravimetric analysis are listed in Table 2.

(a) (b)

Figure 8. (a) TGA test rig. (b) Specimen for TGA test.

6.2 Characterization by DSC

The thermal transitions of a polymer, or the modification(s) to the property of the substance when its temperature changes, are identified using DSC [125]. On a Setram Setsys Evolution 16/18 system, DSC was carried out (Figure 9). The scans are performed between 0°C and 600°C at a rate of 10°C/min. The capsules are exposed to a 10 ml/min nitrogen flow. The canisters come in twos. We placed our sample (m_0 = 40 mg) of polymer in the first one, referred to as "the sample container." The second one is "the reference container" and it is empty. There is a heating device above each container [150].



(a) (b)

Figure 9. (a) DSC test rig. (b) Specimen for DSC test

6.3 Mechanical Characterizations

Mechanical characterizations refer to the organized assessment and measurement of a material's mechanical characteristics and behavior under varied loads and conditions. These evaluations involve a range of tests and analyses to understand how a material responds to forces, stresses, and strains, providing essential data for engineering, design, and material selection.

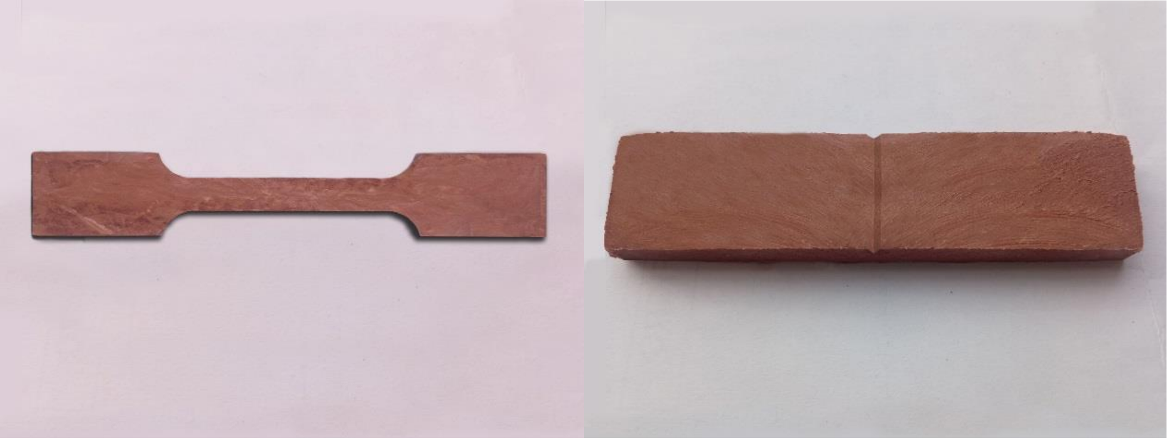
6.3.1 Tensile test

Of all mechanical tests, the tensile test is unquestionably the most basic. To identify the key traits, it is employed. Tensile testing run at room temperature at a speed of 2 mm/min on an IBERTEST-style machine. The jaws have a specimen inserted in either end. This device makes it possible to directly calculate Young's modulus using software that is controlled by a microcomputer.

6.3.2 Charpy impact test

Using a 7.5 J free fall pendulum on a Zwich/Roell RKP 450 machine, the Charpy impact test was conducted.

The specimens in Figure 10 were dried by being baked in an oven at 80 °C for eight hours, which had an impact on the stiffness and strength of the material, and general behavior [151]. The composites' form and how well the filler and polymer adhere to one another's particles are the key determinants of fracture toughness [152].



a b

Figure 10. Specimens for (a) tensile test. Specimens for (b) Charpy test.

6.3.3 Compressive strength test

A cubic specimen of the material is compressed until it breaks during the compressive strength test. The test assists in identifying the highest compressive stress that the material can bear before failing.

6.3.4 Flexural strength test

The flexural strength test, which is commonly carried out on rectangular or prismatic specimens, assesses a material's capacity to sustain bending forces. The specimen is supported at both ends and is subjected to a load at its center during the test.

Figure 11 depicts the results of compression and flexural strength tests on the ELE International ADR-Auto 220-240V machine.

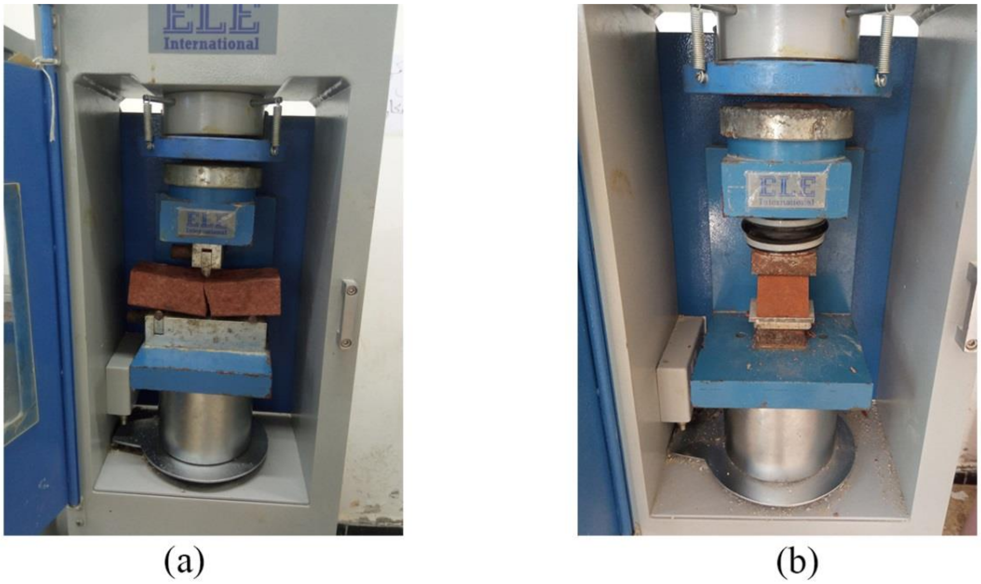

(a) (b)

Figure 11. Specimens under (a) flexural and (b) compressive strength tests

6.3.5 Density test

Cubic specimens were weighed using an electronic scale in Figure 12 to determine their mass in grams (g), then their volume in cubic centimeters (cm^3), which allowed us to use the equation below to determine their density.

$$\rho = \frac{m}{v} \tag{1}$$

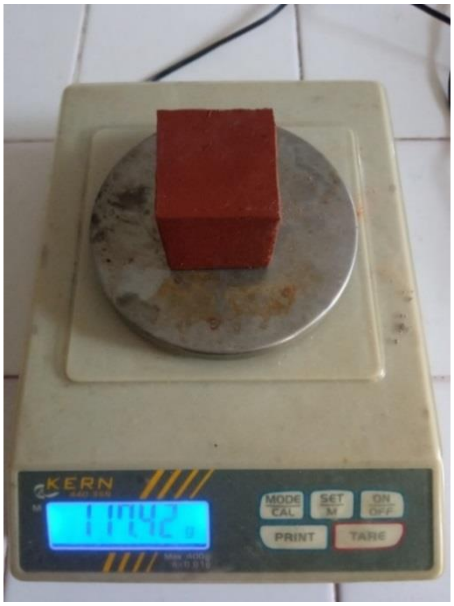


Figure 12. Measurment of a specimen on a scale

6.4 Morphological Characteristic

The morphology of the various materials was examined using the SEM "JSM-5610" as well as t The matrix and reinforcement interaction. The samples were broken, placed on sample holders after being submerged in liquid nitrogen, and then covered in a gold/palladium mixture. In this work, SEM was employed to capture the sample's surface at a 250x magnification. We were able to see the tiny details of the surface of the specimen's structure because to this magnification.

7 SIMULATION

When simulating, we use a step-by-step approach and go through a series of carefully planned steps. Making a model that precisely copies a stone wall is one of these steps, which is followed by testing it under various conditions and stresses to observe how it responds. We examine what other academics have discovered in their studies and take from their ideas and methodologies to ensure that our simulation is robust and accurate. Our efforts to fully understand how brick walls react when we simulate them are built on a foundation of careful preparation and learning from what others have discovered.

8 LITERATURE REVIEW

Masonry is one of the oldest and most prevalent building materials, with a rich history dating back centuries. It has been used widely in construction across various cultures and regions. Masonry consists of units such as bricks, stones, and blocks, Mortar is used to mix and bind them together. These units can be created using various materials and have certain mechanical characteristics. [153].

This diversity in constituents gives masonry its heterogeneous nature, thus, the properties and content of it vary [154].

In present day, many researchers incorporated plastic materials in construction with the aim of adding a new field for the use of plastic and for getting rid of plastic waste. They created a brick made of a mixture of one of plastic types such as PET, PP, PEHD, etc., and sand, clay or brick powder[132-134]. The production process is carried out by mixing different proportions of the mixture to find out which one bears the most mechanical and thermal characteristics.

Youcef et al examinated the reinforcement of brick particles in PET matrix ,Four unique samples, designated C_1, C_2, C_3, and C_4, were examined as part of the investigation. PET made up a different weight proportion in each sample, ranging from 70%, 65%, 50%, and 55%, respectively. To test how well these samples might function as reinforced composites, their mechanical properties were assessed. The results showed that when compared to the other compositions, the C_1 sample produced better outcomes. As a result, the analysis and potential applications of the C_1 sample are going to be discussed in this study's subsequent sections in more detail [155].

Sellakutty and Dinesh conducted a study to investigate how different ratios of HDPE (High-Density Polyethylene) and sand affect compressive strength. They tested three different ratios: 1:3, 1:4, and 1:5 of HDPE to sand. The resulting compressive strengths were 4.78 N/mm^2, 5.12 N/mm^2, and 4.92 N/mm^2, respectively [133].

When Singhal and Netula combined molten PET, LDPE, HDPE, and PP plastic with 3:7 ratio of stone dust, they found that there was no water absorption and that the material had 5.6 N/mm^2 in terms of compressive strength [134].

Gopu Mohan et al; blended thermocol with melted plastic and sand, using different weight percentages of plastic: 5%, 15%, 25%, and 35%. In each sample, 5% of the brick was made up of thermocol and the rest was sand. The research found that all samples had zero water absorption, and the highest compressive strength recorded was 11 N/mm^2 for the sample with 25% plastic weight percentage [132].

There is modest progress in integrating plastic materials into construction materials, however there is no clear use of plastic bricks. Findings from this study will help determine the possibility of integrating plastic bricks into masonry wall using simulation software (abaqus/CAE) [156] to generate a 3D computer model of the masonry wall, plastic bricks are used in place of conventional masonry units in the research. Against confirm correctness, this model will be compared against an earlier numerical [157] and experimental model [158].

Because masonry is heterogeneous and anisotropic, it is regarded as a complicated material. Therefore, it is difficult to understand and precisely portray its structural behavior. Numerical modeling is often needed to understand how these structures react under various stress conditions while dealing with the design of new masonry structures or evaluating existing ones [159].

9 ABAQUS SOFTWARE

The software program Abaqus FEA, also known as ABAQUS, was developed for finite element analysis and computer-assisted engineering. The old abacus, used for calculations when it was first released in 1978, inspired both its name and logo. The Complete Abaqus Environment (CAE), Abaqus/Standard, Abaqus/Explicit, Abaqus/CFD (Computational Fluid Dynamics), and Abaqus/Electromagnetic are the five essential software components that make up the Abaqus product suite. [156].

Python is an open-source programming language that is used in the Abaqus products for customization and scripting [160].

10 NUMERICAL MODELING APPROACHES

Numerous numerical modeling techniques can be used to simulate both the linear and nonlinear behavior of masonry. These techniques include the discrete element method (DEM) [161], limit analysis [162], applied element method (AEM) [163] and finite element method (FEM) [157, 164]. As previously mentioned, we use a FEM-based numerically simulated model created within the Abaqus software for this particular inquiry.

There are two main modeling methods to take into account when using FEM for masonry: micro-modeling and macro-modeling [157]. The level of precision and complexity desired will determine which strategy is best. The simulation is extremely detailed in the Micro-modeling technique because individual units and mortar are represented as continuous components, whereas interfaces between units and mortar are represented as discontinuous elements.

Although the highly detailed Micro-model in Figure 13(a) provides accurate findings, its computing demands limit its use to relatively small masonry components. The goal of employing a simplified micro-modeling approach is to lessen the disadvantages of the detailed micro approach, as shown in Figure 13(b). In this simplified method, the mortar thickness is used to grow units, which are then represented as a series of continuous parts. A collection of discontinuous pieces are used to simulate the interactions between these extended units [165,166].

In the macro-modeling technique, Masonry is regarded as a homogenous material as depicted in Figure 13(c), without separating individual pieces and mortar. The average characteristics of the masonry constituents are used to generate material attributes, and a series of continuous elements are used to represent the overall masonry construction [166]. This method is used to simulate somewhat larger and more complex brick structures, concentrating on their general behavior. It is crucial to remember that it might not record detailed failure modes.

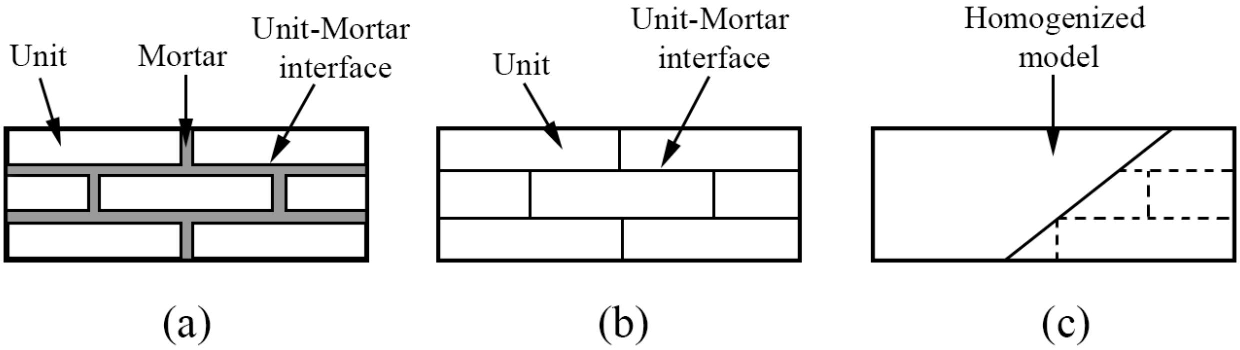


Figure 13. Finite element modelling approaches: (a) detailed Micro-model; (b) simplified Micro-model; (c) Macro-model [166].

Engineers may safely simulate potentially dangerous or destructive loads and failure scenarios using finite element analysis (FEA), which gives them an understanding of how a system behaves physically at any given time.

It has several benefits, including enhanced accuracy by looking at any potential physical stressors that might affect the design. the ability for designers to evaluate how stresses in one component affect materials in other related parts, leading to higher design quality. Early testing during the development phase, where virtual prototypes replace the time-consuming process of making physical prototypes and allow designers to model multiple ideas and materials fast. FEA software facilitates the construction of higher-quality products within faster design cycles and with less material utilization, increasing productivity and income. modeling the interior and exterior of the design will provide deeper insights into important design factors. This aids designers in comprehending how important elements affect the entire structure and in locating possible weak places. efficient use of models since a single model may be used to test several physical events or failure types. Quick computations and inexpensive initial investment. access to previously collected experimental data that can be used to do parametric analysis on new models based on previously tested models [167].

11 BOND PATERN

It’s important to consider the choice of bond pattern When creating a masonry wall model, Stretcher bond, English bond, Flemish bond, and header bond are four distinct bond patterns that should be taken into account (see Figure 14). Rows of headers are arranged in a header bond with a half-brick offset. Similar to header bond, stretcher bond uses stretchers rather of headers, with joints on each row being centered by half a brick above and below. By alternating rows of stretchers and headers, where the joints between the stretchers line up with the headers in the row below, an English bond is produced. In contrast, a Flemish bond alternates the placement of headers and stretchers in each row with the headers of each row being centered on the stretchers of the row below, giving the bond a distinctive appearance [168].

The stretcher bond is used in this simulation as [157].

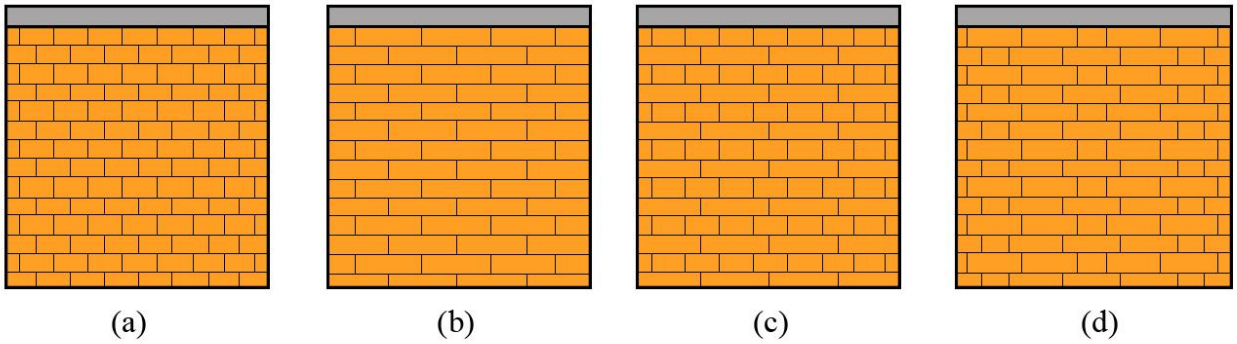

(a) (b) (c) (d)

Figure 14. Masonry bonds, (a) Header bond, (b) Stretcher bond, (c) English bond, (d) Flemish bond [168]

12 FAILURE MECANISM

The five basic masonry failure types are depicted in Figure 15 for your observation. In Figure 15.a, the first failure is primarily shown as a tensile failure, while Figure 15.b shows the second failure as a sliding shear failure. The third category, shown in Figure 15.c, is a failure that includes both shear and diagonal cracking. The fourth form, which is represented in Figure 15.d, deals with the brickwork failing by crushing. The last type is a failure marked by cracking, and it is depicted in Figure 15.e. This section sheds light on how the computational model was created, paying particular attention to how mortar between two bricks was modeled. The performance of the model is assessed in the section that follows by making comparisons with earlier computational and experimental studies that have been reported in the literature [168].

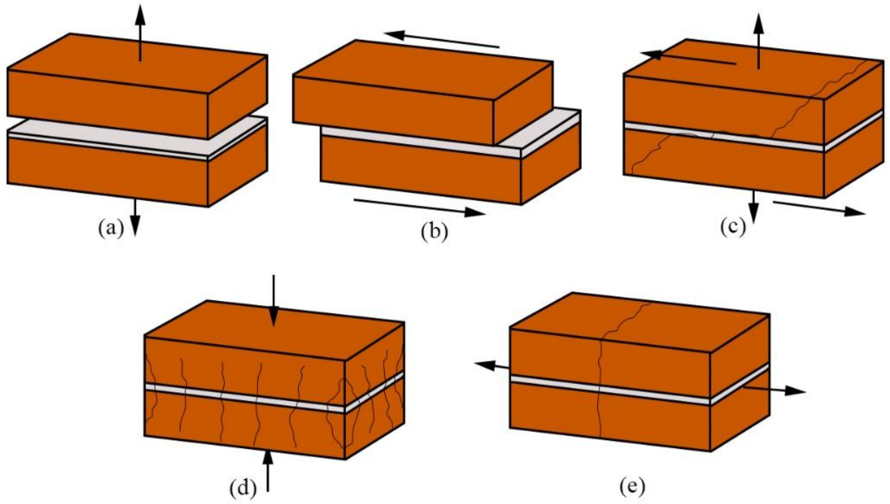


Figure 15. Failure mechanisms: a) tensile failure at the brick–mortar interface, b) shear sliding at the brick–mortar interface, c) diagonal cracking of masonry, d) crushing of masonry, and e) tensile cracking between brick and mortar [169-171]

A simplified micro-modeling technique is used in this study to approximate the three-dimensional responses of masonry specimens. These specimens experience in-plane cyclic loading that is controlled by displacement as well as uniaxial compression. Both the uniaxial and cyclic tests utilize displacement in the horizontal direction. employing finite element modeling (FEM) analysis, the model is built in the commercial software Abaqus employing solids and interaction surfaces. An application of the concrete damaged plasticity model (CDP) is made to depict the behavior of the masonry components. This Abaqus-created model is capable of mimicking plastic bricks and other quasi-brittle materials, such as the plastic bricks used in this instance [156]. Using a surface-based cohesive interaction property, the mortar and the interface between the mortar and the masonry units are modeled. This interaction model makes it possible to express cohesive connections with thin interfaces. In the next sections [172].

These properties are more detailed in sections bellow.

13 SURFACE BASED COHESIVE MODEL FOR THE JOINTS

Through the use of interaction surfaces with cohesive properties, joints are represented in the model. Abaqus is used to implement this. The cohesive model is constructed on the basis of a behavior known as linear elastic traction-separation, which is followed by the beginning and development of damage [172].

The link between the normal and shear separations that happen across the interfaces before damage starts is quantified by the traction-separation behavior. A matrix of elastic stiffness with the symbol "K" serves as the mathematical representation of this phenomenon. The stiffness elements that control this relationship are defined by the matrix K, which creates a connection between the traction forces (t) and the separation vectors (δ). Equation (2) explicitly expresses this formulation.

$$t = \begin{pmatrix} t_n \\ t_s \\ t_t \end{pmatrix} = \begin{bmatrix} K_{nn} & 0 & 0 \\ 0 & K_{ss} & 0 \\ 0 & 0 & K_{tt} \end{bmatrix} = \bar{\bar{K}}\bar{\bar{\delta}} \tag{2}$$

Along the two main axes, the normal and shear directions are indicated by the subscripts "n," "s," and "t" in equation (2), respectively. Vectors are indicated with a single bar priority, while matrices are indicated by a double bar accent. You can express the stiffness components as functions of the individual constituents' elastic or shear moduli and mortar thickness, as illustrated in equations (3) and (4) Lourenço [173], to provide the stiffness components for the unit-mortar interface in the bonded interface. In these equations, the subscripts "m" and "u" stand for mortar and unit, respectively.

$$K_{nn} = \frac{E_u E_m}{h_m(E_u - E_m)} \tag{3}$$

$$K_{ss} = K_{tt} = \frac{G_u G_m}{h_m(G_u - G_m)} \tag{4}$$

The quadratic stress criteria is useful for damage initiation and progression because it indicates the beginning of joint degradation, particularly under mixed-mode loadings. When the masonry joints' quadratic stress ratios reach a value of 1, this condition is said to be met. Equation (5) in Abaqus illustrates the mathematical formulation of this criterion [157].

$$\left(\frac{\langle t_n \rangle}{t_n^{max}}\right)^2 + \left(\frac{t_s}{t_s^{max}}\right)^2 + \left(\frac{t_t}{t_t^{max}}\right)^2 = 1 \qquad (5)$$

In this study, the critical shear stress for the joints is regulated by the Mohr-Coulomb failure criteria, and the tensile strength of the joints determines whether they undergo tensile cracking.

There are two popular methods for monitoring the progression of damage: one based on energy and the other on separation. The Benzeggagh-Kenane (BK) formulation is specifically used in this study's energy-based approach to damage evolution. Equation (6) provides more information on this BK formulation and how it is implemented in Abaqus.

$$G_{IC} + (G_{IIC} - G_{IC})\left(\frac{G_{shear}}{G_T}\right)^{\eta} = G_{TC} \qquad (6)$$

The joint's behavior is described by the Exponent η parameter; a fragile behavior is represented by a setting of 2. In other words, a higher score denotes a more brittle behavior of the joint, making it more susceptible to an abrupt and catastrophic collapse.

The fracture energy related to various joint failure mechanisms are denoted by the words Gshear and GT. Gshear combines the energies linked to the joint's Mode III (out-of-plane shear) and Mode II (shear) fracture behavior. The energy connected to Mode I (tensile) fracture behavior is combined with Gshear to form GT. These variables play a crucial role in describing how the joint responds to various loading scenarios.

Presentation in Graphics Figure 16 illustrates the cohesive behavior of the joints. It probably demonstrates how the joint responds differently under various loading circumstances and how variables like η, Gshear, and GT impact this behavior.

Stiffness degradation: In structural simulations, elements' stiffness frequently drops as a result of damage or fracture. The simulation may experience convergence issues as a result of this drop in stiffness. The process of convergence is when an analysis comes to a stable solution. When stiffness degradation is severe, it can be difficult for the simulation to converge, which can cause problems with the numbers [172].

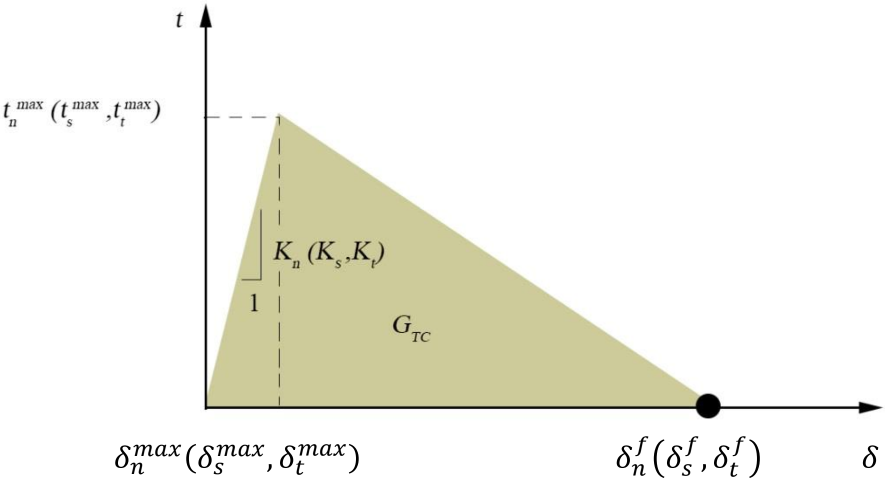


Figure 16. Traction-separation model for the joints [156]

13.1 Compressive behavior

The Concrete Damage Plasticity (CDP) model uses compressive stress data in relation to crushing strain (ε_c^{in}) to characterize the behavior of the material under compressive pressures. The elastic strain (ε_{0c}^{el}), which represents the strain in undamaged material (according to equation 7), is subtracted from the overall strain (ε_c) to determine the crushing strain. The model can simulate a reduction in stiffness to depict the material's response as it goes through compression and ultimately reaches the point of crushing by including a damage parameter for compression (d_c).

$$\varepsilon_c^{in} = \varepsilon_c - \varepsilon_{0c}^{el};\, where\ \varepsilon_{0c}^{el} = \sigma_c/E_0 \tag{7}$$

There is a damage parameter that, under compression conditions, ranges from 0 (signifying no weakening) to 1 (signifying total weakening or failure). Based on the relationship shown in equation (8), the Abaqus software handles this by automatically translating inelastic strain into plastic strain (ε_c^{pl}). Here, "c" stands for compression particularly. This procedure explains the degree of damage the material sustains and explains how it responds plastically to compression.

$$\varepsilon_c^{pl} = \varepsilon_c^{in} - \frac{d_c}{(1-d_c)}\frac{\sigma_c}{E_0} \qquad (8)$$

13.2 Tensile behavior

The Concrete Damage Plasticity (CDP) technique uses a softening curve to represent the tensile behavior. This curve illustrates how a material responds to failure or cracking. In CDP, the deterioration of the material's elastic modulus (E_0) is what causes this post-failure behavior.

This post-failure behavior is a result of how post-failure stress and cracking strain ($\varepsilon_{\mathrm{t}}^{\mathrm{ck}}$) are related. According to equation (9), the cracking strain is determined as the difference between the elastic strain ($\varepsilon_{\mathrm{0t}}^{\mathrm{el}}$) and the total strain ($\varepsilon_t$), where the elastic strain ($\varepsilon_{\mathrm{0t}}^{\mathrm{el}}$) reflects the strain in the undamaged material.

The model takes into account the decrease in stiffness that happens as the material starts to crack under strain by including a damage parameter for tension (d_t). The tension damage parameter ranges from 0 (which indicates no loss of strength) to 1 (which indicates total loss of strength or failure). This characteristic helps us comprehend how the material responds to tension while taking into account the degree of damage it has sustained.

$$\varepsilon_t^{ck} = \varepsilon_t - \varepsilon_{0t}^{el},\ where\ \varepsilon_{0t}^{el} = \sigma_t/E_0 \qquad (9)$$

However, another method for modelling tensile behavior uses fracture energy (G_t) to describe the decline in strength after cracking (as seen in Figure 17). According to the input fracture energy data, there is a linear loss of strength in this model upon breaking. The fracture energy and the tensile strength (σ_t) of the material are used to compute the cracking displacement (u_{t0}), which denotes the point at which the material completely loses strength. The "t" index particularly refers to tension in this instance.

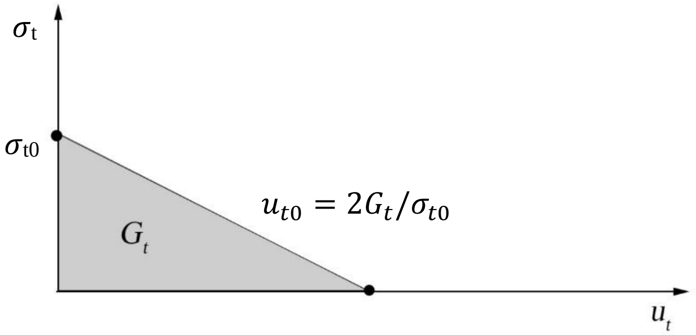


Figure 17. Post-failure fracture energy curve [156]

14 MASONRY WALL MODEL

A key step in finite element analysis is the creation of a mesh, which is made up of millions of tiny elements and collectively shapes the structure under consideration. Each of these components is subjected to calculations, and the results of those calculations when added together produce the overall structure's final output.

Preprocessing, processing, and post-processing are the other two primary divisions of this procedure. The type of analysis (such as modal analysis or structural static analysis) is selected by the user, and specifies the kind of elements to be used during the preprocessing stage. Nodes are created, and material attributes are provided. Then, boundary conditions and loads are applied, and elements are built by connecting them to nodes [174].

The computer handles the second phase, processing. Here, it resolves the boundary value issue and then shows the user the outcomes.

The user reviews the obtained results in the post-processing step, noting elements including Temperature, displacement, duration, stress, strain, and natural frequency [167].

We have taken into account both the linear and non-linear behaviors of the expanded units and their interactions in the 3D finite element micro-model that we have constructed. We have adopted a coherent strategy based on surface modeling to represent how joints interact. Through the discretization of nodes to surfaces and the use of a finite sliding formulation, we have defined the contacts that take place between adjacent masonry pieces. Our model specifically implements a hard contact behavior, where pressure is transmitted when surfaces touch, preventing tensile tension from penetrating and being transmitted between the touching surfaces. This closely mimics the behavior of masonry unit surfaces in practice.

The units are represented as three-dimensional hexaheral eight node linear brick components with reduced integration and hour glass control (C3D8R) [156].

We carried out a mesh sensitivity research to establish the proper mesh size. A masonry wall was the subject of three numerical calculations, which will be applied later for validation under in-plane stresses. The initial study used a mesh made up of 7 X 2 X 3elements to represent each masonry unit (figure.18a), which had dimensions of 110 mm in thickness, 76 mm in height, and 230 mm in length. By employing 7 X 4 X 3 elements for each unit in the second study (Figure.

18b), which practically doubles the amount of elements compared to the first, we doubled the mesh density [157].

Finally, in the third analysis, which employed four times as many elements as the first, we further improved the mesh by using 7 X 4 X 6 elements for each unit (Figure. 18c).

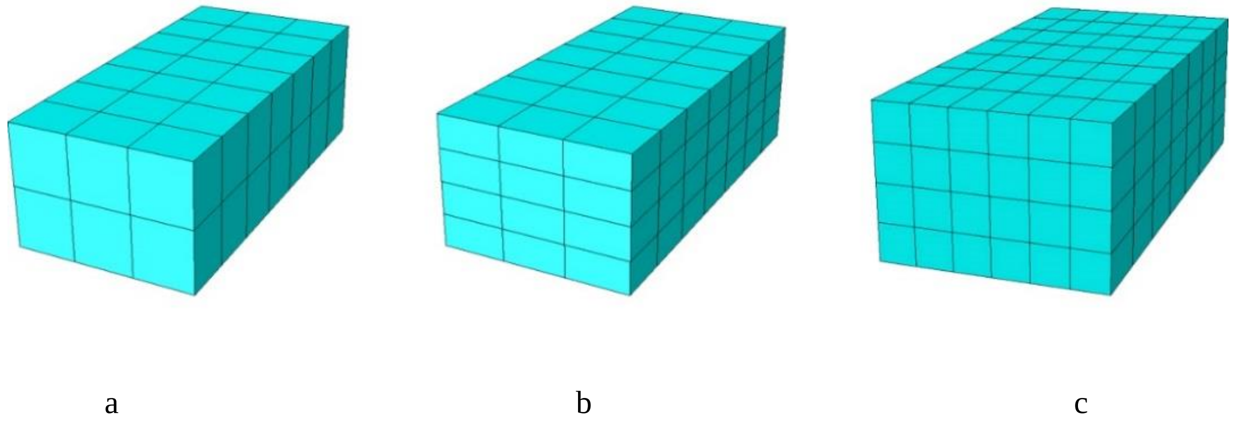


Figure 18. Mesh sizes used in masonry units.

Surprisingly, as shown in Figure 19, all scenarios produced findings that were comparable in terms of patterns of failure and elasticity and plasticity. This comparison demonstrates how little sensitivity there is between the suggested model and the chosen mesh sizes. As a result, it is possible to use coarser meshes, greatly lowering the amount of processing needed.

We sequentially applied actions (load or displacement) to the model when performing the numerical analysis. This indicates that the actions were gradually forced on the model, regardless of whether we used load control or displacement control.

The mesh configuration denoted as (figure.18a) was chosen for the numerical simulation based on the findings obtained.

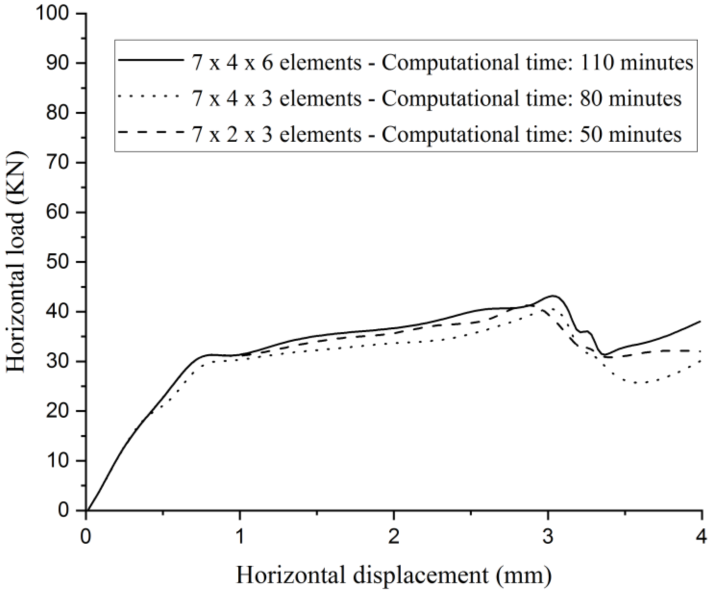


Figure 19. Comparison between different mesh sizes.

The proposed model's validity was assessed by comparing it to experimental findings outlined in reference [158]. These tests were conducted to examine how brickwork would react to static in-plane cyclic (earthquake-simulating) and in-plane stresses. The tested walls had notional 110 mm in thickness, 1200 mm in length, and 1200 mm in height measurements (see figure 20). These walls were built using plastic bricks that had the following dimensions: 230 mm in length, 76 mm in height, and 110 mm in thickness. Mortar joints were 10 mm thick, and cement, lime, and sand were mixed in a 1:1:6 ratio. There were 14 brick courses overall, with 5 bricks in a row, put out in a running bond pattern in each wall.

To model the half brick in abaqus we have to virtually split the full brick in half and vertical, we have to create the instance of the half brick in the assembly module and position them accordingly on the right and left sides of the masonry wall. In the assembly , we have to apply translations and rotations to align the half brick correctly within the wall structure and ensure that the interactions these half bricks and surrounding components are appropriately defined and accounting for interface conditions and contact behavior.

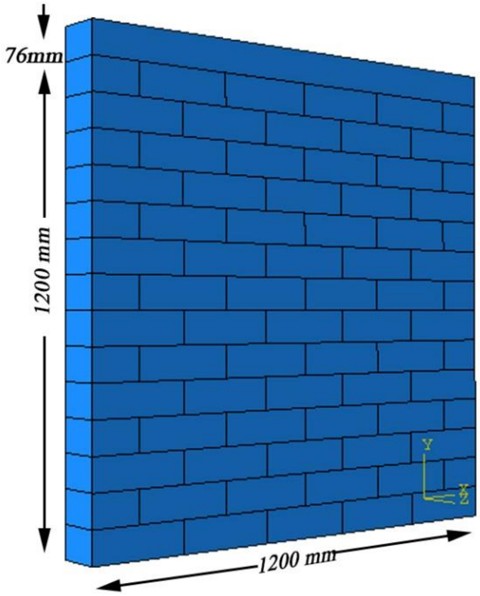


Figure 20. Numerical model of masonry wall

15 PROPERTIES

In this illustration, we aim to replicate the response of the wall to earthquake conditions and in plane loads using Abaqus software, as previously mentioned. We used a simplified micro-modeling technique to join the bricks together, with the mortar being defined as an interaction parameter. Cohesive behavior and damage behavior are both included in these interaction features.

Table 3 shows plastic bricks properties, the plastic bricks' geometric shapes were designed in a 3D modeling environment, and to accurately depict their characteristics, these bricks are shown as solid things. According to the table, the plastic bricks have the following characteristics: a density of 1660 kg/m3, a Young's modulus of 2771 MPa, and a Poisson's ratio of 0.3 [155].

Table.3 plastic brick properties

Density (kg/m3)	Young’s modulus (MPa)	Poisson’s ratio
1660	2771	0.3

The Drucker-Prager model has been used in this study to describe the plasticity features. The mechanical menu was selected, and specifically the plasticity area, where the Drucker-Prager model was found. As shown in table 4, the model is built up with a friction angle of 36 degrees, a flow stress ratio of 1, and a dilation angle of 11.3 degrees. Additionally, 14.18 MPa is listed for the Drucker-Prager hardening.Properties are obtained from [157].

Table.4 Drucker Prager properties

Angle of friction (β)	Flow stress ratio (R)	Dilation angle (ψ)
36	1	11.3

The masonry wall in this building method, has 14 rows, as was previously mentioned. This method does not regard the mortar as a separate component; instead, each brick is fully sculpted and put together. Instead, the Abaqus software defines the mortar's characteristics as interaction properties.

The mechanical menu's normal behavior category has the friction coefficient (μ) set to 0.75 as stated in the article [175]. Additionally, the cohesive behavior is given, and contains the table 5's Knn, Ktt, and Kss parameters. Knn, the shear direction by Kss, and the second shear direction by Ktt represent the mortar's stiffness in the normal direction.

Table.5 joint interface properties

K_{nn} (n/mm^3)	K_{ss} (n/mm^3)	K_{tt} (n/mm^3)
63	25	25

The mechanical behavior settings are shown in Table 6, with the option for damage in tension selected and set to 0.2 MPa [157]. The Benzagagh-Kenan model is the chosen damage law, and a value of 2 denotes brittle behavior as stated in [176]. The fracture energy for the first and second shear modes is set at 0.04 N/mm [177], while the normal fracture energy is set at 0.012 N/mm [178].

Table.6 masonry wall properties

Friction coef (μ)	Tension t_n^{max} (MPa)	B-K	G_{IC} (N/mm)	G_{IIC} (N/mm)
0.75	0.2	2	0.012	0.04

16 LOADS

16.1 In plane loading

The wall underwent a controlled vertical compressive load applied through the top beam. The top beam's vertical movement was constrained once the compressive load was in place. Then, through the top beam, on the wall, a monotonic horizontal load was gradually applied (see figure 21).

Two stages of the numerical analysis were completed. The initial vertical compression load was applied in the first stage. In order to maintain the same boundary conditions as in the experiment, the second stage involved limiting the vertical and out-of-plane horizontal displacements and blocking rotations around all axes at the top of the wall. In this phase, the vertical compression stress was continuously maintained while the horizontal in-plane monotonic load was incrementally applied under displacement control [157].

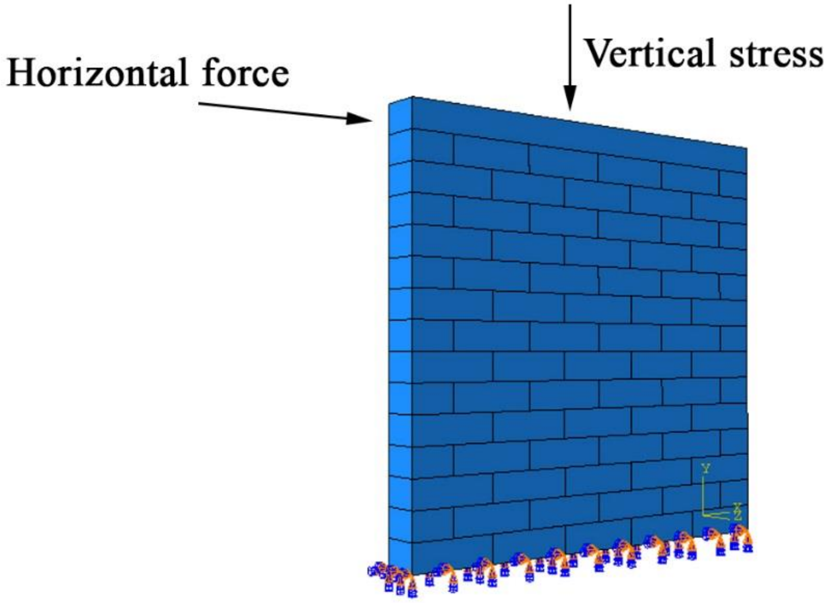


Figure 21. Brick wall with in-plane loading

16.2 In-plane cyclic loading

The wall was subjected to a controlled vertical compressive load, administered through the top beam. Any movement of the upper beam vertically was prohibited once the compressive load had been generated. The top beam then used to apply a progressive, cyclic horizontal load to the wall (see figure 22).

There were two separate steps in the loading procedure. First, there was the pre-compression stage, which involved applying the first amount of vertical stress and keeping it constant throughout the testing. After that, the walls were kept under displacement control and subjected to cyclic horizontal in-plane loads [157].

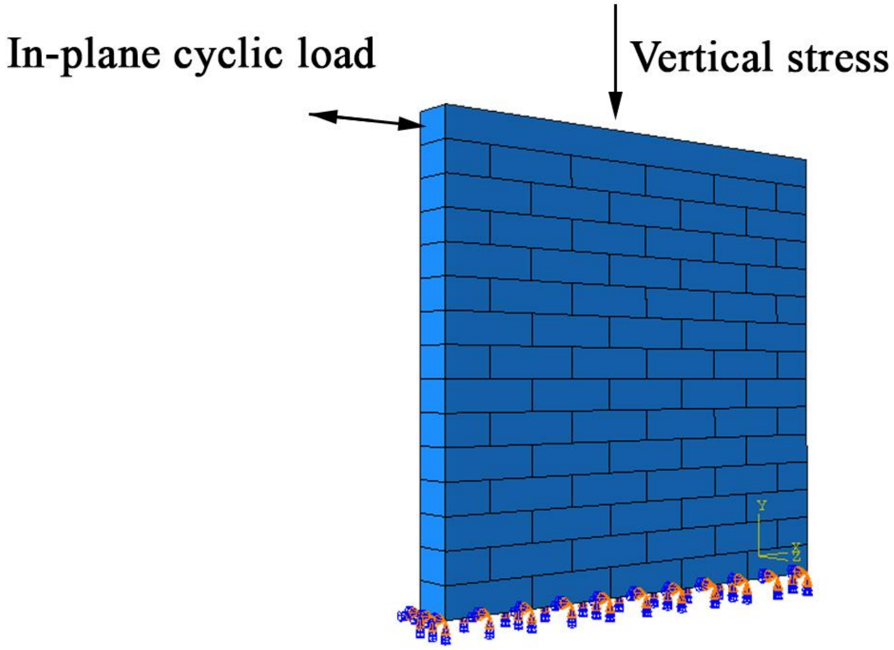


Figure 22. Masonry wall subjected to cyclic in-plane loading

There were a total of 19 loading cycles for the wall in question. Figure23 shows the precise load distribution patterns that are applied to the wall's top.

Our research was centered on a specific wall that had experienced a 0.7 MPa initial vertical stress. The cyclic graph is taken from the experimental work and it is designated as A3-1, from the research of Mojsilović et.al [158].

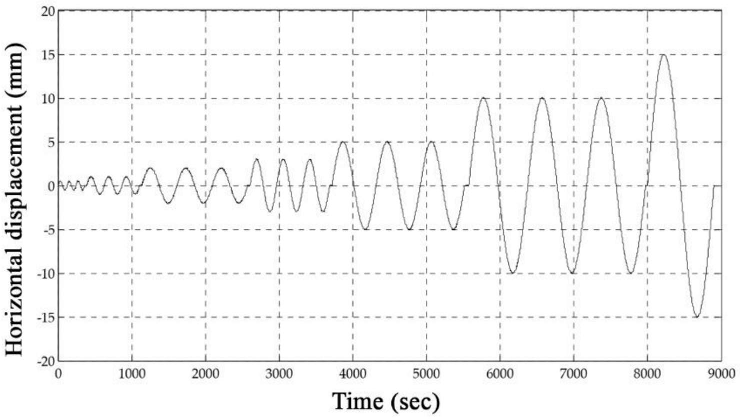


Figure 23. Cyclic loading history [158]

Origin Lab was used to collect (x,y) data [179], which was subsequently input into Abaqus.

CHAPTER IV

RESULTS AND DISCUSSION

1 INTRODUCTION

In this chapter, we present and discuss the experimental and numerical results for the composite material PET/brick powder.

2 EXPEREMENTAL RESULTS

Experimental results obtained from controlled tests bellow are designed to analyze the composite obtained from the production, and to understand the overall properties of the material.

Experimental results are divided to three parts, thermal, mechanical and morphological.

2.1 Thermal results

The findings of the TGA on the samples C_0, C_1, C_2, C_3, and C_4 are shown in Table 1. The "Td" column displays each sample's degradation temperature, which is the point at which the sample begins to deteriorate and lose mass. The weight % of the sample that is still present after being heated to 500°C is shown in the "Residue at 500°C" column. Sample C_0 had a residual of 0.2214% at 500°C and 220.420°C is the degradation temperature. This indicates that the sample began to disintegrate and lose weight at 220.420°C. Sample C_4 showed the highest degradation temperatures and maximum residues at 500°C, despite a marked rise in degradation temperature from sample C_1 to C_4, indicating that of the studied samples, C_4 had the greatest thermal stability.

Table 1. Temperature and weight of PET left over during degradation

Samples	**T_d °C**	**Residue at 500°C (%)**
C_0	220.420	0.2214
C_1	280.325	0.4251
C_2	287.428	0.5772
C_3	310.706	1.9055
C_4	314.323	2.6540

When brick powder is present, the degradation temperature of PET is higher. Figure 1 contrasts the mass loss curves of a mix that contains 45% brick sand weight and an empty blend. These findings concur with those made by previous researchers [180, 181].

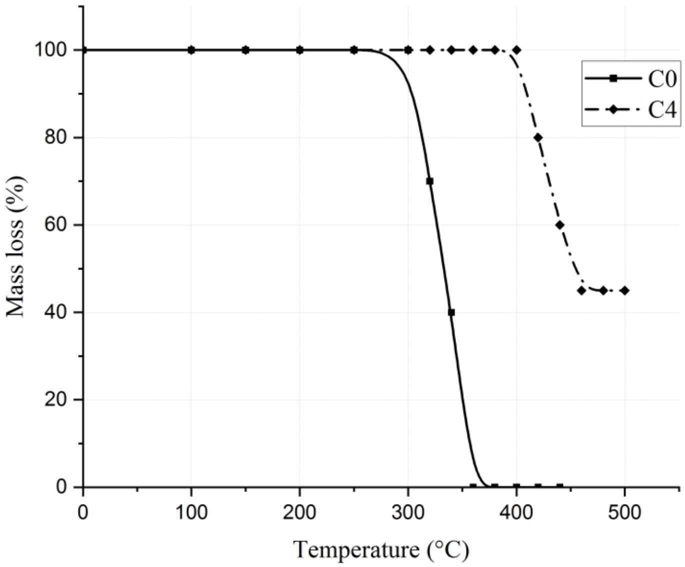


Figure 1. Samples' mass loss curves with and without load

The same mechanism governs the decomposition of both materials, i.e., depolymerization, followed by weight loss from the breakdown of volatile compounds (styrene groups), although the material strengthened by bricks has greater thermal stability, particularly at the outset of the process. This enhancement is reportedly achievable because reinforcing sheets prevent volatiles from escaping into the polymer matrix, so slowing the diffusion of volatiles, according to several authors [182-184]. Thus, reinforcing particles act as thermal insulators, or more specifically, as barriers to the transmission of generated volatile chemicals during the degradation of the material, while also enhancing the thermal stability of a polymer.

The deterioration temperature in this investigation rose from 220.420°C to 314.323°C, the temperature increased by 93.903°C, over the degradation temperature with 45% of weighted brick present. This increase is a result of the surface of the material developing a protective coating. This outcome is reasonably consistent with those of Sellakutty et al. and Lai S-M et al. [133, 185]. After the brick powder is added, the degradation temperature of the polymers rises, improving them and enabling their use at greater temperatures. The degree of filler dispersion within the polymer is a key factor in this improvement in thermal stability [186]. In addition, the polymer's gas and liquid permeability is greatly reduced by the high aspect ratio of brick powder dispersed in a polymer matrix. When the matrix exfoliates the platelet filler particles, the tortuousness of the path taken by the molecules as they diffuse into the polymer is noticeably amplified. The packaging industry is very interested in this feature since it allows for a rise in barrier qualities without a loss of transparency [187]. The TGA curves of the composites with different brick content percentages debris are shown in Figure 2. The observed curves demonstrate a consistent deterioration technique for all samples. Brick powder slows down the degrading process and considerably increases the residues (Table 1). A larger concentration of reinforcement may aid in enhancing the composites' thermal stability and enabling their usage in applications involving high temperatures, according to Kumar, S et al. [188]. The varied samples' DSC results are displayed in Figure 3.

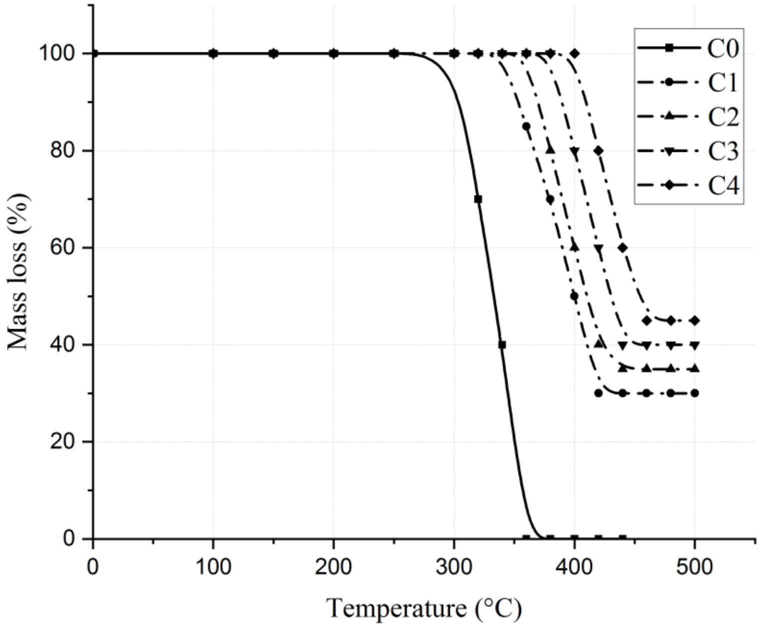


Figure 2. Brick waste rates' impact on TGA curves

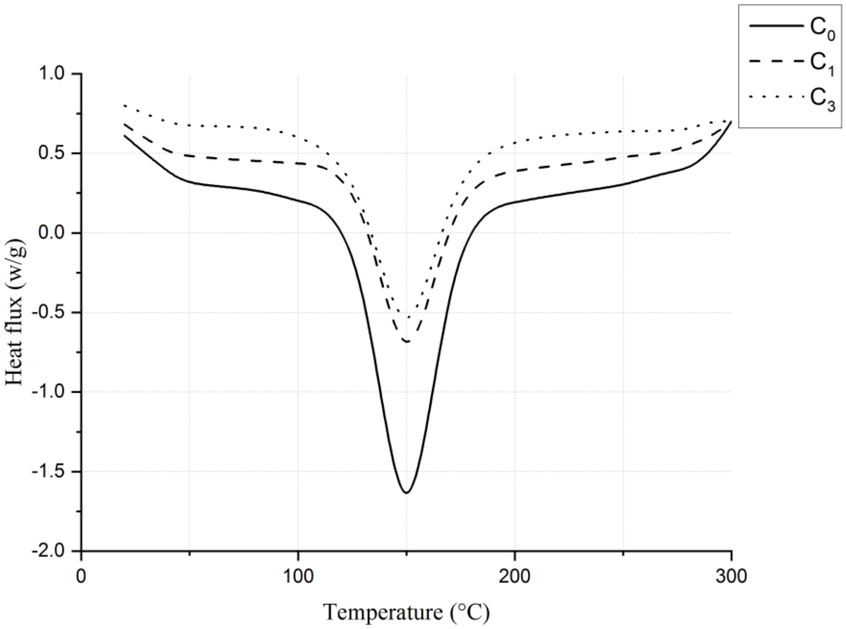


Figure 3. Polyethylene terephthalate/brick DSC curve

The glass transition temperature of blends can be impacted by the inclusion of brick powder. Thermoplastic polymer matrices exhibit the effects of brick powder on the glass transition temperature. Brick powder particles' effects on chain motion bring them on. Such behavior is most likely connected to the morphological changes brought about by the injected brick sand percentages [189]. On the other side, the inclusion of brick particles alters the temperature at which PET crystallizes. These findings are in accordance with Luljeta Raka et al.'s research [190].

Table 2. Results of calorimetric analysis

Samples	Tg (°C)	Enthalpy (J/g)	Effect
C_0	105.103	88.584	Endothermic
C_1	122.045	106.547	Endothermic
C_3	131.365	123.045	Endothermic

Depending on the glass transition or melting temperature, the material's application range or the temperature range in which it demonstrates the desired property may change. Good mechanical strength is provided by a high glass transition temperature (Tg) (Table 2).

2.2 Mechanical results

The impact of brick composition on the stress at failure is depicted in Figure 4. Above 10% of the weight of the brick sand, the increase in stress as a function of the amount of brick powder provided becomes less significant, and eventually becomes negligible above a load of 30% by weight. When the brick sand weight hits 30%, the optimal value is 26.26 (MPa). In fact, only a certain amount of the brick powder can be properly dispersed and distributed in a given volume, and even that amount depends on the size of the filler particles. Beyond 30% of the weight of brick sand, the proximity of one particle to another causes an automatic formation of massive clusters that, due to a lack of available space, prevent the production of a homogeneous material. This result suggests that the evolution of mechanical properties is significantly influenced by the distribution and dispersion of fillers in the matrix [191].

Table 3 displays the stress at break values for the five different samples in megapascals (MPa). A measurement of the maximum stress a material can withstand before breaking under tension is called the stress at break. According to the data in the table, The stress at break values for the five samples range from 24.51 MPa to 26.26 MPa. The stress in sample C1 is the highest, 26.26 MPa as the break value, while the lowest is 24.51 MPa.

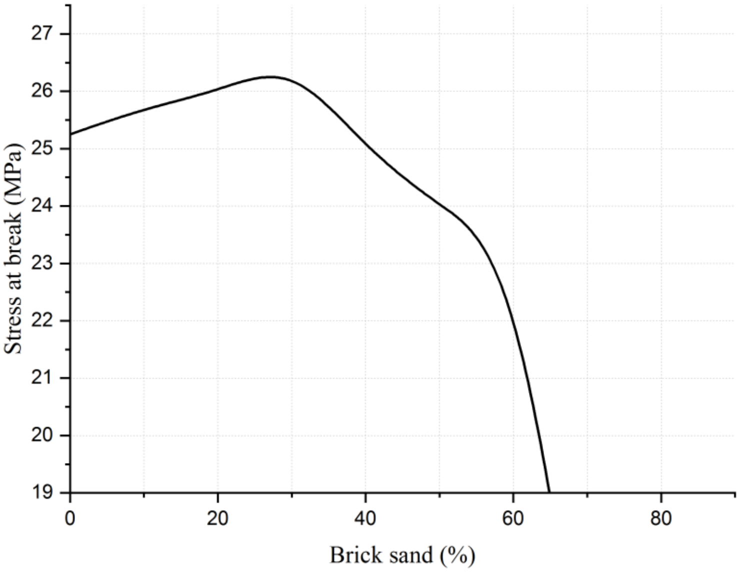


Figure 4. Proportion of brick sand's impact on break stress

Table 3. Five samples' stress at break results

Samples	C0	C1	C2	C3	C4
Stress at break (MPA)	25.24	26.26	25.66	25.06	24.51

Young's modulus (E) variation according to brick content is depicted in Figure 5. Figure 5 shows that the Young's modulus clearly increases when the mass fraction of reinforcements rises up to 30% of the weighted brick sand in comparison to the matrix alone.

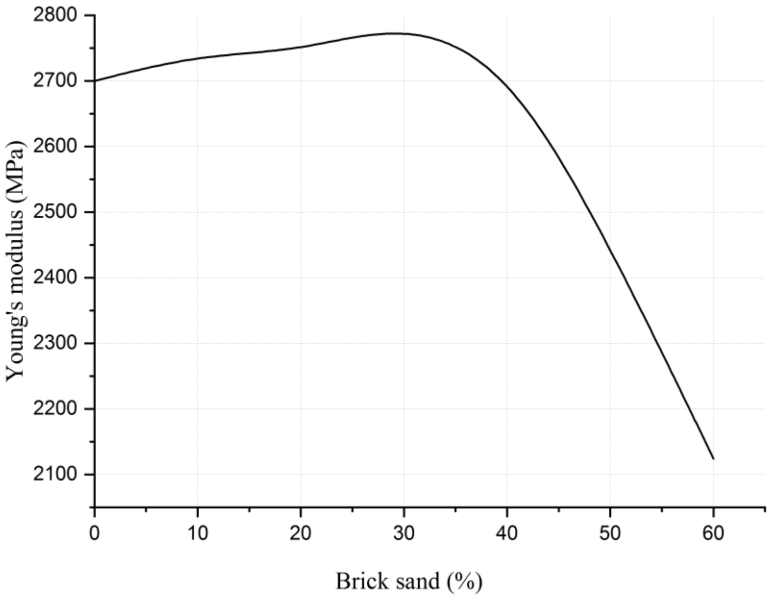


Figure 5. Young's modulus as a function of the percentage of brick sand

According to Table 4, the C_1 sample has the highest Young's modulus value at 2771 (MPa). This increase is likely caused by the reinforcement's size and distribution. Cauvin et al. [192] reported these outcomes. The substance begins to become less elastic at a weight of 30% brick sand in the mixture because the combination has enormous masses as a result of the fusing of the particles between them, which causes a vacuum because the matrix has poor adhesion to this mass, and the material becomes inhomogeneous [193].

Table 4. Young's modulus results for five samples

Samples	C_0	C_1	C_2	C_3	C_4
Young's Modulus (MPa)	2700	2771	2750	2691	2590

Figure 6 depicts how the fractions of brick sand affect impact strength. As brick weight percentages rise, the impact strength falls. Table 5 displays the decreasing values, with C_0 sample reaching 15(KJ/m^2) and C_4 sample having lowest score among all samples. By examining the mechanical characteristics of polyethylene/clay composites, Chungui Zhao et al. found a comparable outcome [194].

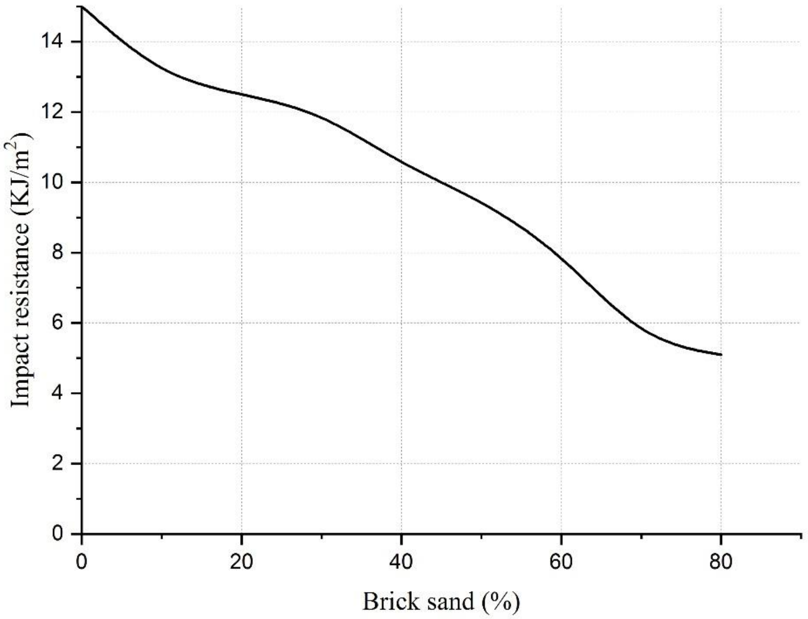


Figure 6. Proportion of brick sand's impact on resistance

Table 5. Results of five samples' resistance impact

Samples	C_0	C_1	C_2	C_3	C_4
Impact resistance(KJ/m^2)	15	11.79	11.14	10.56	9.95

Figure 7 illustrates impact on specimen compressive strength of brick sand proportions. Compressive strength increases with brick sand proportions from 0% to 30% to reach 21.43 MPa, holds a close amount of strength between 21.40 MPa and 21.3 MPa in the proportion range from 35% to 40% of brick sand, and decreases with brick sand proportions from 40% to 60%.

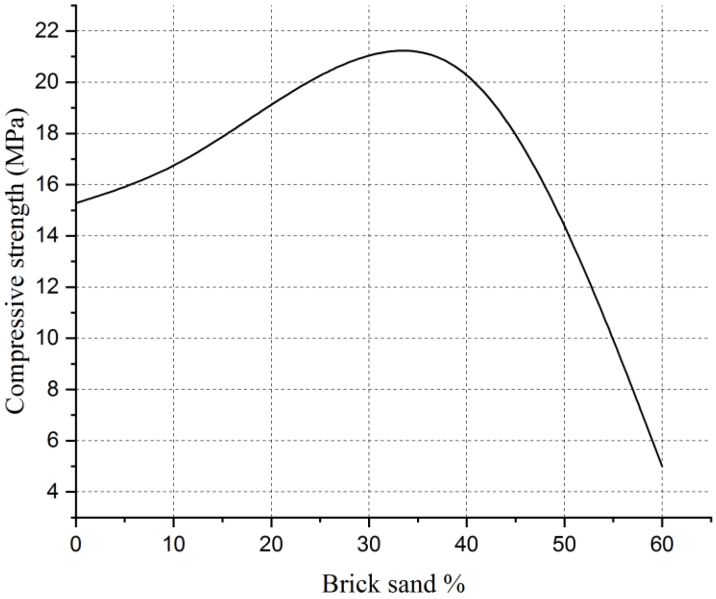


Figure 7. Brick sand proportions impact on compressive strength

Table 6 shows the compressive strength values for five samples. Samples C_1, C_2, and C_3 have values that are similar, indicating that they display similar resistance to compressive forces, whereas sample C_4 has a somewhat lower strength compared to samples C_1, C_2, and C_3. Sample C_0 possesses the weakest compressive strength.

Table 6. Results of compressive strength for five samples

Samples	**C_0**	**C_1**	**C_2**	**C_3**	**C_4**
Compressive strength (MPa)	15.28	21.43	21.40	21.3	16.2

The findings of flexural strength are given in Figure 8. The greatest value is also at 30% of the brick sand percentage, and it is 8.51 MPa. As indicated in Table 7, there is a distinct reduction from C_1 to C_4 sample, and these results are caused by the removal of polyethylene terephthalate from the composite.

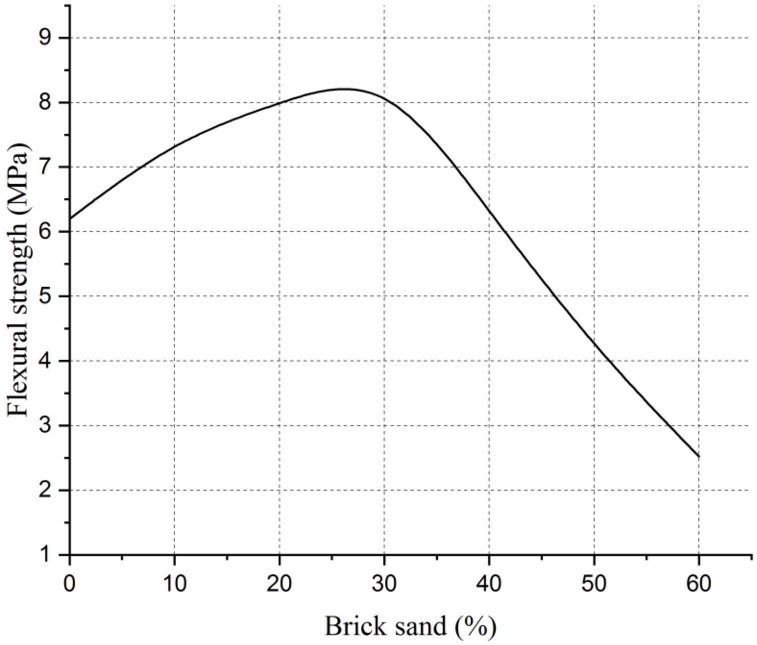


Figure 8. Flexural strength as function of brick sand proportions

Table 7. Results of flexural strength for five samples

Samples	**C_0**	**C_1**	**C_2**	**C_3**	**C_4**
Flexural strength (MPa)	6.2	8.51	7.1	6.2	5.3

The density of sample C_0, which is polyethylene terephthalate, is 1.38 g/cm^3, and it increases from sample C_1 to C_4 with the addition of brick powder, as stated in table 8. Figure 9 displays the density results of the specimens, showing a definite increase with the increase of brick sand proportion. Brick powder, a solid substance made up of minerals and aggregates, often has a higher density than PET, a substance made of plastic. More of the denser substance is integrated into the combination as the quantity of brick powder in the composite rises, raising the mixture's total density.

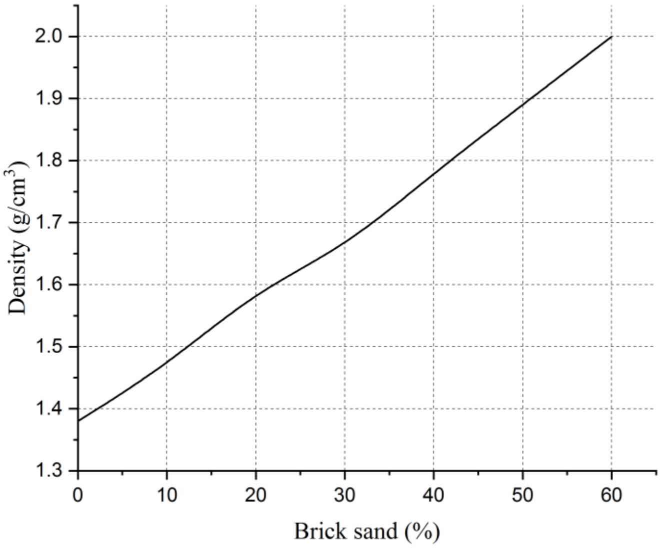


Figure 9. Effect of brick sand percentages on density

Table 8. Results of five samples' density

Samples	**C_0**	**C_1**	**C_2**	**C_3**	**C_4**
Density (g/cm^3)	1.38	1.66	1.72	1.78	1.84

2.3 Morphological results

The brick powder's emulsion with the polymer matrix can be directly observed thanks to Figure 10. This study enables knowledge of and partial comprehension of the phenomena causing subpar mechanical qualities. These depend on the thermomechanical past as well as the make-up of the mixtures and the methods used to apply them.

The level of aggregation of the reinforcements is reflected in the dispersion. In contrast, as illustrated in Figure 11, The sample's homogeneity is demonstrated by the distribution. The capacity to create manufacturing techniques that permit uniform placement of nano-reinforcements is one of the barriers to the development of nanocomposites [148]. Without adequate distribution and dispersion, one not only forfeits the benefit of the vast contact area provided by the nanoscale but also raises the possibility of aggregates, which function as defects and restrict the attributes of the materials.

Figures 10.C$_3$ and 10.C$_4$ show a more homogenous morphology and a definite improvement in the dispersion's quality. This improvement can be attributed to the mixture's higher interfacial adhesion when compared to the mixture in Figures 10.C$_1$ and 10.C$_2$. It is feasible to explain the mechanical results by pointing out micron-sized clusters that are responsible for the material's embrittlement.

However, the addition of brick particles has an impact on the melting point, crystallization point, and rate of crystallinity. However, it depends on the type of composites.

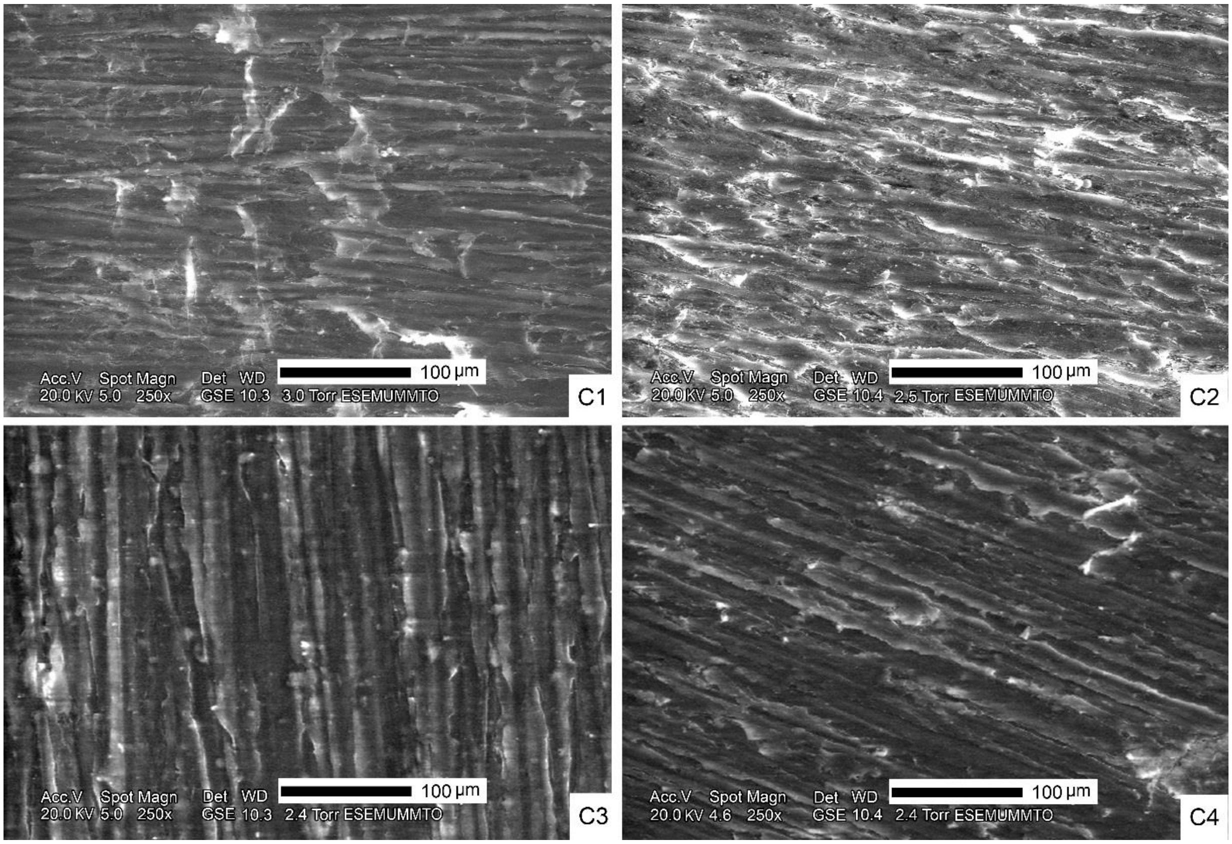
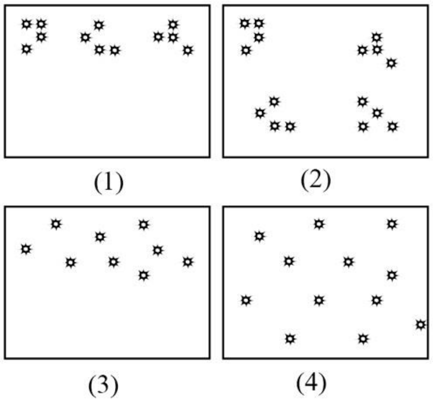


Figure 10. SEM pictures for various brick percentages (x250)



1: Bad dispersion and distribution.
2: Bad dispersion and good distribution.
3: Good dispersion and poor distribution.
4: Good dispersion and distribution.

Figure 11. Dispersion and distribution in composites [195]

According to the morphology shown in Figure 12, there are agglomerates larger than 10 microns, which are primarily present in sample C_4 and less so in C_3. The primary variable that must be managed while polymer matrix composites are being made is the degree of filler dispersion in the matrix. A material with a homogenous structure cannot be obtained when big clusters occur [149].

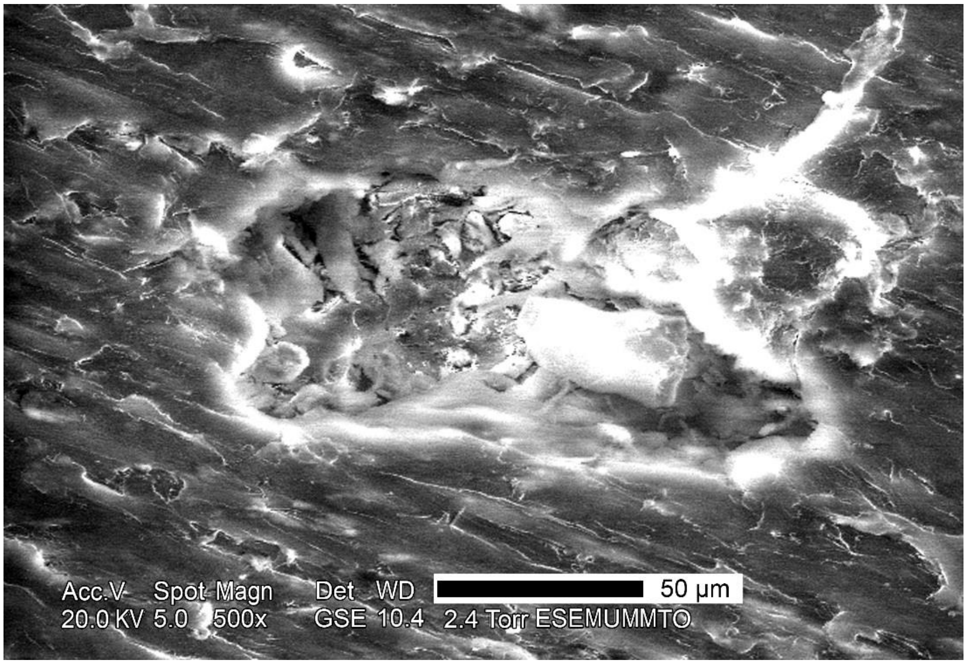


Figure 12. Brick powder misdistribution in a SEM picture (C4) (X 500)

3 NUMERICAL RESULTS

Numerical analyses serve the purpose of introducing the potential and evaluating the effectiveness of a novel masonry wall made from plastic bricks. These analyses aim to assess how this innovative construction method performs when subjected to both in-plane loading and in-plane-cyclic loading conditions.

3.1 In plane loading

The numerical results were compared between the masonry wall made of plastic bricks and the findings from a study by Kurdo F. et al., with a focus on the load-displacement relationships (figure 13). The findings showed consistency and a good agreement in terms of failure modes. It is interesting that the masonry wall constructed from plastic bricks has a lower horizontal load capacity than the masonry wall developed by Kurdo F. et al. For example, in Kurdo F. et al.'s investigation, the highest load for the masonry wall was 53.40 kilonewtons (KN), whereas the maximum load observed for the masonry wall using plastic bricks reached 39.10 KN [157].

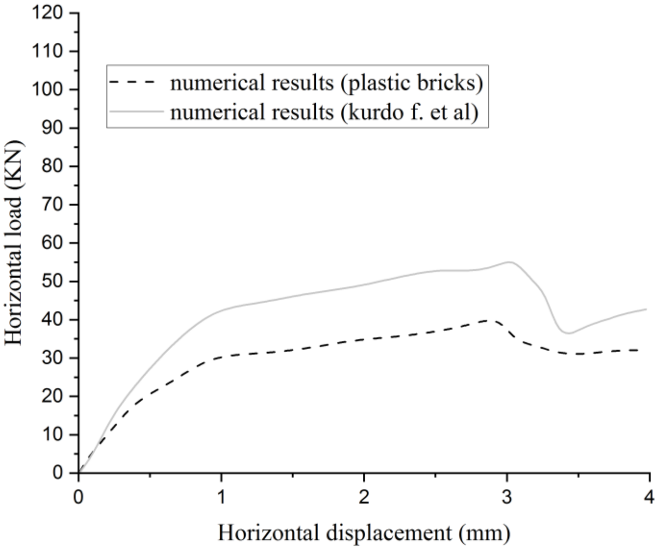


Figure 13. Horizontal load-displacement comparison

The term "STATUSXFEM" in Figure 14 indicates the elements' current state of cracking. A value of 1 denotes total element cracking, while a value of 0 denotes no cracking. Partial elemental cracking is represented by values between 0 and 1. Tensile cracks were started at the base of the wall during the early loading phase of the operation. These cracks subsequently led to the bottom toes being compressed under compression, the development of diagonal stepped cracks between masonry units, the masonry units' own cracking, and finally the masonry units' own cracking.

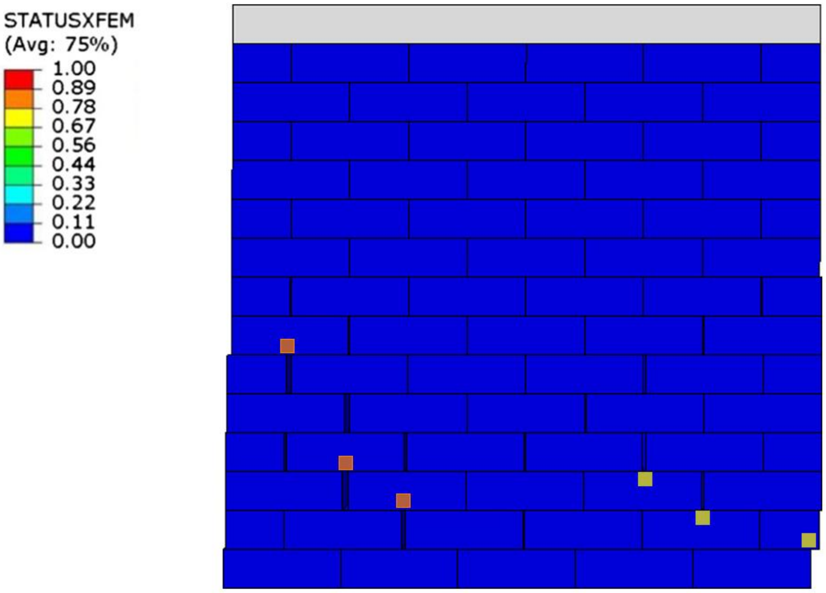
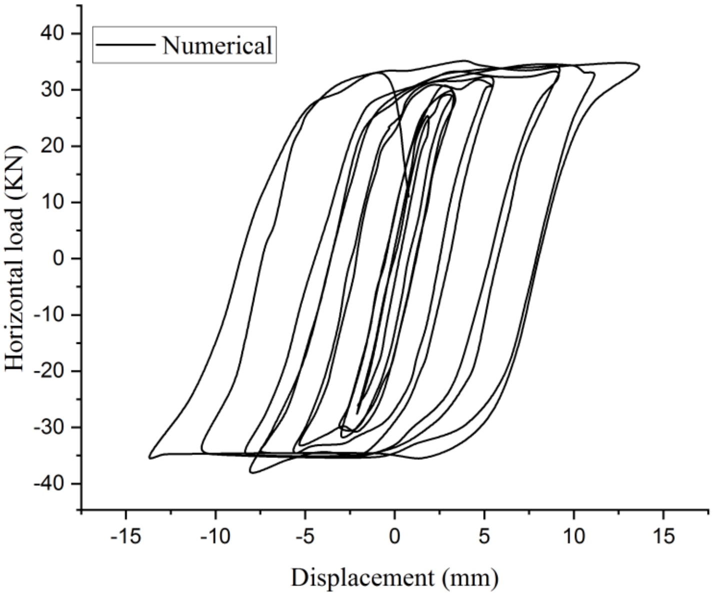


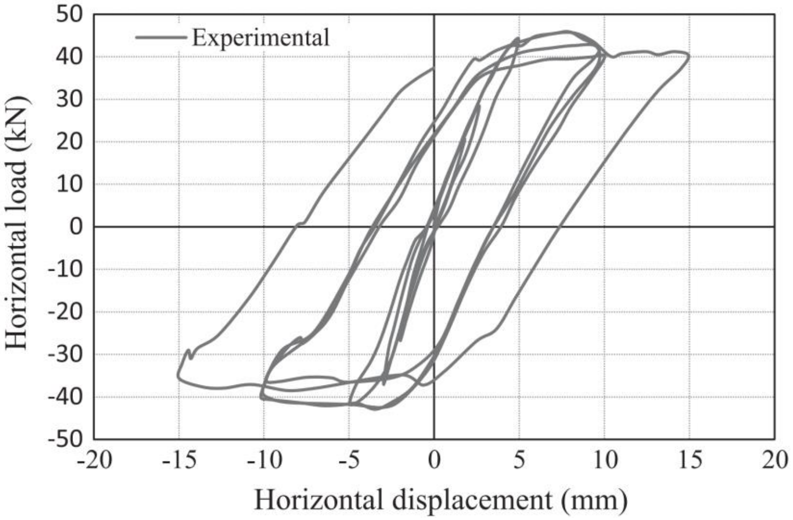
Figure 14. Masonry wall, failure pattern

3.2 In plane cyclic loading

The horizontal force-displacement relationship between the numerical findings and the experimental findings is satisfactorily aligned. It's crucial to remember, however, that the highest horizontal load achieved in the experiment, 45.53 kilonewtons (kN) (figure 15.b) [185], was significantly larger than the highest load observed in the theoretical model, 34.20 kN (figure 15.a). This finding shows that, in contrast to the experimental setting, the horizontal crack that traveled along the bottom masonry units happened earlier in the computational model. There were no cases of crushing under compression, and the main failure mode comprised the development of horizontal cracks along the first bottom joints. Vertical sildings occurred at the lower edges of the masonry wall (see figure 16) .



(a)



(b)

Figure 15. Comparison between numerical and experimental in plane cyclic loading

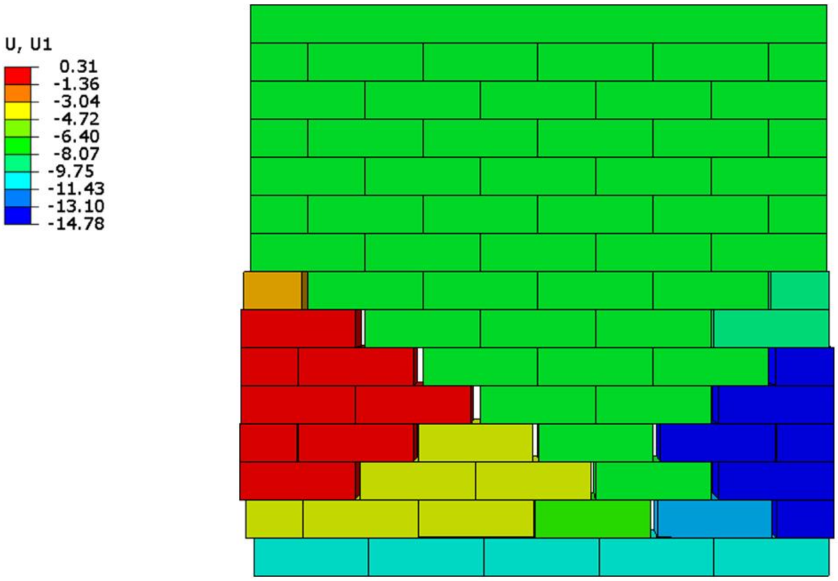


Figure 16. Masonry wall subjected to cyclic in-plane loading

4 CONCLUSION

Cost is the primary obstacle facing the composites business. Brick waste processing and polymer dispersion costs account for a sizable portion of the cost of brick-polymer composites. The general characteristics of polymers like PET are improved by adding fillers like brick powder. Particle size of the filler, which influences how the material behaves, can be used to explain the overall improvement in attributes. This study looked at how a PET mixture behaved when it was pushed by brick trash. The particle size analysis's size distribution diffractogram shows that the range of the particle size distribution is a few micrometers.

The thermogravimetric tests of PET after the addition of the brick powder demonstrated a higher degradation temperature when brick particles were present. The amount and degree of filler dispersion within the mixture have a significant impact on this improvement in thermal stability. Additionally, calorimetric study shows that the glass transition temperature of the combinations can be impacted by the presence of brick sand. When the brick particles were added, the tension at break and Young's modulus, both increased and the impact resistance was significantly reduced.

Brick sand particle dispersion within the matrix is visible using SEM. This study's goal was to evaluate the variables affecting materials' mechanical behavior. The stated results depend on the thermomechanical history as well as the mixture composition and implementation techniques. Conclusion: Recycled PET and leftover bricks can be used to create sustainable tiles or paving bricks.

This study uses a simplified micro-modeling method to simulate 3D masonry structures using a variety of constitutive models within the parameters of the finite element method. For analyzing load-displacement behavior and failure processes in brick wall units under in-plane loads and cyclic loads, the verified finite-element model offers a practical substitute for experimental setups. Units are placed in the specimens in a stretcher bond design. Units are represented as solids in the modeling technique, and mortar is grouped with the interface in the joints. Although the masonry wall manufactured from plastic bricks consistently exhibits lower horizontal load capacities in both in-plane loading and in-plane cyclic loading, the results of the masonry wall display favorable agreement with numerical and experimental investigations in both scenarios

GENERAL CONCLUSION

GENERAL CONCLUSION

With an annual production of over 350 million metric tons, plastics are now among the materials that are most commonly utilized worldwide. However, due to low recycling rates and careless disposal, plastics now make up a sizable component of municipal solid waste. Less than 10% of plastics are thought to be recycled, with the bulk ending up in landfills or the environment. Solutions for the circular economy are urgently needed in order to increase the recycling of plastics into valuable items and prevent the buildup of plastic trash.

The world's solid trash is produced by construction and demolition activities. Structures that use many resource-intensive traditional building materials, like baked clay bricks, cement, and concrete, use a lot of energy and emit many greenhouse gases. These environmental issues may be resolved by using recycled waste streams from other industries as replacements in construction materials.

The goal of this study was to create a sustainable composite material from two readily available waste streams: recycled brick powder and polyethylene terephthalate (PET) plastic trash. One of the most frequently used polymers is PET, which is used in textiles, packaging, and other single-use disposable items. Brick powder used as a filler is made from waste materials removed from construction sites and brick manufacturing facilities.

The thesis' main argument is that by combining these two recycled waste products, it is possible to create a composite material that has enough durability and mechanical strength for prospective uses in building construction. The composite fabrication is made to take advantage of the structural qualities of brick powder while also offering a new way to improve PET recycling.

An organized process of numerical modeling and experimental characterization was used to assess the PET-brick powder composite's applicability.

The effects of the brick powder content on the PET-brick powder composites' characteristics were examined through experimental research. The main conclusions are as follows:

- The sample containing 45% brick powder showed a significant 93.9°C increase in degradation temperature compared to unfilled PET, according to thermogravimetric examination of the composites. This suggests a notable enhancement in thermal stability.
- In the sample containing 30% brick powder, the tension at break rose from 24.51 MPa for the empty PET to 26.26 MPa. However, the increases in tensile strength tapered down with greater quantities of brick powder.
- Young's modulus rose gradually to 2.77 GPa as the weight percentage of brick powder grew from 0% to 30%. The increase in stiffness is explained by the rigid filler particles limiting the mobility of the polymer chain.
- When the filler amount increased from 0% to 45%, the impact resistance decreased from 15 kJ/m2 to 9.95 kJ/m^2. This is a result of poor adhesion and microcrack formation with larger brick powder loadings.
- Compressive strength increased as brick powder was increased from 0% to 30%, going from 15.28 MPa to 21.43 MPa. Then decreased to 16.2 MPa in the specimen C_4, The increased strength results from the brick particles' greater hardness when compared to the PET matrix.
- Flexural strength followed a similar pattern to the tensile properties; the maximum value of 8.51 MPa was attained at 30% brick powder percentage.
- The density of the composites grew consistently when more of the higher density brick powder was added, rising from 1.38 g/cm^3 to 1.84 g/cm^3.

The numerical analyses used finite element modeling to simulate brick wall systems constructed with the developed composite bricks under representative in-plane and cyclic loading conditions. The simulations effectively captured the structural responses and failure modes, which showed good agreement with past experimental studies on brick masonry walls. The results verified the load-bearing capability of the proposed PET-brick powder composite bricks.

The numerical modeling studies provided the following insights:

- Under both in-plane and cyclic loading situations, the brick wall model made from the composite bricks exhibited good agreement with the published experimental results.

- The maximum horizontal load capacity attained in the simulation was lower compared to conventional brick walls. This indicates reduced strength but adequate structural integrity.
- The process of fracture propagation was accurately captured by the failure patterns and evolution of damage, which matched experimental data well.

Based on extensive experimental and numerical work, it appears that a 30% by weight brick powder content is the optimum level for achieving significant gains in stiffness, strength, thermal stability, and compressive properties without significantly degrading the impact toughness or ductility. The manufactured PET-brick powder composite, which is made up of 30% brick powder derived from construction waste and 70% recycled PET plastic, has great potential for use in sustainable building construction.

The techniques described in this thesis for material manufacturing, experimental testing, and simulation analyses serve as a foundation for further practical research aimed at bringing this composite technology to the market. Additional research should assess the long-term durability using accelerated aging studies, assess the costs and viability of manufacturing scale-up, create automated processing technologies specifically designed for the composite, and conduct life cycle analyses. Expanding the applications beyond masonry bricks to include components like tiles, panels, and concrete can be aided by testing under more complicated loading scenarios. To calculate possible environmental effect reductions, the performance must also be contrasted with that of conventional clay and cement bricks. Nevertheless, by converting two problematically accumulating waste streams into a green building material, this thesis offers a significant leap in sustainability. The building industry can gain from the commercial use of the created composite while simultaneously addressing the worldwide issues of plastics pollution and excessive solid waste generation from demolition activities.

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