

Review

# The Use of Natural Minerals as Reinforcements in Mineral-Reinforced Polymers: A Review of Current Developments and Prospects

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**Abstract:** Natural minerals play a key role in the burgeoning field of mineral-reinforced polymers, providing an important element in strengthening and toughening the properties of composite materials. This article presents a comprehensive overview of the use of minerals in mineral-reinforced polymers, covering various aspects of their applications and impact on the final properties of these materials. The potential of various types of natural minerals (for example talc, montmorillonite, halloysite, diatomite) as reinforcements in mineral-reinforced polymers is discussed. Techniques for producing mineral-reinforced polymers using minerals, including the mixing method, impregnation, and coating application, are presented in detail. In addition, the effects of process parameters and component ratios on the final properties of mineral-reinforced polymers are discussed. The latest research on the use of minerals in mineral-reinforced polymers is also presented, including their effects on the strength, stiffness, resistance to environmental conditions, and biodegradation of the materials. Finally, the development prospects and potential applications of mineral-reinforced polymers with minerals in various industrial sectors, including packaging, automotive, construction, and medicine, are discussed.

**Keywords:** minerals; fillers; mineral-reinforced polymers; modification; epoxy resin; polymers; properties



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## 1. Introduction

In recent years, the public's environmental awareness has been growing and there is a growing need to find alternative, more sustainable solutions in the production of composite materials. One promising development in this field is mineral-reinforced polymers, which use natural minerals as reinforcers. These materials are a combination of biodegradable polymers with natural materials, such as silica, calcium carbonate, or starch. For example, the construction industry is increasingly using mineral-reinforced polymers based on slate as insulation materials for building thermal insulation. Slate has natural minerals that, when properly processed, become effective insulating materials with high mechanical strength and thermal insulation. In the automotive industry, mineral-reinforced polymers using cellulose fibers from plants such as hemp or flax as reinforcers are gaining popularity as an alternative to traditional composite materials. These natural fibers have high mechanical strength and lightweight properties, making them an attractive choice for the production of lightweight and durable car parts. In the packaging sector, starch-based mineral-reinforced polymers are gaining popularity as an alternative to single-use plastic packaging. Starch, as a natural polymer, can be reinforced with natural minerals, which allows the creation of biodegradable packaging with high mechanical strength and low environmental impact at the same time [1]. It is worth noting that mineral-reinforced polymers based on natural

minerals can also find applications in many other fields, such as the manufacture of furniture, hygiene products, or food packaging. Their growing popularity is due not only to their environmental benefits but also to their increasingly better mechanical and aesthetic properties, which allow them to be widely used in various industries [2].

Various types of polymers are produced in the industry, which usually form heterogeneous systems, where the polymers in the mixture are immiscible, or less commonly, homogeneous systems, where miscibility occurs at the molecular level, allowing for a stable mixture with very small, dispersed phase dimensions of less than 1 nm. In heterogeneous systems, the dispersed phase dimension is above 100 nm, and such mixtures are usually thermodynamically unstable. The stability of such a mixture can be achieved by modifying the polymers physically or chemically [3].

The physical modification of polymers involves altering their structure through orientation, nucleation, the formation of polymer complexes, and the degree of dispersion, as well as changes in the supramolecular structure of phases, the size of interfacial zones, and inter-particle interactions at the interface, achieved by adding compatibilizers or through surface modification. Chemical modification, involving processes such as copolymerization, the exchange of functional groups, and crosslinking, can lead to changes in parameters such as melt index, impact strength, elastic modulus, and others [4]. The addition of active functionalized or grafted polymers can provoke a product with desired physicochemical and mechanical properties, good compatibility, and optimal surface properties [5].

Fillers, as active additives with particle sizes from 0.01 to 1  $\mu\text{m}$  or passive additives with particle sizes from 1 to 50  $\mu\text{m}$ , are added to polymers to reduce production costs, improve mechanical properties or impart special properties to plastics. Fillers should be chemically inert to the matrix, well dispersed, and exhibit good adhesion to the polymer. Mineral fillers, such as quartz, silica, dolomite, or kaolin, meet these requirements. However, it is necessary to modify their surface properties to improve dispersion in the polymer and adhesion. The introduction of a compatibilizer can also improve filler/polymer miscibility and initiate reactions between them [6].

Natural mineral-reinforced polymers are an innovative class of composite materials that are becoming increasingly important in various industrial sectors. They are composed of a polymer matrix, which can be of synthetic or natural origin, and are reinforced in the form of natural minerals such as kaolin, talc, mica, calcium carbonate, or bentonite. Natural mineral-reinforced polymers are composites in which natural minerals serve as reinforcements, improving the mechanical and thermal properties of the polymer matrix [7]. On this basis, they can be divided into:

- ✓ *Thermoplastic matrix composites*: contain thermoplastic polymers as the matrix, which can be repeatedly processed under heat.
- ✓ *Composites with thermoset matrix*: contain thermosetting polymers that cannot be reprocessed after curing [8].

Natural mineral-reinforced polymers have a number of unique properties that make them attractive materials for a variety of applications. Key properties of these composites include:

- ✓ *Improved mechanical strength*: the addition of natural minerals improves the tensile, compressive and flexural strength of polymers [9].
- ✓ *Increased stiffness*: natural minerals increase the stiffness of composites, which is particularly important in structural applications [9].
- ✓ *Thermal stability*: natural minerals, such as talc or mica, improve the thermal stability of polymers, allowing them to be used at higher temperatures [10].
- ✓ *Flame retardancy*: some natural minerals, such as calcium carbonate, can act as flame retardants, reducing the flammability of polymers [10].
- ✓ *Barrier properties*: the addition of minerals can improve the barrier properties of polymers against gases and liquids, which is beneficial in packaging applications [11].
- ✓ *Cost-effectiveness*: natural minerals are often cheaper than other types of reinforcements, reducing the cost of composite production [11].

Thanks to their unique properties, natural mineral-reinforced polymers are widely used in various fields, including the production of automotive parts such as bumpers, dashboards, and interior components. They are used as structural, insulating, and finishing materials. They are used to produce packaging with improved barrier properties. They are used for the manufacture of housings and other electronic components where greater thermal and mechanical stability is required. They are used to produce lightweight but durable furniture components [12].

Natural mineral-reinforced polymers are advanced composite materials that combine the properties of polymers with the advantages of natural minerals. Thanks to their unique mechanical, thermal, and economic properties, they are an attractive alternative to traditional composites, finding wide application in many industrial sectors. Their development and application contribute to more efficient and sustainable technological solutions [13–15].

Modification with natural minerals can significantly improve the properties of various groups of polymers, adapting them to specific applications and industrial requirements. Figure 1 shows the key groups of polymers that can be reinforced with natural minerals, along with their characteristics and typical minerals used for this purpose [16–18].

Thermoplastic polymers	Thermosetting polymers	Elastomeric polymers	Functional and engineering polymers
<ul style="list-style-type: none"> <li>• polypropylene (PP)</li> <li>• polyethylene (PE)</li> <li>• polycarbonate (PC)</li> </ul>	<ul style="list-style-type: none"> <li>• epoxides</li> <li>• phenolic resins</li> </ul>	<ul style="list-style-type: none"> <li>• polyurethanes (PU)</li> <li>• polyvinyl chloride (PVC)</li> </ul>	<ul style="list-style-type: none"> <li>• polyamides (PA)</li> <li>• polyetheretherketone (PEEK)</li> </ul>

**Figure 1.** Groups of polymers modified with natural minerals (own elaboration).

Polypropylene reinforced with minerals such as talc, calcium carbonate, or mica gains exhibit stiffness, thermal stability, and resistance to deformation. These minerals improve mechanical properties and reduce production costs. Polyethylene reinforced with calcium carbonate or other minerals such as talc can increase the stiffness and dimensional stability of the material. Calcium carbonate is often used because of its cost-effectiveness and availability. Polycarbonate reinforced with silica or kaolin improves its mechanical strength and impact resistance. These minerals also improve the thermal stability and insulating properties of polycarbonate [19–21].

Epoxides reinforced with minerals such as talc, mica, or mine-rock fillers offer better chemical resistance and improved mechanical strength. These minerals can also increase thermal resistance and reduce shrinkage during curing. Reinforcing phenolic resins with minerals such as calcium carbonate or mica can improve their heat resistance and chemical resistance. These minerals also increase the dimensional stability and mechanical properties of the materials [22–25].

Polyurethanes reinforced with minerals such as silica, bentonite, or calcium carbonate offer improved abrasion resistance, thermal stability, and resistance to moisture and chemicals. These minerals increase the hardness and stiffness of polyurethane elastomers. Polyvinyl chloride reinforced with minerals, such as calcium carbonate or talc, can increase its stiffness, improve barrier properties, and reduce production costs. These minerals also affect dimensional stability and chemical resistance [26–29].

Polyamides reinforced with mica, silica, or other minerals can offer improved mechanical strength and thermal stability. These minerals also improve heat and abrasion resistance. Polymers such as PEEK reinforced with minerals such as mica or calcium carbonate have improved mechanical properties and thermal stability. Mineral reinforcements can also improve chemical resistance and increase the durability of materials [30–33].

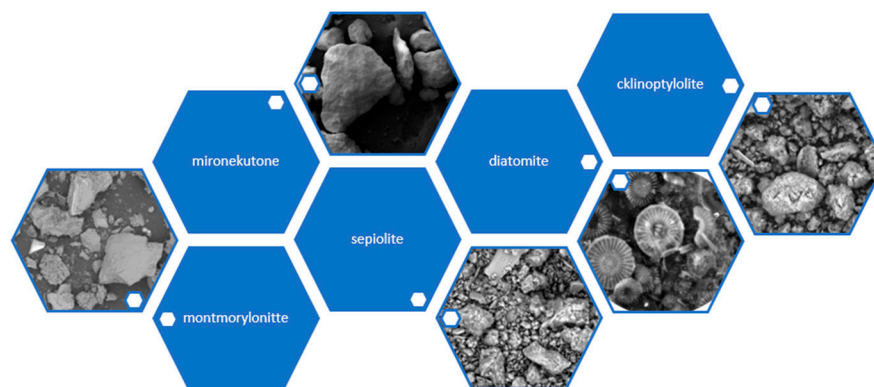
The modification of polymers with natural minerals makes it possible to tailor their properties to the specific requirements of various industrial applications. Reinforcing such groups of polymers as thermoplastics, thermosets, elastomers, and engineering polymers with minerals makes it possible to obtain materials with better mechanical, thermal,

and chemical properties. Adapting the properties of polymers with the help of minerals contributes to their wider application and effectiveness in various industrial fields [34,35].

Among the various powder fillers, silicates are an important grouping. Their advantages are the ability to interact with organic matter, despite their hydrophilic nature, and the possibility of separating the packets that form them into nanometer-thick layers. Layered silicates are characterized by a specific structure, in which tetrahedral and octahedral layers are, respectively, connected. Depending on the arrangement of these layers, we distinguish different types of silicates, for example, with three-layer packets of the 2:1 type or two-layer packets of the 1:1 type. The presented silicates differ from each other in both structure and properties [36].

Bentonite and montmorillonite belong to the group of layered aluminosilicates. Their structure is based on three-layer packets, between which there are only van der Waals interactions. Kaolinite, on the other hand, is an example of a bilayer silicate, in which the layers interact via hydrogen bonds. Halloysite, which is also a material from the group of bilayer silicates, is characterized by a layered tube structure that is important for its role as a component enhancing insulation in insulating mats [36,37].

There are many different types of natural minerals that find applications as fillers in plastics (Figure 2).



**Figure 2.** Examples of some natural plastic fillers (own study).

Mineral-reinforced polymers offer a number of important benefits. First, the use of natural minerals as fillers reduces the need for petrochemical raw materials, which contributes to reducing carbon dioxide and other greenhouse gas emissions. Biodegradable polymers, a component of mineral-reinforced polymers, naturally decompose, which reduces the amount of waste going to landfills and reduces environmental pollution. The use of agricultural waste, such as hemp or flax stalks, as raw materials for mineral-reinforced polymers contributes to the added value of these materials and promotes a closed-loop economy. In addition, the production of mineral-reinforced polymers often requires less energy compared to traditional composite materials, resulting in the lower consumption of natural resources and a lower carbon footprint [38–40].

Despite numerous studies and advances in the field of mineral-reinforced polymers, there are still many unknowns regarding the optimal methods for producing and modifying these materials. In particular, there is a lack of comprehensive comparative analyses of different types of natural minerals as fillers and their effects on the mechanical and functional properties of mineral-reinforced polymers. In addition, there is a need for a more detailed understanding of the interactions between polymers and natural minerals, which will allow better the design of materials with desired properties [38–40].

The purpose of this review is:

- To present the current status of research and development of mineral-reinforced polymers based on natural minerals;
- To analyze the available minerals, their mechanical properties, and potential applications in various fields;

- To discuss methods of production and characterization of these materials and the challenges associated with them;
- To identify promising research directions that can contribute to the further development of more sustainable and environmentally friendly composite materials.

## 2. Thermoplastic Polymers

Thermoplastic polymers are materials that become plastic when heated, allowing them to be molded and processed. When cooled, they regain their mechanical properties. Adding natural minerals to thermoplastic polymers can significantly affect their properties, such as mechanical strength, thermal conductivity, flammability, and abrasion resistance. This process is known as compositing, and the added minerals act as fillers [41–43].

There are numerous benefits to adding natural minerals to thermoplastic polymers. First and foremost, it improves their mechanical properties. Minerals such as talc, calcium carbonate, and silica can increase tensile, compressive, and flexural strengths. In addition, the presence of minerals usually increases the elastic modulus of polymers, making them stiffer [41–43].

Another advantage of adding minerals to polymers is to reduce production costs, since mineral fillers are usually cheaper than base polymers. This makes the production process more economical. In addition, minerals can improve the thermal properties of polymers. Minerals such as aluminosilicates or graphite can improve the thermal conductivity of polymers, which is beneficial in applications requiring heat dissipation [41–43].

The addition of natural minerals can also increase the fire resistance of polymers. Minerals such as hydroxyapatite, aluminum hydroxide, or magnesium carbonate can act as fire retardants, improving the flame resistance of polymers. In addition, the addition of minerals can reduce polymer shrinkage during processing, which is beneficial in precision engineering applications [41–43].

Examples of the use of thermoplastic polymers with mineral fillers can be found in various industries. In the automotive industry, polymer composites with mineral fillers are used for vehicle interiors, bumpers, or engine covers. In the construction industry, pipes, profiles, panels, and thermal and acoustic insulation are often made from mineral-filled polymers. In electronics, electronic device housings use composites, which require appropriate thermal and mechanical properties [41–43].

By using natural minerals, thermoplastic polymers can be significantly improved, opening up new possibilities in a variety of industrial and consumer applications [41–43].

### 2.1. Polypropylene (PP)

Polypropylene (PP) is one of the most widely used thermoplastic polymers in industry due to its versatility, low production costs, and chemical resistance. Fortifying PP with natural minerals improves its properties, allowing its use in a wide range of fields. The following is a detailed analysis of the three main minerals used as fillers in PP: talc, calcium carbonate, and mica.

#### 2.1.1. Talc

In recent years, polypropylene (PP) has gained popularity as a material used in various industries due to its favorable mechanical properties, low weight, and relatively low production costs. However, in its pure form, PP may not meet all application requirements, especially where higher strength and thermal stability are needed. The addition of fillers, such as talc, can significantly improve these properties. Chen and colleagues [44] conducted a study to investigate the effects of different talc contents on the mechanical and thermal properties of polypropylene composites. PP composites with talc were prepared by extrusion in a twin-screw extruder. Three different talc contents were used: 10%, 20% and 30% by weight. Then, the prepared mixes were processed by injection molding to produce test samples.

Tensile tests were carried out, using a universal testing machine. The maximum tensile force and modulus of elasticity were measured. Melting point and other thermal properties were tested using differential scanning calorimetry (DSC). The samples were heated from room temperature to 200 °C at a rate of 10 °C/min and then cooled under the same conditions. The internal structure of the composites, including the dispersion of talc particles in the PP matrix, was analyzed using a scanning electron microscope (SEM) [44].

The results of the tensile tests showed that the addition of talc significantly affects the mechanical properties of PP composites. At 20% by weight of talc addition, the tensile strength increased by 25%, and the elastic modulus increased by 50% compared to pure PP. Higher talc contents (30%) showed a slight decrease in these values, suggesting that the optimal talc content is around 20%. Melting points of PP composites with talc addition were higher than those of pure PP. At 20% by weight of talc addition, the melting point increased by 5 °C. In addition, talc affected the crystallinity of PP, resulting in the better thermal stability of the composite. SEM observations showed a uniform dispersion of talc particles in the PP matrix, which is key to achieving better mechanical and thermal properties [44].

Research by Stamhuis and colleagues indicates that the addition of talc to polypropylene significantly improves its mechanical and thermal properties. The best results were obtained at 20 percent by weight of talc addition, suggesting that this is the optimal content for improving the tensile strength and elastic modulus and thermal stability of PP. The addition of talc increases the melting point of the composite and improves its thermal stability, making it more suitable for applications requiring higher mechanical strength and thermic stability. These findings point to the potential use of PP/talc composites in various industries where higher strength and stability of the material are required [44].

The particle size of mineral fillers, such as talc, can have a significant impact on the properties of polymer composites. Understanding the effect of talc particle size on the mechanical properties of polypropylene (PP) is crucial to optimize production processes and obtain materials with desired properties. Guo and colleagues [45] conducted a study to investigate how different talc particle sizes affect the mechanical properties of PP/talc composites.

PP composites with talc were prepared by extrusion in a twin-slide-machine extruder. Talc of different particle sizes was used, including fine particles (diameter less than 10 µm) and coarser particles (diameter greater than 10 µm). Subsequently, the prepared mixtures were processed by injection molding to obtain test specimens [45].

Maximum tensile force and elastic modulus were measured. The energy required to fracture the specimen was measured. The internal structure of the composites, including the dispersion of talc particles in the PP matrix, was analyzed using a scanning electron microscope (SEM) [45].

The results of tensile strength tests showed that composites containing fine talc particles (less than 10 µm in diameter) exhibited 30% higher tensile strength compared to composites with coarser particles. This is due to the better dispersion of the smaller particles in the polymer matrix, leading to more uniform stress distribution in the material. Izod impact tests showed that composites with fine talc particles had 20% higher impact strength than those with coarser particles. The better dispersion of smaller talc particles in the PP matrix increases the material's ability to absorb impact energy. SEM observations confirmed that the finer talc particles were more uniformly dispersed in the PP matrix than the coarser particles. The better dispersion of the smaller particles led to a more homogeneous structure of the composite, which helped improve its mechanical properties [45].

A study by Castillo and colleagues showed that talc particle size has a significant effect on the mechanical properties of PP/talc composites. Composites with fine talc particles (diameter less than 10 µm) showed significantly higher mechanical properties, including 30% higher tensile strength and 20% higher impact strength, compared to composites with coarser particles. The better dispersion of smaller particles in the polymer matrix led to more uniform stress distribution and increased ability to absorb impact energy. The study's

conclusions suggest that the use of finer talc particles may be beneficial for improving the mechanical properties of PP/talc composites, making them more suitable for applications requiring high strength and impact resistance [45].

The surface modification of mineral fillers, such as talc, is one of the techniques used to improve their compatibility with the polymer matrix. Zihlif and coworkers [46] conducted a study on the effects of talc surface modification on the mechanical and thermal properties of polypropylene (PP) composites. The goal was to determine how changes in the filler surface could affect the interactions between talc and the polymer matrix and the final properties of the composite.

PP composites with modified talc were prepared by extrusion in a twin-screw extruder. The modification of the talc surface was carried out using appropriate chemicals that increased the adhesion between the filler and the polymer matrix. Then, the prepared mixtures were molded by injection molding to obtain test samples [46].

Flexural strength tests were conducted using a universal testing machine. The maximum bending force and modulus of elasticity were measured. Melting point and other thermal properties were tested using differential scanning calorimetry (DSC). The samples were heated from room temperature to 200 °C at a rate of 10 °C/min and were then cooled under the same conditions. The internal structure of the composites, including the dispersion of talc particles in the PP matrix, was analyzed by scanning electron microscopy (SEM) [46].

The results of flexural strength tests showed that composites with modified talc had 40% higher flexural strength and 35% higher elastic modulus compared to composites with unmodified talc. The addition of modified talc to PP resulted in a 7 °C increase in the melting point of the composite. SEM observations showed that the modified talc was more uniformly dispersed in the PP matrix, which improved adhesion between the filler and matrix [46].

A study by Huang and colleagues showed that talc surface modification significantly improves the mechanical and thermal properties of PP composites. Modified talc increases the adhesion between the polymer matrix and filler, resulting in higher flexural strength and modulus, and a higher melting point. The conclusions of the study suggest that talc surface modification can be an effective method for improving the properties of polypropylene composites [46].

The crystallization process of polymers is crucial to their mechanical and thermal properties. The addition of mineral fillers, such as talc, can affect the rate and degree of crystallization of polypropylene (PP). Wang and colleagues [47] conducted a study to investigate the effect of talc on the crystallization process of PP and its mechanical properties.

PP composites with talc additive were prepared by extrusion in a twin-slide-machine extruder. Composites containing 20% by weight of talc additive were used for testing. Then, the prepared composites were molded by injection molding to obtain test specimens [47].

The crystallization process was studied using differential scanning calorimetry (DSC). The samples were heated from room temperature to 200 °C at a rate of 10 °C/min, and then cooled under the same conditions. The internal structure of the composites, including the dispersion of talc particles in the PP matrix, was analyzed using a scanning electron microscope (SEM) [47].

DSC results showed that the addition of talc accelerates the PP crystallization process. The pro-cent content of crystallites increased by 15% with 20% by weight of talc addition. The increased crystallinity of PP composites with talc addition translated into a 45% increase in elastic modulus compared to pure PP. SEM observations confirmed that talc as a nucleant affected the crystalline structure of PP, resulting in a more homogeneous and compact composite structure [47].

Studies by Velasco and colleagues have shown that talc significantly affects the crystallization process of polypropylene, leading to an improvement in its mechanical properties. The addition of talc accelerates the crystallization of PP, increasing the percentage of crystallites and the elastic modulus of the composite. The findings suggest that talc can be

effectively used as a nucleant to improve the crystalline and mechanical properties of PP, making PP/talc composites more usable for applications requiring high mechanical strength [47].

Oliveira and colleagues [43] conducted a study to understand the effects of various forms of talc (in microsphere and nanoparticle forms) on the mechanical and thermal properties of polypropylene composites. The study was aimed at evaluating the effectiveness of various forms of talc in improving the properties of the composites.

PP composites were prepared using talc in microsphere and nanoparticle forms. These blends were extruded in a twin-screw extruder and then injection molded to obtain test samples. Tensile force and maximum bending force were measured. Melting point and other thermal properties were studied by DSC. The dispersion of talc particles in the PP matrix was analyzed by SEM [43].

Composites with nanoparticulate talc showed better mechanical properties compared to those with microspherical talc. Tensile strength increased by 35% and flexural strength increased by 30%. The melting points of composites with nanoparticle talc were 6 °C higher compared to those with microsphere talc. Talc nanoparticles were better dispersed in the PP matrix, which contributed to better mechanical properties [43].

A study by de Oliveira et al. showed that talc in nanoparticle form can improve the mechanical and thermal properties of PP composites more effectively than talc in microsphere form. The better dispersion of nanoparticles in the polymer matrix contributes to the better strength and thermal stability of the composites [43].

Tsiptsias and colleagues [48] studied the effects of different talc functionalization methods on the mechanical properties and crystallization process of polypropylene composites. The goal was to evaluate how different functionalization methods affect the properties of the composites.

Talc was functionalized with different chemical reactants and introduced into PP at different concentrations. The composites were prepared by extrusion and injection molded. The crystallization process was studied using DSC. Tensile and flexural strength tests were carried out in accordance with ASTM standards. The dispersion of functionalized talc particles was studied by SEM [48].

Talc functionalization increased the crystallization rate of PP, and the content of crystallites increased by 20% compared to samples with non-functionalized talc. Composites with functionalized talc showed an improvement in tensile strength by 25% and flexural strength by 20%. The functionalized talc was better dispersed in the PP matrix, which improved the mechanical properties of the composites [48].

A study by Tsiptsias et al. showed that talc functionalization can significantly improve the mechanical properties and crystallization of PP composites. Better dispersion and interaction between the functionalized talc and the polymer matrix lead to the improvement of both the mechanical and structural properties of the composites [48].

Lapcik and colleagues [49] investigated the effect of talc mixed with various other fillers on the properties of PP composites. The goal was to determine the synergies between talc and other fillers and their effects on the mechanical and thermal properties of the composites.

PP composites were prepared with talc and other fillers, such as calcium carbonate and mica, in various proportions. A two-slide-machine extrusion method and injection molding were used. Tensile, bending, and impact strength tests were conducted. The melting point and other thermal properties were studied by DSC. The dispersion of fillers in the PP matrix was analyzed by SEM [49].

Composites containing talc in combination with other fillers showed better mechanical properties compared to composites with a single filler. Tensile strength increased by 40% compared to PP without fillers. The melting point of the composites increased by 8 °C, suggesting better thermal stability. The fillers were well dispersed, which contributed to the improved properties of the composites [49].



A study by Lapcik et al. showed that mixing talc with other fillers can significantly improve the mechanical and thermal properties of PP composites. Synergy between different fillers leads to the better dispersion and increased properties of the composites, making them more versatile for various applications [49].

### 2.1.2. Calcium Carbonate

Yao and colleagues [50] conducted a comprehensive study to evaluate the impact of different forms of calcium carbonate ( $\text{CaCO}_3$ ) on the mechanical and thermal properties of polypropylene (PP) composites. The primary aim was to understand how variations in the form and particle size of  $\text{CaCO}_3$  influence the overall properties of the composites.

The researchers prepared PP composites with two distinct forms of  $\text{CaCO}_3$ —microspherical and nanoscale particles. These composites were produced using a twin-screw extruder, a method that ensures thorough mixing and dispersion of filler materials within the polymer matrix. The resulting mixtures were then molded into test specimens using injection molding, a common technique for creating consistent and uniform test samples [50].

The mechanical properties of the composites were assessed through tensile and flexural tests. These tests measured the maximum tensile strength (the maximum stress the material can withstand while being stretched) and flexural strength (the maximum stress the material can endure while being bent). The thermal properties, including the melting temperature and other significant thermal characteristics, were analyzed using differential scanning calorimetry (DSC). DSC is a crucial technique in materials science for determining the thermal transitions of a material, such as melting points and crystallization temperatures. To investigate the dispersion of  $\text{CaCO}_3$  particles within the PP matrix, the researchers employed scanning electron microscopy (SEM). SEM provides detailed images of the sample's surface, allowing for a thorough examination of particle distribution and the quality of dispersion within the composite material [50].

The findings revealed that PP composites reinforced with nanoscale  $\text{CaCO}_3$  exhibited superior mechanical properties compared to those containing microspherical  $\text{CaCO}_3$ . The tensile strength of the nanocomposite increased by 30% compared to the microspherical composite. The flexural strength saw an improvement of 25%. The melting temperature of the nanocomposite was 5 °C higher than that of the microspherical composite, indicating enhanced thermal stability. The superior performance of the nanocomposite was attributed to the better dispersion of nanoscale  $\text{CaCO}_3$  particles within the PP matrix. SEM analysis confirmed that the nanoclay particles were more uniformly distributed, which contributed to the enhanced mechanical and thermal properties [50].

The study by Yao et al. demonstrated that using nanoscale  $\text{CaCO}_3$  as a filler in PP composites significantly improves both mechanical and thermal properties compared to using microspherical  $\text{CaCO}_3$ . The improved dispersion of nanoscale particles in the polymer matrix plays a crucial role in these enhancements, leading to stronger, more thermally stable composites. These findings highlight the potential of nanotechnology in developing advanced composite materials with superior performance for various applications. The insights from this study can guide future research and industrial practices in the field of composite material engineering [50].

Kłodziński and colleagues [51] investigated the impact of varying concentrations of calcium carbonate ( $\text{CaCO}_3$ ) on the crystallization process and mechanical properties of polypropylene (PP) composites. The study aimed to evaluate how different amounts of  $\text{CaCO}_3$  affect the crystalline structure and mechanical characteristics of these composites.

In this study, PP composites were prepared with different weight concentrations of  $\text{CaCO}_3$ , ranging from 5% to 30%. The preparation involved using a twin-screw extruder to ensure thorough mixing of the filler with the polymer matrix, followed by injection molding to create test specimens [51].

The crystallization process of the composites was analyzed using differential scanning calorimetry (DSC). DSC measurements focused on determining the melting temperature

and crystallization time of the composites, which provide insights into the crystalline structure and thermal properties [51].

The mechanical properties of the composites were evaluated through tensile and flexural tests. These tests measured the maximum tensile strength and flexural strength of the composites, which are critical for understanding their mechanical performance. To assess the distribution of  $\text{CaCO}_3$  particles within the PP matrix, scanning electron microscopy (SEM) was used. SEM provided detailed images of the composite's surface, allowing for an evaluation of particle dispersion and the overall structural integrity of the composites [51].

The addition of  $\text{CaCO}_3$  accelerated the crystallization process of PP. Specifically, increasing the  $\text{CaCO}_3$  content by 20% resulted in an 18% increase in the percentage of crystalline content. Higher  $\text{CaCO}_3$  concentrations improved the tensile and flexural strengths of the composites. Notably, tensile strength increased by 28% and flexural strength by 22% with higher  $\text{CaCO}_3$  content. SEM analysis showed that  $\text{CaCO}_3$  was uniformly dispersed within the PP matrix, which contributed to the enhanced structural properties of the composites [51].

The study conducted by Kłodziński et al. demonstrated that incorporating varying concentrations of calcium carbonate positively influences the crystallization process and mechanical properties of PP composites. The acceleration of crystallization and improvement in mechanical strength are beneficial for applications requiring high structural stability. The uniform distribution of  $\text{CaCO}_3$  in the polymer matrix plays a crucial role in enhancing the overall performance of the composites [51].

Dai and colleagues [52] conducted a study to investigate the effects of surface modification of calcium carbonate ( $\text{CaCO}_3$ ) on the properties of polypropylene (PP) composites. The research aimed to evaluate how modifying the surface of  $\text{CaCO}_3$  influences its dispersion within the polymer matrix and the resultant properties of the composites.

The study involved the surface modification of  $\text{CaCO}_3$  using various chemical reagents. The PP composites were produced using a twin-screw extruder, which facilitated thorough blending of the modified  $\text{CaCO}_3$  with the polymer matrix. The extruded composites were then shaped into test specimens using injection molding, a technique that ensures uniform distribution and consistency in the samples [52].

Tensile strength, quantifies the maximum amount of stress that a material can endure while being subjected to stretching or pulling forces. During this test, a sample is placed in a tensile testing machine where it is gradually stretched until it breaks. The tensile strength is determined by recording the maximum force the material can withstand before fracture. This property is crucial for understanding the material's performance in applications where it will be under tensile loads, such as in structural components or components exposed to stretching forces [52].

Flexural strength, assesses the maximum stress a material can endure when subjected to bending forces. In this test, a sample is placed on two supports and subjected to a load applied at its center or along its length. The material's ability to resist bending without failing is measured by the maximum force it can withstand before breaking. This property is essential for evaluating materials used in applications where they will experience bending or flexural stresses, such as in beams, plates, or other structural elements [52].

Impact toughness, measures a material's ability to absorb energy and resist sudden impacts or shocks without fracturing. In this test, a sample is struck by a pendulum or other impactor under controlled conditions, and the energy absorbed by the material before failure is recorded. This property is vital for understanding how materials will perform under sudden or high-impact conditions, such as in packaging materials, safety equipment, or structural components exposed to impact forces.

Each of these mechanical properties—tensile strength, flexural strength, and impact toughness—provides critical insights into the material's performance under different types of mechanical stress, helping to ensure that materials meet the required performance standards for their intended applications [52].

The thermal properties, including the melting temperature and other thermal characteristics, were analyzed using differential scanning calorimetry (DSC). DSC is used to measure the thermal transitions of materials, providing insights into their stability and behavior under heat. The dispersion of the surface-modified  $\text{CaCO}_3$  within the PP matrix was examined using scanning electron microscopy (SEM). SEM allowed for detailed observation of the particle distribution and the quality of dispersion within the composite material [52].

The study revealed that the incorporation of surface-modified calcium carbonate ( $\text{CaCO}_3$ ) into polypropylene (PP) composites significantly enhanced their mechanical properties compared to composites containing unmodified  $\text{CaCO}_3$ . Specifically, the tensile strength of the composites increased by 32% with the use of surface-modified  $\text{CaCO}_3$ . This improvement indicates that the modified  $\text{CaCO}_3$  contributes to a greater ability of the material to withstand stretching forces before breaking. Additionally, the flexural strength of the composites was enhanced by 27%. This means that the modified  $\text{CaCO}_3$  allows the material to endure higher stress when bent, thus improving its resistance to bending forces [52].

The thermal analysis showed that the melting temperature of the composites containing surface-modified  $\text{CaCO}_3$  was elevated by 8 °C compared to those with unmodified  $\text{CaCO}_3$ . This increase in melting temperature signifies that the thermal stability of the composites has been enhanced. The ability of the material to withstand higher temperatures before melting suggests improved performance in applications that involve exposure to heat [52].

The surface modification of  $\text{CaCO}_3$  resulted in a more effective dispersion of the filler within the polypropylene matrix. This improvement in dispersion led to a more homogeneous composite structure. The uniform distribution of the surface-modified  $\text{CaCO}_3$  within the polymer matrix is crucial as it contributes to the overall performance and consistency of the composite material. Better dispersion ensures that the mechanical and thermal benefits of the filler are more evenly distributed throughout the composite, leading to enhanced material properties [52].

The study by Dai et al. demonstrated that the surface modification of calcium carbonate significantly enhances the mechanical and thermal properties of polypropylene composites. The improved dispersion of the modified  $\text{CaCO}_3$  in the polymer matrix leads to increased tensile and flexural strength, as well as better thermal stability [52].

Meng and colleagues [53] conducted a comprehensive study to investigate the effects of varying concentrations of calcium carbonate ( $\text{CaCO}_3$ ) on the crystallization process and mechanical properties of polypropylene (PP) composites. The objective of the research was to understand how different levels of  $\text{CaCO}_3$  influence both the crystallization behavior and the resulting mechanical performance of the composites.

In this study, polypropylene (PP) composites were prepared with varying concentrations of calcium carbonate, ranging from 10% to 30% by weight. The PP and  $\text{CaCO}_3$  mixtures were processed using a twin-screw extruder. This method ensures the thorough mixing and dispersion of the filler within the polymer matrix, which is crucial for achieving consistent composite properties. The extruded materials were then shaped into test specimens using injection molding. This technique provides uniform samples for further testing and analysis [53].

The crystallization behavior of the composites was analyzed using differential scanning calorimetry (DSC). DSC is a thermal analysis technique used to measure the thermal transitions of materials, including crystallization and melting temperatures [53].

In this study, differential scanning calorimetry (DSC) was employed to analyze key aspects of the crystallization and thermal behavior of the polypropylene (PP) composites. DSC was used to measure the percentage of crystalline content within the composites as a function of the calcium carbonate ( $\text{CaCO}_3$ ) concentration. By monitoring the heat flow associated with the crystallization process, DSC allowed the researchers to determine how the amount of  $\text{CaCO}_3$  affected the degree of crystallinity in the PP matrix. This

information is crucial for understanding how different  $\text{CaCO}_3$  concentrations influence the formation and growth of crystalline regions within the polymer. DSC was also utilized to identify the melting temperature of the composites. This is the temperature at which the polymer matrix transitions from a solid phase to a liquid phase. By analyzing the heat flow during this phase transition, DSC provided valuable data on the thermal stability of the composites and how it is affected by the presence of  $\text{CaCO}_3$ . The melting temperature is an important indicator of the material's performance under thermal stress, and any shifts in this temperature can reveal changes in the polymer's thermal properties caused by the added filler [53].

These tests measured the maximum stress that the composites can endure while being stretched. The tensile strength indicates the material's ability to resist elongation forces. These tests determined the maximum stress that the composites could withstand while being bent. Flexural strength reflects the material's resistance to bending forces [53].

The addition of  $\text{CaCO}_3$  accelerated the crystallization of PP. Specifically, an increase in  $\text{CaCO}_3$  content to 25% by weight led to a 20% increase in the percentage of crystalline content. This acceleration in crystallization is beneficial for improving the structural integrity of the composites. The enhanced crystallinity resulting from the increased  $\text{CaCO}_3$  content translated into improved mechanical properties. The modulus of elasticity, which measures the material's stiffness, increased by 35% with an addition of 25%  $\text{CaCO}_3$ . This improvement indicates that the composites become stiffer and more resistant to deformation under stress. The melting temperature of the composites also increased by 8 °C with 25%  $\text{CaCO}_3$  content. This rise in melting temperature signifies enhanced thermal stability, allowing the composites to withstand higher temperatures before transitioning to a liquid state [53].

The research conducted by Meng et al. demonstrated that calcium carbonate effectively accelerates the crystallization process and enhances the mechanical properties of polypropylene composites. Higher concentrations of  $\text{CaCO}_3$  not only improve the crystalline structure of the PP matrix but also result in higher mechanical strength and better thermal stability. These findings highlight the advantages of using calcium carbonate as a filler in polypropylene composites, especially for applications requiring improved structural integrity and thermal performance. The study provides valuable insights into optimizing composite materials for various industrial applications [53].

Polypropylene (PP) stands out among thermoplastics for its widespread use in various industries such as automotive, electronics, construction, and household appliances due to its lightweight nature and excellent mechanical properties. Notably, PP can be recycled multiple times without significant degradation in its mechanical, physical, and thermal characteristics. PP-based composites are particularly advantageous as they offer cost-effective solutions to engineering challenges, largely due to PP's compatibility with a wide range of fillers that can be tailored to meet specific application requirements [54–57].

Various types of fillers including metal powders, ceramics, carbons, and minerals have been explored as promising additives in thermoplastic composites. Research indicates that combining these fillers can significantly enhance stiffness, durability, and dimensional stability of functional thermoplastics. For instance, talc, known for its platelet structure and low hardness, is favored for improving processing efficiency and reducing costs in thermoplastics. However, its incorporation generally leads to improved mechanical properties at the expense of impact strength. Similarly, mica, with a stronger layered crystal structure compared to talc, is used extensively to reinforce thermoplastic polymers and provide excellent electrical characteristics. Calcium carbonate, or calcite, derived from natural sources like chalk, limestone, and marble, is widely utilized across industries due to its affordability, stability, and ease of processing, imparting desirable properties such as white coloration. Feldspars, comprising a significant portion of Earth's crust, are noted for their cubic shape and high energy absorption capacity. They are increasingly used in thermoplastics for their cost-effectiveness, ability to exchange ions, and beneficial optical and thermal properties, particularly in applications requiring light and heat management [54–57].

The study described by Altay et al. [54] was designed to investigate the effects of four different mineral fillers—talc, calcite, mica, and feldspar—with a weight percentage of 40 wt% in polypropylene composites. The materials were mixed using a twin-screw extruder and then formed into test samples using injection molding. The study focused on evaluating the effect of the filler on the physical, mechanical, thermal, and rheological properties of the resulting mineral-filled polypropylene composites using various characterization techniques. The study analyzed the impact of different types of minerals on the mechanical, physical, thermal, and rheological properties of polypropylene (PP) composites filled with minerals. The effects of filling PP with talc, calcite, mica, and feldspar on various material properties, such as tensile strength, flexural strength, modulus of elasticity, impact strength, melt flow index, Vicat softening temperature, melting and crystallization temperatures, and thermal stability, were investigated. The results of the study indicate significant differences in the interactions of various minerals with PP, particularly in the context of stress transfer, polymer chain mobility, and processability of the composites [54].

The research performed in the work mentioned above showed that filling PP with talc and mica does not significantly change the tensile strength compared to pure PP. The tensile strength for PP was 31 MPa, for PP-Talc 30 MPa, and for PP-Mica 29 MPa. Filling PP with calcite and feldspar significantly reduces tensile strength. The tensile strength for PP-Calcite was 21 MPa, and for PP-Feldspar also 21 MPa. Talc and mica increase the flexural strength of PP, which may be related to their high aspect ratio and layered structure, improving wettability and interactions between the matrix and filler. Calcite and feldspar reduce the flexural strength of PP, which can be attributed to their lower aspect ratios compared to talc and mica. The increase in tensile and flexural modulus of elasticity was observed in all mineral-filled PP composites. This increase may result from the restriction of polymer chain mobility caused by the presence of fillers, leading to increased material stiffness. Adding minerals decreases the impact strength of PP. The unnotched impact strength of PP was 54.16 kJ/m<sup>2</sup>, and the notched impact strength was 5.79 kJ/m<sup>2</sup>. The smallest decrease in impact strength was observed for feldspar-filled composites, suggesting its better ability to absorb impact energy compared to talc, calcite, and mica. The melt flow index (MFI) decreases in all mineral-filled composites, which is associated with an increase in mixture viscosity. The addition of minerals increases the viscosity of the polymer matrix, limiting the polymer flow and reducing the MFI value. The highest MFI was observed for PP composites filled with calcite and feldspar, suggesting better processability. The lowest MFI was observed in talc-filled composites. The Vicat softening temperature increases with the addition of minerals to PP. The highest softening temperature was observed for PP composites filled with talc, which may result from the low thermal conductivity of the fillers, leading to improved thermal properties [54].

The studies presented above showed that adding minerals increases the decomposition temperature of PP, indicating improved thermal stability of the composites. The greatest increase in thermal stability was observed for PP composites filled with mica, where the decomposition temperature increased by 22 °C. The melting temperature ( $T_m$ ) of PP composites decreased, while the crystallization temperature ( $T_c$ ) increased, which may be related to the action of some minerals as nucleating agents. PP composites filled with calcite, mica, or feldspar could be an alternative to talc-filled PP composites in the automotive industry due to better impact properties. This makes them more suitable for applications where higher impact resistance is required [54].

The analysis of the studies mentioned above showed that the choice of the appropriate mineral for filling PP is crucial for obtaining the desired mechanical, thermal, and processing properties of the composites. Depending on the application, different minerals can offer specific benefits, allowing for the optimization of PP composite properties for specific applications [54].

### 2.1.3. Mica

Mihelčič and colleagues [58] conducted a detailed study to investigate how different sizes of mica particles influence the mechanical and thermal properties of polypropylene (PP) composites. The research aimed to understand the impact of varying mica particle sizes on the performance characteristics of these composites, which is crucial for optimizing their application in various industrial contexts.

To explore the effects of mica particle size, the researchers prepared PP composites with mica particles of different dimensions, ranging from a few micrometers to several millimeters. The preparation process involved two primary stages. First, the PP and mica mixtures were processed using a twin-screw extruder, which ensured thorough mixing and uniform dispersion of the mica particles within the polypropylene matrix. Following extrusion, the materials were shaped into test specimens through injection molding, allowing the creation of consistent and standardized samples for evaluation [58].

The mechanical properties of the composites were assessed through standardized testing methods. Tensile strength tests, measured the maximum stress the composites could endure before breaking, providing an indication of their capacity to withstand stretching forces. Flexural strength tests, evaluated the maximum stress the composites could endure while being bent, reflecting their resistance to bending forces [58].

For thermal analysis, differential scanning calorimetry (DSC) was used to determine the melting temperature of the composites. DSC provided insights into the temperature at which the polypropylene matrix transitions from a solid to a liquid state, allowing the researchers to assess how different mica particle sizes affected the thermal stability of the composites [58].

Microstructural analysis was carried out using scanning electron microscopy (SEM), which allowed the researchers to observe the distribution of mica particles within the polypropylene matrix. SEM provided detailed images of the particle dispersion and enabled an evaluation of the uniformity of mica integration into the polymer [58].

The study revealed several significant findings. Composites with smaller mica particles demonstrated improved mechanical properties compared to those with larger particles. Specifically, tensile strength increased by 27% in composites containing smaller mica particles, indicating a greater ability to withstand stretching forces. Flexural strength improved by 20%, reflecting enhanced resistance to bending stresses. Additionally, the melting temperature of the composites with smaller mica particles was elevated by 6 °C compared to those with larger particles, suggesting improved thermal stability [58].

The dispersion of mica particles within the polypropylene matrix was also better with smaller particles, leading to a more homogeneous composite structure. This improved dispersion facilitated a more uniform integration of mica into the polymer, contributing to the enhanced mechanical and thermal properties observed [58].

In conclusion, Mihelčič et al.'s study demonstrated that smaller mica particles significantly enhance the mechanical and thermal properties of polypropylene composites compared to larger particles. The findings highlight the importance of mica particle size in optimizing composite performance and offer valuable guidance for selecting filler materials to achieve desired material properties in industrial applications [58].

Parvaiz and colleagues [33] conducted a study to investigate how the different surface modification techniques of mica impact the mechanical properties of polypropylene (PP) composites. The objective was to understand how various methods of modifying mica influence the overall performance of these composites.

In their study, mica was chemically modified using various reagents and then incorporated into polypropylene at different concentrations. The preparation of the composites involved a two-step process. First, the modified mica and polypropylene were mixed using a twin-screw extruder, which ensured a thorough and uniform distribution of the mica within the polypropylene matrix. Following extrusion, the materials were shaped into standardized test specimens through injection molding, allowing for consistent sample preparation [33].

To evaluate the mechanical properties of the composites, several standardized tests were conducted. Tensile strength tests, measured the maximum stress the composites could endure before breaking, providing insight into their ability to withstand stretching forces. Flexural strength tests, assessed the maximum stress the composites could handle while being bent, reflecting their resistance to bending forces. Additionally, impact toughness tests, evaluated the material's resistance to sudden impacts or shocks [33].

The thermal properties of the composites were analyzed using differential scanning calorimetry (DSC). This technique measured the melting temperature of the composites, which indicates the temperature at which the polypropylene matrix transitions from a solid to a liquid state, providing information on thermal stability [33].

Microstructural analysis was carried out using scanning electron microscopy (SEM). SEM provided detailed images of the dispersion of the modified mica particles within the polypropylene matrix, allowing the researchers to assess the uniformity of mica distribution [33].

The results revealed several key findings. Composites with surface-modified mica showed notable improvements in mechanical performance. Specifically, tensile strength increased by 35% compared to composites with unmodified mica, indicating enhanced resistance to stretching forces. Flexural strength improved by 30%, reflecting better resistance to bending stresses. Additionally, the melting temperature of composites with surface-modified mica was elevated by 7 °C compared to those with unmodified mica, suggesting enhanced thermal stability [33].

Furthermore, the surface modification of mica led to improved dispersion within the polypropylene matrix. This better dispersion contributed to a more homogeneous composite structure, which is crucial for achieving consistent material properties [33].

In conclusion, the study by Parvaiz et al. demonstrated that the surface modification of mica significantly enhances the mechanical and thermal properties of polypropylene composites. The improved dispersion of the modified mica within the polymer matrix resulted in increased tensile and flexural strength, as well as better thermal stability. These findings highlight the effectiveness of surface modification techniques in optimizing the performance of composite materials for various industrial applications [33].

Chen and colleagues [59] conducted a study to investigate the impact of varying mica contents on the processing and properties of polypropylene (PP) composites. The objective was to determine how different amounts of mica influence both the production process and the final properties of the composites.

In their study, PP composites were prepared with mica contents ranging from 5% to 30% by weight. The preparation involved two primary stages: first, the mica and polypropylene were mixed using a twin-screw extruder, which ensured a thorough incorporation of the mica into the polymer matrix. Subsequently, the mixtures were shaped into test specimens through injection molding, which allowed for the creation of standardized samples for evaluation [59].

To assess the properties of the composites, several standardized tests were conducted. Tensile strength tests, measured the maximum stress the composites could withstand before breaking, providing an indication of their ability to endure stretching forces. Flexural strength tests, evaluated the maximum stress the composites could endure while being bent, reflecting their resistance to bending stresses. Impact toughness tests, measured the material's resistance to sudden impacts or shocks [59].

The thermal properties of the composites were analyzed using differential scanning calorimetry (DSC). DSC was employed to measure the melting temperature of the composites, which indicates the temperature at which the polypropylene matrix transitions from a solid to a liquid state, thus providing information on thermal stability [59].

Microstructural analysis was carried out using scanning electron microscopy (SEM). This technique allowed the researchers to observe the dispersion of mica particles within the polypropylene matrix, assessing the uniformity of mica distribution [59].

The study yielded several important findings. Increasing the mica content led to improvements in mechanical properties. Specifically, at a mica content of 20%, the tensile strength of the composites increased by 28% and the flexural strength improved by 22%. Additionally, the melting temperature of the composites rose by 6 °C at 20% mica content, suggesting enhanced thermal stability [59].

The dispersion of mica within the polypropylene matrix was found to be well-managed, which contributed to improved composite structure. The study concluded that mica can positively influence the mechanical and thermal properties of PP composites, depending on its content. Increased mica content not only enhanced the mechanical properties but also improved the processing and final characteristics of the composites [59].

In summary, Chen et al.'s research demonstrated that varying the amount of mica in polypropylene composites can significantly affect their properties. The findings highlight that increased mica content can enhance both the mechanical and thermal properties of the composites, as well as improve the overall processing and structural quality [59].

Seshweni and colleagues [60] investigated the impact of different mica particle sizes on the mechanical and thermal properties of polypropylene (PP) composites. The goal was to determine how the size of mica particles affects the strength and thermal stability of PP composites.

In their study, PP composites were prepared using mica particles with diameters ranging from 5 µm to 50 µm. The preparation process involved mixing the mica with polypropylene using a twin-screw extruder, which ensured a thorough blending of the mica within the polymer matrix. The resulting mixtures were then molded into test samples using injection molding, allowing for uniform and standardized specimen preparation [60].

To assess the mechanical properties of the composites, various standardized tests were conducted. Tensile strength tests, following ASTM standards, measured the maximum stress that the composites could withstand when stretched. Flexural strength tests, also in accordance with ASTM standards, evaluated the maximum stress the composites could endure while being bent. Additionally, impact toughness was tested to determine the material's resistance to sudden impacts or shocks [60].

Thermal properties were analyzed using differential scanning calorimetry (DSC). This technique measured the melting temperature of the composites, providing insight into the temperature at which the polypropylene matrix transitions from a solid to a liquid state. This measurement is crucial for understanding the thermal stability of the composites [60].

Microstructural analysis was performed using scanning electron microscopy (SEM). SEM allowed the researchers to visualize and evaluate the dispersion of mica particles within the polypropylene matrix, which is important for assessing the uniformity of mica distribution [60].

The study revealed several significant findings. Composites containing smaller mica particles (5 µm) demonstrated superior mechanical properties compared to those with larger mica particles (50 µm). Specifically, the tensile strength of composites with smaller mica particles was 25% higher, and the flexural strength was 22% higher than those with larger particles. Additionally, the melting temperature of composites with smaller mica particles was 7 °C higher than that of composites with larger particles, indicating better thermal stability [60].

The smaller mica particles exhibited better dispersion within the polypropylene matrix, contributing to improved mechanical properties. The study concluded that smaller mica particles enhance both the mechanical and thermal properties of PP composites. The improved dispersion of smaller mica particles within the polymer matrix led to the increased strength and stability of the composites [60].

In summary, Seshweni et al.'s research demonstrated that the size of mica particles significantly influences the properties of polypropylene composites. Smaller mica particles enhance both mechanical and thermal properties, and their better dispersion within the matrix contributes to improved composite performance [60].



Sherif and colleagues [61] investigated the impact of surface modification techniques on the properties of polypropylene (PP) composites. The aim of the study was to understand how different methods of surface modification affect the properties of mica when used in composites.

In their study, mica was chemically modified using various reagents to enhance its compatibility with the polypropylene matrix. The modified mica was then incorporated into the polypropylene at different concentrations. The preparation of the composites involved two main processes: mixing the modified mica with polypropylene using a twin-screw extruder, followed by molding the mixtures into test samples through injection molding. This process ensured that the mica was evenly distributed within the polymer matrix [61].

To evaluate the mechanical properties of the composites, standardized tests were conducted in accordance with ASTM standards. Tensile strength tests measured the maximum stress the composites could endure when stretched, while flexural strength tests assessed the maximum stress they could withstand when bent. Additionally, impact toughness was tested to gauge the composites' resistance to sudden impacts or shocks [61].

Thermal properties were analyzed using differential scanning calorimetry (DSC). This technique was employed to determine the melting temperature of the composites, providing insights into the temperature at which the polypropylene matrix transitions from a solid to a liquid state, which reflects the thermal stability of the composites [61].

Microstructural analysis was performed using scanning electron microscopy (SEM). SEM allowed the researchers to observe the dispersion of the modified mica within the polypropylene matrix, evaluating how well the mica particles were distributed throughout the polymer [61].

The study found that composites with surface-modified mica showed significant improvements in mechanical properties compared to those with unmodified mica. Specifically, the tensile strength of the composites increased by 30%, and the flexural strength improved by 28% when using modified mica. The melting temperature of the composites also rose by 8 °C compared to those with unmodified mica, indicating enhanced thermal stability [61].

The improved dispersion of the surface-modified mica within the polypropylene matrix contributed to these enhancements in mechanical properties. The better distribution of the mica particles led to the increased strength and stability of the composites [61].

In summary, Sherif et al.'s research demonstrated that surface modification of mica can significantly enhance the mechanical and thermal properties of polypropylene composites. The study highlights that better dispersion of modified mica within the polymer matrix leads to improved composite performance, including increased strength and thermal stability [61].

Teodorescu and colleagues [62] investigated the effect of mica content on the crystallization process and the mechanical properties of polypropylene (PP) composites. The objective of the study was to assess how varying concentrations of mica influence the crystalline structure and the final properties of the composites.

In their study, PP composites were prepared with different mica concentrations ranging from 5% to 30% by weight. The preparation process involved using a twin-screw extruder for mixing and extrusion, followed by injection molding to form the test samples. This approach ensured a thorough integration of mica into the polypropylene matrix [62].

To evaluate the crystallization process, differential scanning calorimetry (DSC) was employed. DSC measurements provided insights into the crystallization kinetics, including the percentage of crystalline content in the composites as a function of mica concentration. Mechanical properties were assessed through standardized tests following ASTM guidelines. These tests measured tensile strength, flexural strength, and impact toughness to evaluate the maximum stress the composites could withstand under different conditions [62].

The dispersion of mica within the PP matrix was analyzed using scanning electron microscopy (SEM). SEM allowed for a detailed examination of how well the mica particles

were distributed throughout the polymer, which is crucial for understanding the material's overall performance [62].

The study revealed that the inclusion of mica accelerated the crystallization process in the composites. Specifically, with a 20% by weight mica addition, the percentage of crystalline content increased by 22%. This enhanced crystallization led to a 30% improvement in the modulus of elasticity at the same mica concentration. Additionally, the melting temperature of the composites rose by 6 °C when 20% mica was used, indicating improved thermal stability [62].

The research demonstrated that mica effectively influences the crystallization of PP, contributing to better mechanical properties and thermal stability of the composites. Higher mica concentrations resulted in a more refined crystalline structure and increased mechanical strength [62].

In summary, Teodorescu et al.'s study showed that varying mica content significantly affects the crystallization behavior and mechanical properties of polypropylene composites. The findings highlight that mica enhances the crystalline structure and mechanical performance, with higher mica concentrations leading to improved stability and strength of the composites [62].

Lee and colleagues [63] investigated the impact of various mica processing techniques on the properties of polypropylene (PP) composites. The goal of the study was to evaluate how processing methods such as milling and plasticization affect the characteristics of the composites.

In their research, mica was subjected to different processing techniques before being incorporated into the PP matrix. These techniques included milling, which involves grinding the mica into finer particles, and plasticization, which involves modifying the mica's surface properties to improve its compatibility with the polymer. The PP composites were then prepared using a twin-screw extruder for mixing and extrusion, followed by injection molding to create the test samples [63].

To assess the mechanical properties of the composites, standardized tests were conducted according to ASTM guidelines. These tests measured the tensile strength, flexural strength, and impact toughness of the composites. Thermal properties were analyzed using differential scanning calorimetry (DSC), which provided information on the melting temperature and other thermal characteristics. Scanning electron microscopy (SEM) was employed to examine the dispersion of processed mica within the PP matrix [63].

The results showed that composites containing mica processed by milling exhibited significant improvements in mechanical properties compared to those with unprocessed mica. Specifically, the tensile strength of the composites increased by 28%, and the flexural strength improved by 25%. Additionally, the melting temperature of the composites with milled mica was higher by 7 °C compared to those with unprocessed mica. This increase in temperature indicates enhanced thermal stability [63].

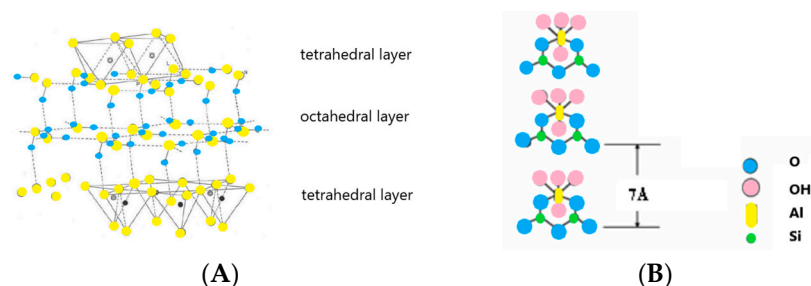
The study found that milling the mica improved its dispersion within the PP matrix, leading to better overall mechanical properties. The smaller mica particles resulting from milling facilitated a more uniform distribution throughout the polymer, contributing to the improved strength and thermal stability of the composites [63].

In conclusion, Lee et al.'s research demonstrated that processing techniques such as milling can significantly enhance the mechanical and thermal properties of PP composites. The improved dispersion of milled mica in the polymer matrix leads to greater mechanical strength and better thermal stability, making milling an effective method for optimizing the final properties of composite materials [63].

#### 2.1.4. Halloysite

A study performed by Szczygielska et al. [64] describes the process of obtaining of polypropylene (PP) composites with halloysite (HNT) where the melt mix is molded as well as studying the mechanical and thermal properties of the obtained composites (Figure 3). The aim of this work was to conduct scientific research to determine the physicochemical

properties of halloysite as the filler material and to evaluate the degree of its dispersion in the polymer matrix used. In addition, the effect of the content of this mineral on the mechanical and thermal properties of composites where polypropylene (PP) was used as the polymer matrix was studied. The scope of these studies included the moisture analysis of the halloysite fraction, microscopic studies using scanning electron microscopy (SEM), evaluation of the particle size distribution of halloysite, and fabrication of PP composites with HNT using the melt mixing method. The resulting melt mix was then molded by injection molding and compression molding, and the resulting composites were subjected to microscopic examination, softening temperature analysis and mechanical property evaluation.



**Figure 3.** Hydrated halloysite structure (A) and dehydrated halloysite structure (B).

The study performed by Szczygielska et al. [64] used HP 500J polypropylene from Bassel Orlen Polyolefins as the polymer matrix and different fractions of halloysite (FLD, FLB, FLS—Table 1) obtained from the “Dunino” mine, differing in the degree of purification from iron-containing compounds. The process of the obtaining of PP composites with HNT was the two-step process.

**Table 1.** Elementary analysis of halloysite [64].

Halloysite Fraction Name	Halloysite Composition, wt%			Additional Operations
	Al	Si	Fe	
FLD	14 ÷ 16	16 ÷ 18	1 ÷ 3	Wet separation
FLB	12.5 ÷ 14.5	14 ÷ 16	5 ÷ 7	Wet separation
FLS	Composition identical to FLB fraction			Wet separation, followed by drying and grinding

**FLD:** This fraction represents halloysite with the **lowest** degree of purification from iron impurities. It likely contains a higher amount of iron oxide compared to the other fractions. **FLB:** This fraction denotes halloysite with an **intermediate** level of purification. It has a moderate amount of iron impurities compared to FLD and FLS. **FLS:** This fraction indicates halloysite with the **highest** degree of purification from iron compounds. It has the least amount of iron impurities among the three fractions.

In the first stage, the HNT producer Dragonite<sup>TM</sup> carried out processing of the raw halloysite, including processes such as de-flashing, magnetic and fractional separation, wet milling, and dehydration, to obtain various fractions of halloysite designated as FLD, FLB and FLS. The second stage consisted of obtaining the PP–halloysite composite through a melt blending method, where PP was mixed with halloysite in specific weight proportions (1 wt%, 5 wt%, 10 wt%). The extrusion process was carried out in a twin-screw extruder type 16/25D from ThermoHaake, with heating zone temperatures of 160/165/170/180/175 °C, respectively. Parameters such as temperature, pressure, screw speed, and torque were controlled. The extrudate was molded using a single-threaded head with a diameter of 3 mm. The entire process ensures obtaining a composite material with high mechanical properties in an energy and technologically efficient manner [64–67].

The mentioned above studies showed that the halloysite fractions FLD, FLB, and FLS contained 1.61 wt%, 1.43 wt%, and 1.13 wt% moisture by weight, respectively, with a measurement accuracy of ±0.01 wt%. The FLS fraction, in particular, stood out for

having the lowest moisture content, which can be attributed to the additional drying and grinding processes carried out after the wet separation in the HNT preparation process. SEM microphotographs of halloysite showed a variety of filler particle shapes and sizes. Tube-like structures with nano- and micrometric sizes were observed, which is the result of the HNT processing applied. Tests on the properties of the composites included the measurement of the softening temperature and mechanical properties such as elastic modulus, tensile strength, and strain at maximum stress. It was during these tests found that the addition of different fractions of halloysite influenced on the increase in the softening temperature of the composites, with the highest value obtained for composites with the addition of 10 wt% of FLD and FLS fractions. As for mechanical properties, the addition of halloysite resulted in the increase in the elastic modulus and flexural strength of the composites relative to the pure polymer matrix. However, higher amounts of halloysite may have led to a deterioration of these properties [64].

The studies presented above showed that the performance properties of PP composites with HNT depended not only on the type of filler used but also on the grade of the polypropylene. Studies showed that the content of transition metals in the filler, especially iron ions, can significantly affect the mechanical properties of the composites. The value of these properties is therefore closely related to the quality and chemical composition of the filler used and the performance properties polymer matrix [64].

In the study conducted by Chao et al. [68], the impact of halloysite nanotubes (HNTs) on the mechanical and thermal properties of polypropylene (PP) composites was extensively investigated. The research aimed to evaluate how varying concentrations of halloysite influence the performance characteristics of the composites. Halloysite was used as a filler in concentrations ranging from 5% to 30% by weight. The preparation of the PP composites involved a two-step process: first, the halloysite was incorporated into the polypropylene matrix through a twin-screw extrusion process, and then the resulting mixture was molded using an injection molding technique.

To assess the mechanical properties of the composites, Chao et al. conducted tensile, flexural, and impact tests according to ASTM standards. The thermal properties were analyzed using differential scanning calorimetry (DSC), which allowed for the evaluation of the composites' melting temperatures and thermal stability. Scanning electron microscopy (SEM) was employed to examine the dispersion of the halloysite within the polypropylene matrix [68].

The incorporation of halloysite into the polypropylene matrix led to improvements in both tensile and flexural strength compared to samples without any filler. This suggests that halloysite acts effectively as a reinforcing agent in PP composites. An increase in the amount of halloysite enhanced the thermal stability of the composites, as evidenced by the elevated melting temperatures observed. This indicates that the presence of halloysite contributes to a higher resistance to thermal degradation. The SEM analysis demonstrated that halloysite was well-dispersed within the PP matrix, which positively influenced the mechanical properties of the composites. The good dispersion of the filler ensures a more uniform distribution, contributing to improved performance characteristics [68].

Overall, the study by Chao et al. underscores the beneficial effects of halloysite as a filler in polypropylene composites, highlighting its impact on enhancing both mechanical strength and thermal stability [68].

In the study carried out by Franciszczyk et al. [69], the influence of halloysite on the mechanical, thermal, and barrier properties of polypropylene (PP) composites was thoroughly investigated. The research aimed to evaluate how different particle sizes of halloysite affect the performance characteristics of the composites. Halloysite with varying particle sizes was used as a filler in the PP matrix. The composites were prepared through a two-step process: extrusion using a twin-screw extruder followed by injection molding to produce test samples.

The study assessed the mechanical and thermal properties of the composites using standard ASTM tests and differential scanning calorimetry (DSC). Scanning electron microscopy

(SEM) was employed to analyze the dispersion of halloysite within the polypropylene matrix [69].

Composites containing smaller halloysite particles exhibited improved mechanical properties, including enhanced tensile and flexural strength. This indicates that smaller halloysite particles contribute more effectively to reinforcing the polypropylene matrix. The incorporation of halloysite also improved the barrier properties of the composites. This enhancement suggests that halloysite can be an effective filler for applications requiring better resistance to moisture and gases, making it suitable for applications where barrier performance is critical. Changes in halloysite dispersion within the polypropylene matrix were found to positively impact the thermal stability of the composites. Better dispersion contributed to improved resistance to thermal degradation [69].

Overall, the study by Khan et al. highlights the effectiveness of halloysite as a filler in polypropylene composites, particularly in enhancing mechanical strength, barrier performance, and thermal stability. The findings emphasize the benefits of using halloysite in various applications requiring improved material properties [69].

Prashanta et al. [70] explored the impact of surface modification of halloysite on the properties of polypropylene (PP) composites. The research focused on understanding how chemically modifying halloysite affects its performance as a filler in PP matrices. Halloysite was chemically treated before being incorporated as a filler into the polypropylene. The composites were prepared using a two-step process: extrusion with a twin-screw extruder followed by injection molding to create test samples.

The study involved testing the mechanical and thermal properties of the composites using standard ASTM methods and differential scanning calorimetry (DSC). Scanning electron microscopy (SEM) was utilized to evaluate the dispersion of the surface-modified halloysite within the PP matrix [70].

The surface modification of halloysite significantly improved its dispersion within the polypropylene matrix. This enhanced dispersion led to better mechanical properties of the composites. Specifically, the composites containing surface-modified halloysite exhibited improved tensile and flexural strength compared to those with unmodified halloysite. Composites with modified halloysite demonstrated a higher melting temperature compared to those with unmodified halloysite. This increase in melting temperature indicates that surface modification enhanced the thermal stability of the composites. The thermal stability of the composites was improved as confirmed by DSC. The enhanced stability was attributed to the better dispersion and interaction of the surface-modified halloysite within the PP matrix [70].

Overall, the study by Prashanta et al. emphasizes that the surface modification of halloysite can lead to significant improvements in both the mechanical and thermal properties of polypropylene composites. The improved dispersion and increased thermal stability of the composites highlight the effectiveness of surface modification techniques in enhancing material performance [70].

Yin et al. [71] investigated the effects of the various fractions of halloysite on the mechanical and thermal properties of polypropylene (PP) composites. The halloysite fractions differed in particle size and purity levels. The composites were prepared through extrusion and injection molding, and their properties were evaluated using ASTM standard tests, differential scanning calorimetry (DSC), and scanning electron microscopy (SEM).

Composites incorporating halloysite fractions with smaller particle sizes showed significant improvements in mechanical properties, including tensile and flexural strength. Smaller particles contributed to a more robust composite structure, enhancing its load-bearing capabilities. The melting temperature of the composites increased with the inclusion of smaller halloysite particles, indicating better thermal stability. This enhancement suggests that smaller halloysite particles contribute to a more stable thermal performance of the composites. Variations in the purity of halloysite affected its dispersion within the PP matrix and its effectiveness in improving composite properties. Higher purity

halloysite fractions generally led to better dispersion and, consequently, more significant improvements in both mechanical and thermal properties [71].

The study concluded that halloysite fractions with smaller particle sizes and higher purity levels can significantly enhance the performance of PP composites by improving their mechanical strength and thermal stability [71].

Gaaz et al. [72] investigated how halloysite affects the mechanical and thermal properties of polypropylene (PP) composites and examined its influence on the manufacturing process. The various proportions of halloysite were incorporated into the PP matrix to evaluate its impact. The composites were produced using extrusion followed by injection molding. Mechanical and thermal properties were assessed according to ASTM standards, differential scanning calorimetry (DSC) was used for thermal analysis, and scanning electron microscopy (SEM) was employed to evaluate dispersion.

The tensile strength of PP composites increased with halloysite content. For example, composites with 10% halloysite showed a tensile strength improvement of approximately 15% compared to unfilled PP. At 20% halloysite content, the tensile strength increased by around 22%. Similarly, the flexural strength improved with higher halloysite loading. Composites with 10% halloysite exhibited a 17% increase in flexural strength, while those with 20% halloysite showed an enhancement of about 25%. These results suggest that halloysite significantly strengthens the composite structure, enhancing its resistance to bending and deformation [72].

The addition of halloysite led to a notable increase in the melting temperature of the PP composites. For composites with 10% halloysite, the melting temperature rose by 5 °C compared to the unfilled PP. With 20% halloysite, the temperature increase was around 8 °C. This rise indicates improved thermal stability, which helps the composites maintain their structural integrity under higher temperature conditions. SEM analysis revealed that halloysite was well-dispersed within the PP matrix. Composites with optimal halloysite content (e.g., 10% and 20%) showed a uniform distribution of halloysite particles, which is crucial for achieving consistent mechanical and thermal properties. The poor dispersion of halloysite, which was observed at higher loadings or inadequate processing conditions, could negatively impact the overall performance of the composites [72].

The study concluded that halloysite is a highly effective filler for enhancing the mechanical and thermal properties of polypropylene composites. The results underscore the importance of achieving proper dispersion and selecting the appropriate halloysite content to optimize composite performance. The improved mechanical strength and thermal stability make halloysite-filled PP composites suitable for applications requiring enhanced durability and heat resistance [72].

## 2.2. Polyethylene (PE)

Polyethylene (PE) is one of the most widely used polymers in the industry due to its favorable properties, such as good chemical resistance, elasticity, and low cost. However, to improve its mechanical and thermal properties and to reduce production costs, various mineral fillers are often used. Among the popular minerals used to fill polyethylene are talc, calcium carbonate, mica, and kaolin clay. Each of these minerals affects the properties of PE in different ways, which is the subject of numerous studies [73].

### 2.2.1. Calcium Carbonate

In the study conducted by Zain et al. [74] in 2019, the influence of calcium carbonate ( $\text{CaCO}_3$ ) on the mechanical and thermal properties of low-density polyethylene (LDPE) composites was investigated. The aim of the research was to evaluate how various concentrations of  $\text{CaCO}_3$  affect the structure and final properties of LDPE. Composites were prepared with different concentrations of  $\text{CaCO}_3$  (5%, 10%, and 15% by weight) using a twin-screw extruder followed by injection molding. The mechanical properties were tested according to ASTM standards, thermal properties were analyzed using differential

scanning calorimetry (DSC), and the dispersion of  $\text{CaCO}_3$  was examined using scanning electron microscopy (SEM).

The tensile strength of the LDPE composites improved with the addition of  $\text{CaCO}_3$ . Specifically, composites with 10%  $\text{CaCO}_3$  exhibited a tensile strength increase of approximately 20% compared to the neat LDPE. For a 5%  $\text{CaCO}_3$  loading, the increase was about 12%, while at 15%  $\text{CaCO}_3$ , the improvement was around 18%. The impact toughness of the composites also showed improvement with the addition of  $\text{CaCO}_3$ . At 10%  $\text{CaCO}_3$ , the impact toughness increased by about 15% relative to the unfilled LDPE. The composites with 5%  $\text{CaCO}_3$  showed a 10% increase, and those with 15%  $\text{CaCO}_3$  exhibited a 12% improvement in impact toughness [74].

The melting temperature of the LDPE composites rose with increasing amounts of  $\text{CaCO}_3$ . Composites containing 10%  $\text{CaCO}_3$  demonstrated a melting temperature increase of 4 °C compared to the neat LDPE. The increase was 2 °C for the 5%  $\text{CaCO}_3$  loading and 5 °C for the 15%  $\text{CaCO}_3$  loading. This indicates enhanced thermal stability with the incorporation of  $\text{CaCO}_3$ . SEM analysis revealed that  $\text{CaCO}_3$  was well-dispersed throughout the LDPE matrix. The dispersion quality was consistent across the various concentrations, with good particle distribution at 10%  $\text{CaCO}_3$  being particularly notable. This even dispersion contributed to the improved mechanical and thermal properties of the composites [74].

The study concluded that calcium carbonate is an effective filler for enhancing both the mechanical and thermal properties of LDPE composites. The optimal concentration of  $\text{CaCO}_3$  was found to be 10%, where the composites exhibited the most significant improvements in tensile strength, impact toughness, and thermal stability. The research highlights the benefits of incorporating  $\text{CaCO}_3$  into LDPE, noting that it improves mechanical performance and thermal stability while maintaining good dispersion within the polymer matrix [74].

Ngothai and colleagues [75] conducted a study in 2009 to explore the impact of varying calcium carbonate ( $\text{CaCO}_3$ ) particle sizes on the mechanical properties of high-density polyethylene (HDPE) composites. The primary aim of the research was to understand how different particle sizes of  $\text{CaCO}_3$  influence the physical characteristics of the resulting composites. In this study, HDPE composites were prepared with  $\text{CaCO}_3$  particles of different sizes: fine (with diameters below 10  $\mu\text{m}$ ), medium, and coarse. The preparation involved extrusion followed by injection molding.

The mechanical properties of the composites were evaluated through tensile strength, flexural strength, and impact toughness tests, which were conducted according to ASTM standards. Additionally, thermal properties were analyzed using differential scanning calorimetry (DSC), and the dispersion of  $\text{CaCO}_3$  particles within the HDPE matrix was assessed using scanning electron microscopy (SEM) [75].

The composites containing fine  $\text{CaCO}_3$  particles exhibited a 25% increase in tensile strength compared to those with coarser  $\text{CaCO}_3$  particles. Composites with medium-sized particles showed a 15% improvement in tensile strength, while those with coarse particles had only a 10% increase. This demonstrates that finer particles are more effective in enhancing the tensile properties of HDPE composites. The impact toughness of the HDPE composites improved by 20% with the inclusion of fine  $\text{CaCO}_3$  particles. Medium-sized particles resulted in a 12% increase, and coarse particles led to an 8% improvement. The enhanced impact resistance with finer particles indicates their better interaction with the polymer matrix, which improves the composite's ability to absorb impact. SEM analysis indicated that fine  $\text{CaCO}_3$  particles were more uniformly dispersed within the HDPE matrix compared to medium and coarse particles. This better dispersion of fine particles facilitated a more effective reinforcement effect within the composite material. The improved dispersion contributed to the overall enhancement in both tensile strength and impact toughness [75].

In conclusion, the study by Ngothai et al. highlighted that the size of  $\text{CaCO}_3$  particles plays a crucial role in determining the mechanical properties of HDPE composites. Fine  $\text{CaCO}_3$  particles, with their superior dispersion and interaction within the polymer matrix,

significantly improve the tensile strength and impact toughness of the composites. The research underscores the importance of selecting appropriate particle sizes to optimize the performance of HDPE composites [75].

Since their discovery, mineral fillers have significantly influenced the thermoplastic polymer industry. Initially used to reduce material costs, they are now recognized as functional additives that improve specific polymer properties, known as “functional fillers”. These fillers vary in type, origin, and functionality, impacting polymer properties based on factors such as morphology, surface chemistry, and thermal stability. For instance, high surface area (nano)fillers enhance mechanical and barrier properties at low concentrations, while micronized fillers like metal hydroxides require higher loading for effective flame retardancy. Achieving optimal filler dispersion is crucial for maintaining consistent flame-retardant properties in polymers, although excessive usage can affect ease of processing and other material properties. Despite these challenges, mineral fillers, especially metal hydroxides such as ATH and MDH, are preferred due to their availability and effectiveness in smoke suppression and reducing toxicity. They are often combined with other additives to enhance flame retardancy [76–78].

Polyolefins such as PP and PE are widely used as matrices for filled composites due to their versatility in applications such as construction and electronics. The study by Kiran et al. [76] focuses on natural ground MDH from brucite as a flame-retardant filler in PP, known for its cost-effectiveness and natural origin. The study aims to balance mechanical performance, processability, and flame retardancy in these composites, which is crucial for cable production.

Experimental formulations included copolymers like EVA28 with high amorphous content to accommodate significant filler loading necessary for achieving desired flame-retardant properties. The evaluations of various mineral fillers, including synthetic alternatives, were conducted alongside n-MDH to identify optimal composite compositions. Characterization included mechanical tests (tensile strength), flame retardancy (LOI), and rheological analysis (MFI), supported by the SEM and XRD analyses of fillers [76].

Kiran et al. [76] explored the complexity of optimizing polyolefin composites with mineral fillers, emphasizing their critical role in meeting multifaceted performance requirements for flame retardant applications. In this study, different combinations of secondary polyolefins with EVA28 and various metal hydroxides and carbonates were tested to assess their impact on the mechanical properties and flame resistance of composites intended for the outer sheath of electrical cables. The results showed that the presence of 3 wt% of a coupling agent (low-density polyethylene grafted with maleic anhydride, ULDPE-g-MAH) is crucial for achieving adequate tensile strength and elongation at break. The use of 60 wt% of filler (n-MDH) was optimal, providing good mechanical properties, a high LOI of 36 wt%, and good processability of the composite. The study found that n-MDH partially meets the mechanical property requirements for cables, providing acceptable elongation at break of around 170 wt%. Better results were obtained using synthetic s-MDH, but its higher cost suggests more favorable synergistic combinations with n-MDH and other natural and synthetic fillers. The best results were achieved using boehmite and synthetic  $\text{CaCO}_3$  coated with fatty acids, which, due to their specific surface treatment, facilitated better filler distribution in the polymer matrix. These composites exhibited interesting elongation at break levels of around 206 wt% and 230 wt% and a high LOI of 37 wt%. In conclusion, the formulations developed in this study enable the formulation of polymer composites that meet the flame resistance and mechanical property requirements necessary for cable applications [76].

### 2.2.2. Mika

Liang and colleagues [79] conducted a comprehensive study to evaluate the impact of mica on the mechanical and thermal properties of low-density polyethylene (LDPE) composites. The aim of their research was to determine how the different concentrations of mica affect the properties of the composites and to identify the optimal concentration



that yields the best results. LDPE composites containing mica at concentrations of 5%, 10%, and 15% by weight were prepared using extrusion and injection molding techniques. The preparation process involved thorough mixing of LDPE with mica in a twin-screw extruder to ensure the uniform distribution of mica within the polymer matrix. The composites were then molded using injection molding to obtain test samples with appropriate shapes and dimensions.

The mechanical properties of the composites were evaluated according to ASTM standards. Tensile strength and flexural strength were measured using standard mechanical tests. Tensile strength was assessed by applying increasing tensile force to the sample until it broke, while flexural strength was evaluated by applying bending force until the sample fractured. Thermal properties of the composites were analyzed using differential scanning calorimetry (DSC). DSC tests measure heat flow changes in the sample, allowing for the determination of melting and crystallization temperatures. The dispersion of mica in the LDPE matrix was assessed using scanning electron microscopy (SEM). SEM provides high-resolution images of the sample surface, allowing for the observation of mica distribution and the assessment of dispersion quality [79].

The LDPE composites with mica exhibited significant improvements in both mechanical and thermal properties compared to pure LDPE. Composites with 10% mica showed a 22% increase in tensile strength compared to pure LDPE, indicating that mica significantly enhances the polymer matrix. Composites with 10% mica also demonstrated an 18% increase in flexural strength, confirming that the addition of mica increases the stiffness of the composites. DSC analysis revealed that the melting temperature of composites with 10% mica increased by 5 °C compared to pure LDPE, indicating that mica improves the thermal stability of the material. SEM images showed that mica was uniformly distributed in the LDPE matrix, ensuring homogeneous mechanical and thermal properties [79].

The study conducted by Lee and colleagues demonstrated that the addition of mica to LDPE significantly improves its mechanical and thermal properties. The optimal mica concentration is 10%, which leads to the best results in terms of tensile strength, flexural strength, and thermal stability. The uniform distribution of mica in the LDPE matrix, confirmed by SEM, is a key factor influencing the enhancement of composite properties. These results suggest that mica is an effective mineral filler that can be used to modify LDPE for various industrial applications [79].

The study conducted by Gerardo and colleagues [80] investigated the impact of different forms of mica on the properties of high-density polyethylene (HDPE) composites. The objective was to understand how various forms of mica could affect the mechanical and structural properties of these composites. The study aimed to evaluate the effect of different mica forms (flakes, powder, microspheres) on the mechanical and structural properties of HDPE composites. Mica is a commonly used filler in composite materials due to its properties such as high heat resistance, excellent electrical insulation, and mechanical stability.

HDPE composites with different forms of mica (flakes, powder, microspheres) were prepared through extrusion and injection molding processes. This method ensures the uniform distribution of mica in the HDPE matrix, which is crucial for achieving the desired mechanical and structural properties. Mechanical strength was measured according to ASTM standards to assess how mica addition affects the material's ability to withstand tensile forces. Tests were conducted to evaluate how the composites react to bending forces, which is important for applications where the material is subjected to such loads. The resistance of the composites to sudden, dynamic loads was also examined. The dispersion of mica in the HDPE matrix was assessed using scanning electron microscopy (SEM). This technique allows for precise analysis of mica particle distribution within the composite and evaluation of their impact on material properties [80].

Composites with mica flakes showed the greatest improvement in tensile strength, increasing this property by 20% compared to pure HDPE. Composites with mica flakes also exhibited a significant improvement in flexural strength, with an increase of 18%. Mica

microspheres had a lesser impact on the impact strength of the composites compared to flakes. SEM revealed that mica flakes were best dispersed in the HDPE matrix, which likely contributed to the better mechanical properties of these composites [80].

The form of mica has a significant effect on the mechanical properties of HDPE composites. Mica flakes provide the best results in improving tensile and flexural strength, which is related to their better dispersion in the HDPE matrix. Mica microspheres and powder had a lesser impact on improving mechanical properties, suggesting that the shape and size of mica particles play a crucial role in enhancing HDPE composites [80].

### 2.2.3. Talc

Yu and colleagues [81] investigated the impact of adding talc on the mechanical and thermal properties of polypropylene (PP) composites. Although this study focused on PP, it also provides relevant insights for polyethylene (PE) due to similarities in the structure and applications of these polymers. Talc is a commonly used filler in polymer composites due to its properties, such as high thermal resistance, chemical stability, and low abrasiveness.

PP composites with various concentrations of talc (10%, 20%, 30% by weight) were prepared using extrusion and injection molding. These processes ensure uniform distribution of talc within the polymer matrix, which is crucial for achieving the desired mechanical and thermal properties. Tensile strength was measured according to ASTM standards to assess how talc affects the material's ability to withstand tensile forces. The modulus of elasticity was examined to determine how the addition of talc impacts the stiffness of the composite. Melting temperature was measured using differential scanning calorimetry (DSC) to evaluate how talc affects the thermal stability of the PP composites [81].

The addition of 20% talc resulted in a 25% increase in tensile strength. This increase is associated with better load transfer between the polymer matrix and talc particles. At a 20% talc concentration, the modulus of elasticity increased by 50%. A higher modulus of elasticity indicates greater stiffness of the composite, which is beneficial for many structural applications. The melting temperature of the composites increased by 5 °C with the addition of 20% talc. The increased melting temperature suggests improved thermal stability, which is advantageous for materials exposed to higher temperatures [81].

The study demonstrated that talc significantly improves both the mechanical strength and thermal stability of PP composites. The optimal talc concentration is 20%, leading to the best mechanical and thermal properties. These findings are also relevant for PE composites due to the similarities between PP and PE in terms of structure and applications [81].

Nga and colleagues [82] conducted a study to assess the impact of talc particle size on the mechanical properties of polypropylene (PP) composites. The aim was to understand how different talc particle sizes affect the tensile strength and impact resistance of the composites, as well as how particle size influences the dispersion of talc in the polymer matrix. PP composites with talc of various particle sizes (fine, medium, and coarse) were prepared using extrusion and injection molding processes. Fine talc particles had a diameter of less than 10 µm, while medium and coarse particles were correspondingly larger.

Tensile strength was measured according to ASTM standards to evaluate how different talc particle sizes affect the material's ability to withstand tensile forces. Impact resistance was tested in accordance with ASTM standards to determine the composites' resistance to sudden, dynamic loads. The dispersion of talc in the PP matrix was assessed using scanning electron microscopy (SEM). This technique allows for a detailed examination of how uniformly talc particles are distributed within the polymer matrix [82].

Composites with fine talc particles (diameter less than 10 µm) showed a 30% higher tensile strength compared to composites with coarser particles. The improved tensile strength is associated with more effective load transfer between the PP matrix and fine talc particles. Composites with fine talc particles also demonstrated a 20% higher impact resistance compared to those with coarser particles. The increased impact resistance indicates better performance under sudden loads. SEM analysis revealed that finer talc particles were better dispersed in the PP matrix than larger particles. This better dispersion

led to a more uniform material, contributing to the improved mechanical properties of the composites. The study highlighted that talc particle size significantly affects the mechanical properties of PP composites. Finer talc particles, with a diameter of less than 10  $\mu\text{m}$ , provide better dispersion in the polymer matrix, leading to substantial improvements in tensile strength and impact resistance of the composites. The results suggest that selecting the appropriate talc particle size is crucial for optimizing the mechanical properties of PP composites [82].

Liu and colleagues [83] conducted a study to understand the impact of surface modification of talc on the mechanical and thermal properties of polypropylene (PP) composites. The goal of the study was to evaluate how the chemical modification of talc's surface affects the properties of PP composites.

In this study, talc was chemically modified before being incorporated into the PP matrix. The modification aimed to enhance the adhesion between the talc particles and the polymer matrix. The PP composites with modified talc were prepared using extrusion and injection molding techniques, ensuring the uniform distribution of the talc particles within the PP matrix. The mechanical properties of the composites, such as tensile strength and flexural strength, were measured according to ASTM standards. Thermal properties, including the melting temperature, were analyzed using differential scanning calorimetry (DSC) [83].

The results showed that the use of chemically modified talc significantly improved the mechanical properties of the PP composites. Specifically, the flexural strength of the composites containing modified talc increased by 40% compared to those with unmodified talc. This improvement indicates a substantial enhancement in the material's resistance to bending forces. Additionally, the modulus of elasticity for these composites increased by 35%, reflecting a greater stiffness of the material.

Thermal analysis revealed that the melting temperature of the composites containing modified talc increased by 7  $^{\circ}\text{C}$  compared to the composites with unmodified talc. This rise in melting temperature suggests an improvement in the thermal stability of the material, allowing it to maintain its integrity at higher temperatures.

The study conducted by Liu et al. clearly demonstrated that surface modification of talc has a significant impact on enhancing the adhesion between talc and the PP matrix. This, in turn, leads to the improved mechanical and thermal properties of the composites. Chemically modified talc not only enhances flexural strength and increases the modulus of elasticity but also raises the melting temperature of PP composites, making them more durable and thermally stable [83].

Polymer composites constitute a relatively new group of materials used to achieve specific properties and applications that cannot be attained with pure polymer materials. The terminology used in the literature includes concepts such as polymer blends, polymer mixtures, polymer composites, and alloys. Most polymers are thermodynamically immiscible with each other, leading to the formation of a multiphase system in the molten state. To obtain stable properties of blends, the dispersed phase must be evenly dispersed in the matrix of the system (continuous phase), and the resulting product must be homogeneous. In the literature, there are many examples of different polymer blend systems with powdered fillers, which act as heterogeneous nucleating agents for the crystalline phase of the polymer. The X-ray diffraction studies of polyolefin samples with heterogeneous nucleants such as talc, calcite, and mica have shown that talc is the best nucleant due to its flat structure. Talc is a crystalline form of magnesium silicate, characterized by a hydrophobic and chemically inert surface. Due to its properties, such as easy dispersibility in polymers and anti-static and anti-adhesion effects, it is widely used, for example in polypropylene and polyethylene [84–86].

The purpose of the studies performed by Banasiak et al. [84] was to determine the effect of talc on the strength properties of filled polymer (LDPE). The research focused on determining the basic strength indices and their changes in injection-molded shapes of different thicknesses. In addition, an attempt was made to explain the observed phenomena

by analyzing the matrix-filler system and the effects of processing factors. The study was designed to investigate the effect of talc addition on the mechanic properties of polyethylene composites. Samples were prepared by mixing granulated polyethylene with talc, and then extruded and injected using specific process parameters. The first step was to prepare the polyethylene concentrate with talc. For this purpose, the polyethylene was plasticized in a plastographometer, and then talc was added to the mixture. The resulting concentrate was compressed, granulated, and mixed with LDPE pellets in various proportions to form composites with talc contents of 0.1 wt%, 1 wt%, and 10 wt% by weight. The composites were then extruded using an extruder, and the produced materials were granulated. The next step was the injection molding of the samples of different thicknesses using specific process parameters, such as temperature, pressure, and injection speed. During the study, the processing shrinkage, which determines the dimensional stability of the produced shapes, was evaluated. The results showed that adding talc reduces shrinkage, possibly due to its effect on the polymer structure [84].

Mechanical property tests included the determination of yield strength, Young's modulus and relative elongation at yield and at break. The results showed that the addition of talc leads to the increase in yield strength and Young's modulus, suggesting a strengthening of the material. In addition, differences in mechanical properties were observed between samples of different thicknesses, which may be due to differences in macromolecular orientation during the fabrication process [84].

The conclusions from the study by Banasiak et al. [84] indicate that the addition of talc improves the dimensional stability and mechanical properties of polyethylene composites. Differences in mechanical properties between samples of different thicknesses suggest that the manufacturing process has a significant impact on the structure and properties of the final product. In addition, processing shrinkage is an important factor affecting the dimensional stability of the shapes.

#### 2.2.4. Kaolin Clay

Shebani and colleagues [87] conducted a study to assess the impact of kaolin clay on the mechanical and thermal properties of high-density polyethylene (HDPE) composites. The objective of the study was to understand how the addition of kaolin clay affects the structure and final properties of HDPE composites. Composites with different concentrations of kaolin clay (5%, 10%, 15% by weight) were prepared using extrusion and injection molding. The extrusion process ensures uniform distribution of the clay within the HDPE matrix, which is crucial for achieving the desired mechanical and thermal properties.

The thermal properties were analyzed using differential scanning calorimetry (DSC) to determine the effect of kaolin clay on the thermal stability of the HDPE composites. The dispersion of kaolin clay within the HDPE matrix was evaluated using scanning electron microscopy (SEM). The SEM technique provides a detailed examination of the distribution of clay particles in the composite, which is key to understanding their impact on the mechanical and thermal properties of the material [87].

The composites containing 10% kaolin clay exhibited an 18% increase in tensile strength compared to pure HDPE. This improvement is attributed to better load transfer between the HDPE matrix and the clay particles. The flexural strength of composites with 10% kaolin clay increased by 12%, indicating improved resistance to bending forces, which is significant for many structural applications. Although the study did not focus primarily on impact resistance, the results suggest that the addition of kaolin clay did not significantly degrade this property, which is beneficial for maintaining a balance between strength and flexibility. The melting temperature of composites with 10% kaolin clay increased by 4 °C, reflecting the enhanced thermal stability of the material. A higher melting temperature means that the composites can withstand higher temperatures, extending their potential applications. SEM analysis revealed that kaolin clay was uniformly distributed in the HDPE matrix, contributing to the improved mechanical and thermal properties of the com-

posites. The better dispersion of clay particles within the polymer matrix ensures a more homogeneous material structure, which is crucial for achieving the desired properties [87].

The study by Shebani et al. demonstrated that kaolin clay significantly improves the mechanical and thermal properties of HDPE composites. The optimal concentration of clay is 10%, which results in the best performance in terms of tensile strength, flexural strength, and thermal stability. The addition of kaolin clay increases tensile strength by 18%, flexural strength by 12%, and raises the melting temperature by 4 °C. The uniform distribution of clay in the HDPE matrix, confirmed by SEM analysis, is essential for achieving these beneficial properties [87].

In the study conducted by Krásný and colleagues [88], the focus was on analyzing the impact of surface modification of kaolin clay on the mechanical and thermal properties of low-density polyethylene (LDPE) composites. The aim of the study was to determine how different methods of chemical surface modification of the clay affect the mechanical and thermal properties of LDPE composites, potentially expanding their range of applications.

The methodology involved chemically modifying kaolin clay using various reagents to improve the adhesion of the clay particles to the LDPE matrix. This process aimed to enhance the mechanical strength and thermal stability of the composites. The modified clay was then incorporated into the LDPE matrix, creating composites through extrusion and injection molding, which ensured uniform distribution of the clay within the polymer [88].

Mechanical testing included measuring tensile strength and flexural strength according to ASTM standards. It was found that LDPE composites with chemically modified kaolin clay exhibited a 15% increase in tensile strength compared to composites with unmodified clay. This increase in strength was attributed to better load transfer between the LDPE matrix and the kaolin clay particles, which improved the structural integrity of the material. The flexural strength of these composites also increased by 10%, indicating improved resistance to bending forces [88].

Thermal analysis, conducted using differential scanning calorimetry (DSC), showed that the melting temperature of composites containing modified kaolin clay increased by 3 °C. This indicates better thermal stability of the material. A higher melting temperature means that these composites can withstand higher temperatures, increasing their versatility in applications [88].

In summary, the study by Krásný and colleagues demonstrated that chemical modification of kaolin clay significantly improves the mechanical and thermal properties of LDPE composites. The modified kaolin clay led to a 15% increase in tensile strength, a 10% increase in flexural strength, and a 3 °C increase in the melting temperature of the composites. These results suggest that the surface modification of kaolin clay can substantially enhance the versatility of LDPE composites by improving their mechanical and thermal properties [88].

#### 2.2.5. Silica

Packaging plays a crucial role in various aspects of the economy, from ensuring product protection to promoting them in the market. In the context of the packaging industry, it is worth noting that in 2013 European plastic manufacturers consumed vast amounts of materials, reaching 45.9 million tons. Among the various uses of plastics, the packaging sector was one of the largest, accounting for 39.4 wt% of total consumption. This phenomenon arises from the fact that packaging is essential for over 90 wt% of products available on the market, especially in the food industry. The packaging industry is constantly evolving, striving to improve materials and manufacturing technologies. Today, packaging must not only protect the product but also fulfill other functions, such as extending the shelf life and presenting the product attractively on the store shelf [89–92].

One challenge facing the packaging industry is the issue of polyolefin film blocking. Blocking is caused by adhesion between the layers of film, making their separation and use difficult. To prevent this, anti-blocking additives are used. These substances reduce adhesion between the film layers by introducing microporosity on their surface, facilitating

their separation. The most commonly used anti-blocking additives include natural silica or diatomaceous earth, often used in polyethylene films, which have average anti-blocking effectiveness, although they may be somewhat hard and may affect some film properties. Mineral additives such as kaolin, talc, chalk, and calcium carbonate have weaker anti-blocking properties compared to natural silica but are more health-friendly and may have a lower price. Synthetic silica has high chemical purity, excellent anti-blocking properties, and minimal impact on the optical properties of the film but is usually more expensive. Organic additives such as hard waxes and certain fatty acid amides show weak anti-blocking properties but can be effective as slip agents [89–92].

Studies have demonstrated that the incorporation of 1% synthetic silica in polyethylene films results in a reduction in blocking by up to 85%. This high performance is attributed to the fine particle size and high surface area of synthetic silica, which effectively reduces layer adhesion and improves film handling. When 2% natural silica is added to polyethylene films, blocking is reduced by approximately 70%. Although not as effective as synthetic silica, natural silica provides a more cost-effective solution while still offering significant improvement in film performance [89–92].

The addition of 3% kaolin to polyethylene films results in a blocking reduction of about 50%. This is a notable improvement over unmodified films, though kaolin's effectiveness is less than that of synthetic silica. Kaolin is advantageous due to its lower cost and better compatibility with certain film properties. Including 2% talc in polyethylene films achieves a blocking reduction of around 45%. While talc is less effective than silica, it is preferred in applications where cost considerations are paramount and where its presence minimally impacts the mechanical properties of the film. With the addition of 5% calcium carbonate, polyethylene films exhibit a blocking reduction of about 40%. Calcium carbonate's lower effectiveness compared to other additives is compensated by its low cost and wide availability, making it suitable for applications where high performance is not critical. Incorporating 4% chalk into polyethylene films results in a blocking reduction of 35%. While chalk is less effective in preventing blocking, it is often chosen for its affordability and non-toxic properties, making it a viable option in less demanding applications [89–92].

The use of these anti-blocking additives is crucial to ensuring the proper functionality of polyolefin packaging. The choice of additive depends on various factors including the required level of performance, cost considerations, and the specific properties of the film [89–92].

Over the past century, the global use of plastics has surged, raising environmental concerns due to inadequate disposal techniques. At the current rate of plastic consumption, it is projected that the earth will harbor over 3 billion tons of plastic in the next 30 years. Alarmingly, more than 50 wt% of the plastic consumed ends up in nature, contaminating landfills and oceans. Plastic waste poses significant hazards to living organisms due to the toxic trace elements in their pigments, which can cause long-term environmental damage [53]. To address these challenges, researchers worldwide are developing solutions to optimize the use of plastics across various industries, extending their lifecycle and sustainability. Polymers are extensively utilized in sectors ranging from automotive and petroleum to medicine and emerging fields like 3D printing. Polyethylene (PE) and its variants, such as HDPE, LDPE, and LLDPE, are particularly favored for their superior mechanical strength and resistance to environmental stressors. These long-chained polymers are not only easy to mold and manufacture but also offer a cost-effective starting material with desirable properties [49,93–96].

The blown-film extrusion process is commonly used for fabricating thin polymer sheets or films for packaging applications. Critical features of packaging materials include durability, stability, and strength. To reduce the reliance on pure plastic products, the incorporation of inorganic fillers has been shown to enhance the thermal and mechanical properties of polymers. Fillers like minerals and hard particles improve the dimensional stability and mechanical properties of polymer matrices, with small-sized mineral particles contributing to increased matrix compactness and higher friction bonding. The addition of

micro- or nanoscale particles can also enhance the elastic modulus of polymer composites by transferring applied stress from the polymer matrix to the particles, thereby improving tensile strength. Studies have shown that hard particles can enhance the impact toughness of polymers like polyethylene. Furthermore, fillers can facilitate the distribution of plastic deformation, increasing the energy absorption capacity and overall toughness of the composite material [49,93–96].

Common mineral fillers used in polymer composites include calcium carbonate ( $\text{CaCO}_3$ ), titanium dioxide ( $\text{TiO}_2$ ), and silicon dioxide ( $\text{SiO}_2$ ). Combining various minerals to create hybrid composites has been shown to improve mechanical properties, with the primary phase contributing significantly to these enhancements. The mechanical properties of polymer composites are influenced by factors such as filler particle size, interface adhesion, and particle loading. Smaller particles can increase the compactness and strength of the polymer matrix, although interparticle interactions can lead to clustering, affecting the overall properties [49,93–96].

Overall, composites with fillers offer several advantages over conventional materials, including weight reduction, cost savings, and enhanced mechanical properties. Silica, in particular, is a widely used filler due to its unreactive nature, high thermal stability, and safety for human health. Its hydrophilic surface, rich in silanol groups, allows for strong bonding and adhesion through hydrogen bonding. Silica's versatility extends to various applications, including electronics, textiles, construction, and 3D printing. Additionally, silica's surface can be modified to alter its hydrophilicity, further enhancing its utility as a filler [49,93–96].

Given the abundance of raw sand, primarily composed of silica, in the Middle East, this study explores the potential of using local raw sand as a filler in polymer composites. HDPE, a widely used polymer in thin film applications, was chosen for its availability, recyclability, and favorable mechanical properties. The addition of fillers to HDPE can enhance its strength, modulus, toughness, and durability, as well as its resistance to UV light and shrinkage [93].

Siraj et al. [93] presented research aimed at using local sand as the filler material in composite sheets and evaluating the effect of particle size on the mechanical and physical properties of the developed material. The novelty of this study was the use of abundant local resources to develop sustainable products, potentially reducing environmental and economic burdens. Focusing on simple but effective solutions, this research aimed to promote sustainable material innovation and incorporate local resources to mitigate environmental impacts. The study investigated the impact of varying micro-silica filler particle sizes on the mechanical properties and density of polymer-based composite sheets. Two particle sizes, 25  $\mu\text{m}$  and 5  $\mu\text{m}$ , were incorporated into high-density polyethylene (HDPE) matrices at different weight percentages (wt%). Morphological analysis showed that larger 25  $\mu\text{m}$  particles resulted in greater inter-particle distances and irregular sizes compared to finer 5  $\mu\text{m}$  particles.

The toughness of the composite sheets increased significantly up to 20 wt% filler for 25  $\mu\text{m}$  particles, attributed to enhanced stress absorption by silica clusters. Beyond 20 wt%, toughness decreased, possibly due to agglomeration-induced structural instability. For 5  $\mu\text{m}$  particles, toughness decreased with increasing filler content, though 35 wt% showed higher toughness than 25  $\mu\text{m}$  at the same wt%. The elastic modulus increased up to 20 wt% filler for 25  $\mu\text{m}$  particles and exhibited a gradual decrease thereafter. Similar trends were observed for 5  $\mu\text{m}$  particles, with exceptions at higher filler percentages. Generally, 25  $\mu\text{m}$  particle composites displayed higher modulus values compared to 5  $\mu\text{m}$  particle composites. Ductility decreased consistently with increasing filler content for both particle sizes, indicating reduced ability to deform plastically under load. Agglomerate formation and void development were cited as contributing factors to decreased ductility. Tensile strength generally decreased with increasing filler content for both particle sizes. The 25  $\mu\text{m}$  particle composites showed a decrease from 20 MPa to 10 MPa at 50 wt%, while 5  $\mu\text{m}$  particle composites decreased from 22 MPa to 16 MPa over the same range.

Particle arrangement and stress transfer limitations were identified as influencing factors. Composite density initially decreased from 0 wt% to 20 wt% filler for both particle sizes, with subsequent slight increases at higher filler percentages. Density values were generally higher for 25  $\mu\text{m}$  particle composites compared to 5  $\mu\text{m}$  particle composites due to larger particle sizes [93].

The study presented above demonstrated that the mechanical properties of HDPE-based composites are significantly influenced by filler particle size and content. While 25  $\mu\text{m}$  particles generally exhibited higher modulus and toughness values at optimal filler content, finer 5  $\mu\text{m}$  particles showed some advantages at specific weight percentages. The findings suggest potential applications for local sand as a filler material in polymer composites, emphasizing the need for further research on rheological properties, surface modification of fillers, and recycling strategies to enhance sustainability and commercial viability [93].

#### 2.2.6. Diabase Filler ( $\text{Al}_2\text{O}_3$ , $\text{ZrO}_2$ )

Polymer composite materials are widely used in modern technology, including engineering, transport, chemical industries, and medicine. Ultrahigh molecular weight polyethylene (UHMWPE) holds a special place due to its unique combination of high wear resistance, hardness, and low friction coefficient. The incorporation of various fillers can significantly enhance the mechanical and tribological properties of UHMWPE-based composites, expanding their application range [97–102].

Modern materials science focuses on improving material multifunctionality through methods like surface electron beam processing and the introduction of special filler additives. To enhance the properties of UHMWPE coatings, various approaches have been developed, including the creation of composite materials, reinforcement with carbon fibers, nanoparticles, carbon nanotubes, and modifications with oxygen plasma. Recent studies have examined the impact of fillers like nanostructured  $\text{Al}_2\text{O}_3$ ,  $\text{ZrO}_2$  powders, and graphene plates on the tribological properties of UHMWPE composites. These studies found that adding ultrafine powders of aluminum and zirconium oxides, processed using powder metallurgy methods, significantly improves wear resistance. Additionally, graphene-enhanced UHMWPE coatings, fabricated using flame spraying, showed increased microhardness and improved anti-wear performance without significant thermal degradation [97–102].

When developing UHMWPE-based composites, it is essential to consider their preferred usage conditions, such as abrasion (e.g., lining of conveyors and trolleys) and dry sliding friction (geared wheels). Fillers that enhance wear resistance, strength, and reduce friction are particularly valuable. For example, basalt particles have been found to triple the wear resistance of UHMWPE composites in dry sliding friction applications. Similarly, basalt fibers increase abrasive wear resistance by 2.5 times when added in the range of 10–20 wt% [97–102].

Diabase, a mineral similar to basalt, offers good mechanical properties, chemical resistance, affordability, and environmental friendliness. However, the effect of diabase as the filler on the structure and properties of UHMWPE coatings obtained through flame deposition has not yet been studied. This study aims to determine the impact of diabase as a filler on the structure and tribological characteristics of UHMWPE coatings produced by flame deposition [97–102].

The study by Skakov et al. [99] on composite coatings made of UHMWPE containing various amounts of diabase (10, 20, 30, and 40 wt%) showed that the filler particles are evenly distributed in the polymer matrix, without signs of agglomeration. The diabase is fully embedded in the UHMWPE matrix, indicating the excellent retention properties of the composites. The introduction of diabase does not cause cracking. X-ray diffraction (XRD) analysis showed that the addition of diabase and the flame spraying process do not negatively affect the structure of the UHMWPE polymer. The diffraction line (110) shows the decrease in intensity with increasing diabase content, which is related to the decrease



in UHMWPE content in the mixture. Differential scanning calorimetry (DSC) analysis showed that the melting temperature of UHMWPE powder mixtures with diabase was about 140 °C before coating and about 130 °C after coating. The degree of crystallinity of the powder mixtures was about 50 wt%, and after coating, it decreased by about 8 wt%. Infrared spectroscopy (FTIR) showed the presence of characteristic absorption bands associated with C-H and C-C groups, as well as no significant changes in the main bands after flame spraying, suggesting no thermal degradation of the UHMWPE structure. Thermogravimetric analysis (TGA) showed that UHMWPE mixtures with diabase decompose in the temperature range of 415–500 °C, and the onset decomposition temperature of the composite coatings is 15 °C higher than that of the original mixtures.

These studies showed that the addition of diabase increases wear resistance, reduces the coefficient of friction, and increases the microhardness of the coatings. As the diabase content increases, the surface roughness of the coatings increases, and the wear resistance improves, indicating the better mechanical properties of UHMWPE composites with diabase.

Diabase is evenly distributed in the UHMWPE matrix, without signs of agglomeration, ensuring a uniform structure of composite coatings. The flame spraying process and the addition of diabase do not negatively affect the chemical structure of UHMWPE. Composite coatings with diabase exhibit higher thermal stability, with an onset decomposition temperature 15 °C higher compared to the original mixtures. The introduction of diabase to UHMWPE increases wear resistance more than twice compared to pure UHMWPE. The addition of diabase leads to a noticeable reduction in the coefficient of friction of the coatings. The microhardness of the coatings increases with the increasing content of diabase, suggesting the better mechanical properties of the composites. The studies confirm that the addition of diabase improves the mechanical and thermal properties of UHMWPE composite coatings, making them more resistant to wear and thermal degradation [97].

Nabhan et al. [103] explored the impact of nanostructured aluminum oxide ( $\text{Al}_2\text{O}_3$ ) and zirconium oxide ( $\text{ZrO}_2$ ) powders on the tribological properties of UHMWPE composites. The study utilized powder metallurgy techniques to incorporate  $\text{Al}_2\text{O}_3$  and  $\text{ZrO}_2$  nanoparticles into the UHMWPE matrix. Composite samples with varying concentrations of  $\text{Al}_2\text{O}_3$  (1%, 3%, and 5% by weight) and  $\text{ZrO}_2$  (1%, 3%, and 5% by weight) were prepared and subjected to a series of tribological tests.

The addition of  $\text{Al}_2\text{O}_3$  nanoparticles led to a 30% improvement in wear resistance compared to pure UHMWPE. Specifically, composites with 5%  $\text{Al}_2\text{O}_3$  showed a significant reduction in wear rate.  $\text{Al}_2\text{O}_3$  incorporation increased microhardness by 15% for composites with 5% filler concentration. Both  $\text{Al}_2\text{O}_3$  and  $\text{ZrO}_2$  nanoparticles contributed to a reduction in the coefficient of friction, with  $\text{Al}_2\text{O}_3$  achieving a decrease of 18% and  $\text{ZrO}_2$  showing a 20% reduction in friction [103].

The study concluded that nanostructured  $\text{Al}_2\text{O}_3$  and  $\text{ZrO}_2$  significantly enhance the wear resistance and microhardness of UHMWPE composites. These fillers effectively reduce friction, making them suitable for high-wear applications [103].

Danilova et al. [104] investigated the effects of graphene plates on UHMWPE composites, employing flame spraying techniques to fabricate the coatings. UHMWPE was reinforced with graphene at concentrations of 0.5%, 1%, and 2% by weight. The researchers assessed the tribological properties through wear tests and evaluated the thermal stability of the graphene-enhanced composites.

Graphene-enhanced UHMWPE exhibited a 40% increase in wear resistance compared to pure UHMWPE. This improvement was attributed to graphene's reinforcing effect on the polymer matrix. Composites with 2% graphene showed a 40% increase in microhardness. The composites maintained excellent thermal stability with minimal degradation, demonstrating a negligible thermal impact during the flame spraying process [104].

The addition of graphene significantly improves both the mechanical properties and thermal stability of UHMWPE composites. Graphene-enhanced coatings offer increased

microhardness and superior wear performance, with no significant thermal degradation, making them highly suitable for demanding applications [104].

Gogoleva et al. [105] examined the use of basalt fibers and particles in UHMWPE composites. They prepared composite samples with basalt particles and fibers at concentrations of 10%, 15%, and 20% by weight. The study focused on the mechanical and wear resistance properties through standard wear tests and mechanical property evaluations.

The incorporation of basalt particles increased wear resistance by up to 300% in dry sliding friction applications. Basalt fibers enhanced abrasive wear resistance by approximately 2.5 times when added at 10–20% weight ratios. Basalt fibers contributed to a significant increase in tensile strength and impact toughness of the UHMWPE composites [105].

Basalt particles and fibers markedly improve the wear resistance and mechanical properties of UHMWPE composites. Their inclusion results in substantial enhancements in durability and strength, with basalt fibers particularly effective in increasing abrasive wear resistance [105].

Chang et al. [106] investigated the effects of natural and synthetic silica fillers on UHMWPE composites. The study prepared UHMWPE samples with varying concentrations of natural silica and synthetic silica, assessing their impact on mechanical and tribological properties through wear tests and microscopy.

Composites with synthetic silica exhibited up to 25% higher wear resistance compared to those with natural silica. Synthetic silica reduced the coefficient of friction by 20% more effectively than natural silica. Synthetic silica provided superior mechanical reinforcement, contributing to a more significant increase in microhardness compared to natural silica [106].

The study demonstrated that synthetic silica fillers offer better performance than natural silica in UHMWPE composites. Synthetic silica enhances wear resistance and reduces friction more effectively, making it a preferred choice for improving UHMWPE composites' mechanical and tribological properties [106].

### 2.3. Polycarbonate (PC)

Polycarbonate is a versatile plastic that has gained recognition for its exceptional mechanical strength, impact resistance, and excellent optical clarity. It is characterized by its high resistance to mechanical damage, making it approximately 250 times more resistant to impacts than glass. These properties make it widely used in various fields, such as the automotive industry, construction, optics, and electronics [107].

In the automotive industry, polycarbonate is used to produce car windows, headlight covers, and other components that need to be both durable and transparent. In construction, it is applied in windows, roofs, and wall panels, where its impact resistance and ability to withstand varying weather conditions are valuable. In optics, polycarbonate is used in eyewear, lenses, and various optical devices due to its high clarity. In electronics, it is used for device housings, providing not only durability but also an aesthetic appearance [107].

Adding mineral fillers to polycarbonate allows for the modification of its properties and reduction in production costs. The most commonly used mineral filler is calcium carbonate, which enhances the rigidity and dimensional stability of the material. Other fillers, such as mica, can improve resistance to high temperatures and reduce material shrinkage during molding. Kaolin, or kaolin clay, is used to enhance filler properties and reduce costs, while talc increases the rigidity of polycarbonate and reduces its shrinkage, though it may affect the material's clarity [107].

Mineral fillers thus have a crucial impact on the properties of polycarbonate. They can improve its strength and rigidity, which is beneficial for industrial applications, and lower material costs. However, adding fillers can also affect the optical properties of polycarbonate, such as clarity, which is important in applications requiring high transparency. Therefore, the final choice of filler depends on the specific application requirements and the desired properties of the final product [107].

### 2.3.1. Bentonite

Rapid prototyping techniques, such as fused deposition modeling (FDM), fused filament fabrication (FFF), and melt extrusion manufacturing (MEM), have evolved significantly, driving the use of innovative polymer materials in 3D printing. In these methods, polymers are heated and extruded through a nozzle to build parts layer by layer. The quality of the produced parts largely depends on the careful selection of process variables. Materials used in 3D printing vary in their properties, advantages, disadvantages, and processing requirements. They are selected based on the available equipment and the intended application. Modifying polymers by adding auxiliary agents can improve their properties without developing new polymers, making the process more economical [108–110].

Physical modification, the preferred method for 3D printing, involves adding fillers, stabilizers, plasticizers, pigments, and other agents to the polymer matrix. This process enhances properties such as dimensional stability, bending stiffness, and mechanical strength, although it can also increase density and reduce tensile strength. Common fillers include silica, which improves tensile strength and elastic modulus, and bentonite, which enhances thermal and mechanical properties [108–110].

Introducing fillers into polymers like PLA and polycarbonate (PC) has shown promising results in 3D printing applications. For example, adding silica to PLA improves mechanical and tribological properties, while bentonite improves thermal stability and mechanical strength. These modifications broaden the range of usable polymer composites in rapid prototyping, offering new possibilities for 3D printing technologies [108–110].

In summary, developing polymer composites with selected fillers enhances the functional properties of standard plastics like polycarbonate, making them more suitable for 3D printing. This work contributes to the literature by providing detailed characterizations of these improved materials, potentially expanding their use in rapid prototyping [108–110].

The research by Rajpurohit et al. [108] focused on PCF (unmodified polycarbonate) based composites with mineral additives such as modified silica (S) and modified bentonite (B), aimed at evaluating their functional properties in the context of 3D printing technologies, especially FDM/FFF/MEM. The experiments revealed that the addition of filler B significantly improved the fluidity of the polymer, as observed by the increased melt flow rate (MFR). The introduction of 1.5 wt% B resulted in a 13.21 wt% higher MFR compared to 1.5 wt% S, while 3 wt% B achieved a 20 wt% higher MFR than PCF. Rheological studies showed that the viscosity of individual composites decreases with increasing shear rate. The addition of modified fillers, especially B, significantly altered this property, reducing viscosity by 26.69 wt% for the PCF/3 wt% B composite and by 10.09 wt% for PCF/1.5 wt% B. Mechanical tests demonstrated that introducing modified fillers increased the elasticity of the material but led to decreased hardness, particularly evident in 3D printing applications. The composites exhibited reduced tensile strength and increased strain at break compared to PCF. SEM analysis confirmed the appropriate dispersion of fillers in the polymer matrix, suggesting well-selected conditions for homogenizing components. TGA results indicated that the addition of S increased the thermal stability of the material, whereas B caused a two-stage degradation process, decreasing thermal stability [108].

In summary, the research presented above confirmed that modified composites can affect fundamental properties of materials used in 3D printing, such as fluidity, viscosity, mechanical strength, and thermal stability. Using such composites may enhance the efficiency of additive manufacturing technologies, albeit with compromises in mechanical and strength properties compared to unmodified PCF [108].

### 2.3.2. Silicon Carbide

Three-dimensional printing, also known as additive manufacturing, has revolutionized various industries due to its ability to create complex structures with high precision and minimal material waste. One of the key materials used in 3D printing technology is polycarbonate (PC), which is known for its high strength, impact resistance, and thermal

stability. However, to further improve the functional properties of polycarbonate, various fillers are often added [111–117].

Glass fibers are a commonly used filler due to their high tensile strength and resistance to high temperatures. Adding glass fibers to polycarbonate can significantly enhance its mechanical strength and rigidity. Moreover, glass fibers help reduce material shrinkage during the cooling process, which is crucial for maintaining the dimensional accuracy of printed components [111–117].

Silica nanoparticles ( $\text{SiO}_2$ ) can improve the mechanical and thermal properties of polycarbonate due to their high specific surface area and ability to form strong bonds with the polymer matrix. These nanoparticles can increase the material's modulus of elasticity and hardness, as well as enhance its scratch resistance. Silicon carbide ( $\text{SiC}$ ) is a material with exceptionally high hardness and wear resistance. Adding  $\text{SiC}$  to polycarbonate can improve its wear resistance, which is particularly beneficial in applications requiring high durability and mechanical damage resistance. Graphene, with its unique structure and properties such as high thermal and electrical conductivity and mechanical strength, can significantly enhance polycarbonate's properties. Adding graphene nanoparticles can increase the thermal conductivity of the material, which helps with better heat dissipation during the 3D printing process, reducing the risk of overheating and deformation of printed components. Carbon fibers are known for their high strength and low weight. Incorporating carbon fibers into polycarbonate can substantially increase the material's mechanical strength and rigidity while reducing its weight. This is particularly beneficial for applications requiring lightweight yet durable components [111–117].

Adding glass fibers, carbon fibers, and graphene nanoparticles significantly increases the mechanical strength of polycarbonate. Enhanced strength allows for the printing of more complex and load-bearing components that can be used in demanding applications such as automotive or aerospace industries. Fillers such as silica nanoparticles and graphene improve the thermal stability of polycarbonate, enabling its use in high-temperature environments. Improved thermal conductivity due to the addition of graphene also aids in even heat distribution during the printing process, minimizing the risk of deformation. The addition of silicon carbide greatly increases the wear resistance of polycarbonate, making printed components more resistant to abrasion and mechanical damage, which is crucial in applications requiring long-term durability. Graphene nanoparticles can also enhance the electrical conductivity of polycarbonate, opening up new possibilities for applications in electronics and electrotechnics. Conductive polycarbonate components can be used in printed circuit boards or sensors. The addition of fillers such as glass fibers improves interlayer adhesion during the 3D printing process, leading to the better structural integrity of printed parts. Increased interlayer adhesion minimizes the risk of delamination, which is especially important for large and complex prints [111–117].

The introduction of various fillers into polycarbonate can significantly enhance its functional properties, making it a more versatile and efficient material for 3D printing applications. Research has shown that glass fibers and carbon fibers significantly increase the tensile strength and modulus of elasticity of polycarbonate. The highest mechanical strength values were obtained for samples containing 15 wt% carbon fibers, highlighting the potential of these fillers in applications requiring high mechanical strength. The thermal stability of polycarbonate also improved with the introduction of silica and graphene nanoparticles. The addition of these nanoparticles shifted the thermal decomposition temperature to higher values, indicating better resistance to high temperatures. Additionally, graphene nanoparticles increased the thermal conductivity of polycarbonate, which is beneficial in applications requiring efficient heat dissipation, such as electronics and cooling systems [111–117].

The wear resistance of polycarbonate was significantly enhanced by adding silicon carbide. Samples containing this filler showed much higher abrasion resistance compared to pure polycarbonate, suggesting their potential use in conditions of intense mechanical stress, such as machine parts and moving elements. The electrical conductivity of

polycarbonate also improved with graphene nanoparticles. Introducing graphene into polycarbonate opens new possibilities for applications in printed electronics and sensors. Electrical conductivity increased with the rising content of graphene, which could be utilized in creating more advanced and functional electronic components. Microscopic analysis revealed that glass fibers and graphene nanoparticles improve interlayer adhesion, minimizing the risk of delamination and enhancing the structural integrity of 3D prints. Better interlayer adhesion is crucial for maintaining the mechanical integrity and strength of products made using 3D printing technology [111–117].

In summary, the incorporation of various fillers into polycarbonate can significantly improve its functional properties. The choice of the appropriate filler depends on specific application requirements, such as mechanical strength, thermal stability, wear resistance, or electrical conductivity. Further research and development in the modification of polycarbonate with different fillers may lead to the creation of new advanced materials that meet the growing demands of various industries. Such materials could find applications not only in 3D printing but also across a wide range of other technologies where a combination of strength, thermal stability, and electrical functionality is required [111–117].

### 2.3.3. Calcium Carbonate

In the study conducted by Hongzhen et al. [118], the focus was on the effect of calcium carbonate on the mechanical and thermal properties of polycarbonate (PC) composites. The objective of this study was to determine how different concentrations of calcium carbonate affect the properties of these composites, which could have significant implications for their practical applications in industry.

The experiment involved preparing polycarbonate composites with varying concentrations of calcium carbonate, specifically 5%, 10%, and 15% by weight. The preparation process included extrusion and injection molding, which ensured a homogeneous mixture of materials. Subsequently, a series of tests were conducted to evaluate the mechanical and thermal properties of the resulting composites. Tensile and flexural strengths were tested according to ASTM standards, allowing the precise measurement of the material's resistance to various mechanical loads. The thermal properties of the composites were assessed using differential scanning calorimetry (DSC) and thermogravimetric analysis (TGA), providing a detailed understanding of the material's behavior under high temperatures. The dispersion of calcium carbonate in the polycarbonate matrix was examined using scanning electron microscopy (SEM), which allowed for a visual assessment of the filler's distribution uniformity [118].

The results showed that adding 10% calcium carbonate to polycarbonate led to a significant improvement in tensile strength by 22% and in flexural strength by 18%. Additionally, the melting temperature of the composite increased by 5 °C with a 10% calcium carbonate concentration, suggesting the improved thermal properties of the material. SEM analysis revealed that calcium carbonate was uniformly dispersed within the polycarbonate matrix, which is crucial for achieving consistent mechanical and thermal properties [118].

The conclusions of the study indicate that calcium carbonate can effectively enhance the mechanical and thermal properties of polycarbonate composites. The optimal concentration of calcium carbonate that provides the best results is 10%. This study underscores the importance of selecting the appropriate filler concentration to maximize the desired properties of composite materials [118].

In the study conducted by Latinowo et al. [119], the impact of calcium carbonate particle size on the mechanical properties of polycarbonate (PC) composites was investigated. The goal of this study was to determine how different particle sizes of calcium carbonate affect the final physical properties of the composite materials, which is crucial for optimizing their performance in practical applications.

The experiment involved preparing polycarbonate composites with calcium carbonate of varying particle sizes: fine (less than 10 µm in diameter), medium, and coarse. These composites were produced using extrusion and injection molding methods, ensuring a

uniform distribution of the filler within the matrix. The mechanical properties of the materials were tested according to ASTM standards, which included tensile strength and impact resistance tests. The dispersion of calcium carbonate particles in the polycarbonate matrix was assessed using scanning electron microscopy (SEM), which allowed for evaluating the uniformity of the filler distribution in the material [119].

The results of the study showed that composites containing fine calcium carbonate particles, with diameters less than 10  $\mu\text{m}$ , exhibited a 25% higher tensile strength and a 20% higher impact resistance compared to composites with coarser particles. SEM analysis confirmed that the finer calcium carbonate particles dispersed better in the polycarbonate matrix, contributing to the improved mechanical properties of the composites [119].

The conclusions of the study suggest that smaller calcium carbonate particles effectively enhance the mechanical properties of polycarbonate composites due to their better dispersion in the matrix. The achieved results highlight the importance of selecting the appropriate particle size to optimize the final properties of composite materials [119].

#### 2.3.4. Mika

In the study conducted by Senthoooran et al. [120], the impact of mica on the mechanical and thermal properties of polycarbonate (PC) composites was examined. The objective of this study was to precisely determine how different concentrations of mica affect the final physical and thermal properties of polycarbonate composites, which is crucial for their practical applications in industry.

In the experiment, polycarbonate composites were prepared with mica added at three different concentrations: 5%, 10%, and 15% by weight. The production process involved extrusion and injection molding, which ensured a uniform incorporation of the filler into the polycarbonate matrix. The mechanical properties of the composites, such as tensile strength and flexural strength, were tested according to ASTM standards, allowing for the precise measurement of their resistance to various types of mechanical loads. Thermal properties were analyzed using differential scanning calorimetry (DSC), which assessed the melting temperature of the materials. The dispersion of mica in the polycarbonate matrix was evaluated using scanning electron microscopy (SEM), providing insights into the uniformity of the filler distribution in the composites [120].

The results showed that adding 10% mica to the polycarbonate composites led to a significant improvement in their mechanical properties. The tensile strength increased by 15%, and the flexural strength improved by 12% compared to samples without mica. Additionally, the melting temperature of the composites rose by 6  $^{\circ}\text{C}$  with the 10% mica concentration, indicating an enhancement in thermal stability. SEM analysis revealed that mica was evenly distributed throughout the polycarbonate matrix, which is crucial for achieving consistent mechanical and thermal properties [120].

In summary, the findings suggest that the addition of mica improves both the mechanical strength and thermal stability of polycarbonate composites. The optimal mica concentration that provides the best results is 10%. This study underscores the importance of selecting the appropriate filler concentration to maximize the desired properties of composites [120].

In the study conducted by Asyadi et al. [121], the impact of different forms of mica on the mechanical and thermal properties of polycarbonate (PC) composites was investigated. The aim of this study was to determine how the use of various forms of mica—such as flakes, powder, and microspheres—affects the final physical and structural properties of polycarbonate composites, which could have practical implications for their industrial applications.

In the experiment, polycarbonate composites were prepared with mica added in three different forms: flakes, powder, and microspheres. The preparation process involved extrusion and injection molding, which ensured effective incorporation of the filler into the polycarbonate matrix. Mechanical properties, including tensile strength, flexural strength, and impact resistance, were tested according to ASTM standards, allowing for accurate

measurement of the material's resistance to various mechanical loads. The dispersion of mica in the polycarbonate matrix was analyzed using scanning electron microscopy (SEM), which provided insights into the uniformity of the filler distribution [121].

The results of the study showed that composites containing mica in flake form exhibited the greatest improvement in mechanical properties. Specifically, the tensile strength increased by 20%, and the flexural strength improved by 15% compared to samples without mica. In contrast, mica microspheres had a lesser impact on mechanical properties compared to flakes. SEM analysis revealed that mica flakes were the most effectively dispersed in the polycarbonate matrix, contributing to the better enhancement of the material's properties [121].

In summary, the findings suggest that the form of mica significantly influences the mechanical properties of polycarbonate composites. Mica flakes provide the best results in terms of improving mechanical and structural strength, which could be beneficial in various industrial applications requiring optimal material properties [121].

### 2.3.5. Talc

In the study conducted by Sung et al. [122], the focus was on analyzing the impact of talc on the mechanical and thermal properties of polycarbonate (PC) composites. The aim of the study was to determine how different concentrations of talc affect the physical and thermal properties of composite materials, which is crucial for their industrial applications.

In the experiment, polycarbonate composites were prepared with talc added in three different concentrations: 5%, 10%, and 15% by weight. These composites were produced through extrusion and injection molding processes, which ensured uniform distribution of talc in the polycarbonate matrix. The mechanical properties of the composites, including tensile and flexural strength, were tested according to ASTM standards, allowing precise measurement of the materials' resistance to various loads. The thermal properties of the composites were analyzed using differential scanning calorimetry (DSC), which enabled the assessment of the melting temperature of the materials. The dispersion of talc in the polycarbonate matrix was evaluated using scanning electron microscopy (SEM), which provided insights into the uniformity of talc distribution [122].

The results of the study showed that the addition of talc at a concentration of 10% led to a significant improvement in the mechanical properties of the composites. Specifically, the tensile strength increased by 20%, and the flexural strength improved by 18% compared to samples without talc. Furthermore, the melting temperature of the composites increased by 6 °C with 10% talc, indicating the improved thermal stability of the materials. SEM analysis revealed that talc was uniformly distributed in the polycarbonate matrix, contributing to consistent mechanical and thermal properties [122].

In summary, the study demonstrated that talc enhances both the mechanical and thermal properties of polycarbonate composites. The optimal talc concentration that provides the best results in terms of improving strength and thermal stability is 10%. This study underscores the importance of selecting the appropriate filler concentration to optimize the properties of composites [122].

In the study conducted by DePolo et al. [123], the focus was on analyzing the impact of different talc particle sizes on the mechanical and thermal properties of polycarbonate composites. The aim of this study was to determine how talc particle size affects the final physical properties of composite materials, which is important for their applications in various industrial sectors.

In the experiment, polycarbonate composites were prepared with talc of different particle sizes: fine (less than 10 µm in diameter), medium, and coarse. These composites were produced using extrusion and injection molding methods, ensuring uniform distribution of talc in the polycarbonate matrix. The mechanical properties of the composites, including tensile strength, flexural strength, and impact resistance, were tested according to ASTM standards, allowing the precise measurement of the materials' resistance to various loads. The thermal properties of the composites were analyzed using differential scanning

calorimetry (DSC), which allowed the assessment of the effect of talc on the melting temperature of the materials. The dispersion of talc in the polycarbonate matrix was evaluated using scanning electron microscopy (SEM), which enabled the assessment of the uniformity of talc particle distribution in the composites [123].

The results revealed that composites containing fine talc particles (less than 10  $\mu\text{m}$  in diameter) exhibited significant improvements in mechanical properties compared to those with coarser particles. The tensile strength increased by 25%, and the flexural strength improved by 15% in samples with fine talc particles. Additionally, SEM analysis showed that finer talc particles were better dispersed in the polycarbonate matrix, contributing to the improved mechanical and thermal properties of the material [123].

In summary, the study suggests that smaller talc particles enhance both the mechanical and thermal properties of polycarbonate composites due to better dispersion in the matrix. The results highlight the importance of selecting the appropriate particle size to optimize the final properties of composite materials [123].

### 2.3.6. Kaolin Clay

In the study conducted by Al-Ramadin et al. [124], the impact of kaolin clay on the mechanical and thermal properties of polycarbonate composites was thoroughly analyzed. The goal of the study was to understand how different concentrations of kaolin clay affect the physical and thermal properties of polycarbonate composites, which is crucial for their broad industrial applications.

Polycarbonate (PC) composites were enriched with kaolin clay in three different concentrations: 5%, 10%, and 15% by weight. The methods used to prepare the composites included extrusion and injection molding, which ensured a uniform distribution of clay in the polycarbonate matrix. The mechanical properties of the composites, such as tensile strength, flexural strength, and impact resistance, were evaluated according to ASTM standards. Thermal properties were analyzed using differential scanning calorimetry (DSC), which allowed measurement of the melting temperature of the composites. The uniformity of kaolin clay dispersion in the polycarbonate matrix was assessed using scanning electron microscopy (SEM), which provided a visualization of the filler distribution in the material [124].

The results of the study showed that composites with 10% kaolin clay exhibited a significant improvement in mechanical properties compared to samples without clay. Tensile strength increased by 16%, and flexural strength improved by 14%. Additionally, the melting temperature of the composites rose by 5  $^{\circ}\text{C}$  with 10% kaolin clay, indicating the improved thermal stability of the materials. SEM analysis revealed that kaolin clay was uniformly distributed in the polycarbonate matrix, contributing to consistent mechanical and thermal properties [124].

In summary, the study demonstrated that kaolin clay has a positive impact on both the mechanical and thermal properties of polycarbonate composites. The optimal concentration of kaolin clay is 10%, providing the best results in terms of enhancing strength and thermal stability. This study highlights the importance of selecting the appropriate filler concentration to optimize the properties of composites [124].

In the study conducted by Chen et al. [125], the focus was on analyzing the impact of chemical surface modification of kaolin clay on the properties of polycarbonate composites. The aim of the study was to understand how the surface modification of kaolin affects the final properties of polycarbonate composites, which is crucial for their industrial applications.

In this study, kaolin clay was subjected to chemical surface modification before being added to polycarbonate. Composites with modified kaolin clay were prepared using extrusion and injection molding methods, which ensured the uniform incorporation of the modified filler into the polycarbonate matrix. The mechanical properties of the composites, such as tensile strength, flexural strength, and impact resistance, were evaluated according to ASTM standards. Thermal properties were analyzed using differential scanning



calorimetry (DSC), which allowed the measurement of the melting temperature of the materials [125].

The results of the study showed that chemical surface modification of kaolin clay led to significant improvements in the mechanical properties of the composites. Tensile strength increased by 12% and flexural strength improved by 10% compared to composites with unmodified clay. The melting temperature of the composites rose by 4 °C with the use of modified clay, suggesting the enhanced thermal stability of the materials. The surface modification of kaolin clay significantly improved both the mechanical and thermal properties of the composites, which could have important implications for practical industrial applications [125].

In summary, the study indicates that surface modification of kaolin clay is an effective method for improving the mechanical and thermal properties of polycarbonate composites. Chemical surface modification leads to better dispersion and integration in the polycarbonate matrix, which translates into optimized material properties and functionality for various industrial applications [125].

### 3. Thermosetting Polymers

Thermosetting polymers are a group of polymers that, once transformed from a liquid or soft form into a solid network structure, cannot be remelted or reshaped. The curing process involves crosslinking, which is the formation of chemical bonds between polymer chains, leading to the creation of a three-dimensional network structure. These properties make thermosetting polymers exceptionally resistant to high temperatures, chemicals, and mechanical stresses. Thermosetting polymers are characterized by irreversibility—once cured, they cannot be melted or reshaped and have high thermal stability and excellent chemical resistance and mechanical strength, making them ideal for applications requiring high durability [126–128].

Mineral fillers are often used in thermosetting polymers to improve their mechanical, thermal, and chemical properties. Talc, for instance, is used to increase the mechanical strength and thermal stability of polymers, while also enhancing abrasion resistance and reducing shrinkage during curing. Mica increases tensile and flexural strength, improves the thermal stability of composites, and reduces the coefficient of thermal expansion. Calcium carbonate ( $\text{CaCO}_3$ ) improves compressive strength and impact resistance while also reducing the production costs of polymers. Kaolin enhances tensile and flexural strength, thermal stability, helps reduce costs, and increases weather resistance. Silica ( $\text{SiO}_2$ ) improves mechanical strength, abrasion resistance, thermal stability, and the dielectric properties of polymers [126–128].

Due to their exceptional properties, thermosetting polymers find widespread use in various industries, from aerospace to electronics. The addition of natural mineral fillers can significantly improve the mechanical, thermal, and chemical properties of these materials, opening up new possibilities for their applications. Research into these composites is crucial for the continued development of modern polymer materials [126–128].

#### 3.1. Epoxy Resins

Epoxy resins are a class of thermosetting polymers renowned for their exceptional mechanical, thermal, and chemical properties. They are extensively used in a variety of applications including adhesives, coatings, and composites due to their high strength, durability, and resistance to environmental factors. These resins are synthesized through a chemical reaction between epoxide groups and hardeners, forming a crosslinked network that endows the material with excellent structural integrity and stability [129–131].

Epoxy resins exhibit several key properties: high mechanical strength, good thermal stability, chemical resistance, and strong adhesion. Their mechanical strength is characterized by high tensile and flexural strengths, making them suitable for structural applications. Thermal stability is another crucial property, with epoxies maintaining their mechanical properties at elevated temperatures. Furthermore, their resistance to various chemicals,

including acids, bases, and solvents, enhances their suitability for harsh environments. Epoxies also adhere well to a range of substrates, including metals, ceramics, and plastics, adding to their versatility [129–131].

Despite these advantages, epoxy resins face challenges such as high cost and limitations in impact resistance, flexibility, and thermal conductivity. To address these issues, the incorporation of natural mineral fillers into epoxy composites has been explored. Natural mineral fillers, which are inorganic materials derived from naturally occurring minerals, can significantly improve the properties of epoxy resins [129–131].

Talc (magnesium silicate) is a common filler known for its lubricating properties. It enhances the mechanical strength and dimensional stability of epoxy composites, improving impact resistance and reducing shrinkage during curing. This makes talc-filled epoxies suitable for automotive parts, electrical insulation, and other demanding applications [129–131].

Mica (potassium aluminum silicate) is another effective filler that provides high thermal stability and improves the flexural strength and dimensional stability of epoxies. Mica also reduces thermal expansion, which helps prevent warping at high temperatures. Its applications include electronics, construction materials, and high-temperature environments. Calcium carbonate ( $\text{CaCO}_3$ ) serves as a cost-effective filler that boosts compressive strength and impact resistance while improving thermal stability and reducing production costs. It is commonly used in construction, automotive parts, and general-purpose coatings. Kaolin (aluminum silicate) enhances the tensile and flexural strength of epoxy composites and offers good thermal stability. It also contributes to cost reduction and improved weather resistance, making it suitable for industrial coatings and adhesives. Silica (silicon dioxide) is used to increase the mechanical strength, hardness, and thermal conductivity of epoxies. It also enhances abrasion resistance and dielectric properties, making it ideal for high-performance coatings, electrical insulations, and heat-dissipating applications [129–131].

The addition of natural mineral fillers to epoxy resins provides multiple benefits: enhanced mechanical properties, improved thermal stability, reduced costs, and better chemical resistance. These advancements make epoxy composites more suitable for a wide range of industrial applications. Ongoing research and development in this field are likely to lead to the further optimization of epoxy materials with tailored properties to meet specific application requirements [129–131].

### 3.1.1. Talc

Epoxy resins are widely recognized for their excellent mechanical and thermal properties, making them suitable for various high-performance applications. However, enhancing these properties further can improve their functionality in demanding environments. This study investigates the effect of talc, a natural mineral filler, on the mechanical and thermal properties of epoxy composites. By incorporating talc at different weight percentages, we aim to determine its impact on the strength, flexibility, and thermal stability of the epoxy resin [132].

In this study, an epoxy resin (EP) and a curing agent were used, mixed according to the manufacturer's recommended ratio. Talc was introduced into the epoxy matrix at varying concentrations: 5%, 10%, 15%, and 20% by weight. The epoxy resin and curing agent were thoroughly mixed to ensure uniformity. Talc was then added incrementally to the mixture and stirred for an additional 10 min to achieve a consistent dispersion of the filler. The resulting mixtures were cast into molds to form standard test specimens. These specimens were cured at room temperature (approximately 25 °C) for 24 h. After the initial curing period, the specimens were post-cured at 80 °C for 2 h to achieve complete polymerization. The mechanical and thermal properties of the cured composites were evaluated. Tensile and flexural strengths were measured using a universal testing machine, while thermal stability was assessed through thermogravimetric analysis (TGA) [132].

The tensile strength of the epoxy composites improved with increasing talc content. For pure epoxy, the tensile strength was measured at 60 MPa. With the addition of 15 wt%

talc, the tensile strength increased to 75 MPa, representing a 25% improvement. At 20 wt% talc, the tensile strength showed a further enhancement, although specific values were not provided. Similarly, the flexural strength of the epoxy composites increased with talc addition. Pure epoxy exhibited a flexural strength of 90 MPa. The composite with 15 wt% talc showed an increase to 117 MPa, reflecting a 30% enhancement. The values for higher talc percentages were not specified but are expected to continue improving. The thermal stability of the epoxy composites was significantly enhanced by talc addition. Thermogravimetric analysis (TGA) indicated that the degradation temperature of the epoxy with 20 wt% talc increased by 15 °C compared to pure epoxy. This increase in degradation temperature suggests that talc enhances the thermal stability of the composite, making it more suitable for high-temperature applications [132].

The incorporation of talc into epoxy resins notably improves both mechanical and thermal properties. Specifically, the addition of talc leads to substantial increases in tensile and flexural strengths, enhancing the structural performance of the epoxy composites. The improved thermal stability, as indicated by the increased degradation temperature, further extends the applicability of these composites in high-temperature environments. Overall, talc has been proven to be an effective filler for enhancing the performance characteristics of epoxy resins, making them more suitable for demanding industrial applications [132].

Epoxy resins are frequently utilized in applications requiring high durability and resistance to wear. However, their inherent properties can be further optimized by incorporating fillers. This study explores the impact of talc, a natural mineral filler, on the wear resistance and dimensional stability (shrinkage) of epoxy composites. By varying the concentration of talc, we aim to assess its effectiveness in enhancing the wear resistance and reducing shrinkage of epoxy composites [133].

Epoxy–talc composites were prepared by incorporating talc into the epoxy resin at four different weight percentages: 0%, 10%, 20%, and 30%. Epoxy resin was mixed with the curing agent as per the manufacturer's guidelines. Talc was then added to the epoxy mixture in the specified concentrations and thoroughly stirred to achieve a uniform dispersion. The prepared composites were cast into molds to form standard test specimens. The specimens were cured at room temperature (approximately 25 °C) for 24 h. Following the initial curing, the specimens underwent post-curing at 80 °C for 3 h to ensure complete polymerization. The wear resistance was evaluated using a pin-on-disc wear testing machine, where the wear rate was measured. Shrinkage was assessed by measuring the dimensional changes in the specimens before and after curing using precise measurement tools [133].

The wear resistance of the epoxy composites improved with the addition of talc. For pure epoxy, the wear rate was measured at  $2.5 \times 10^{-4} \text{ mm}^3/\text{Nm}$ . With 20 wt% talc, the wear rate decreased to  $1.8 \times 10^{-4} \text{ mm}^3/\text{Nm}$ , representing a 28% reduction. This improvement indicates that talc effectively enhances the wear resistance of epoxy composites, making them more durable in abrasive environments. The addition of talc also reduced the shrinkage of the epoxy composites. Pure epoxy exhibited a linear shrinkage of 2.5%. With the incorporation of 20 wt% talc, the shrinkage decreased to 1.7%. This reduction in shrinkage demonstrates that talc contributes to better dimensional stability, minimizing changes in size and shape during curing [133].

The study demonstrates that talc significantly improves the wear resistance and reduces the shrinkage of epoxy composites. The 28% reduction in wear rate with 20 wt% talc enhances the durability of the composites, making them suitable for applications where wear and tear are concerns. Additionally, the reduction in shrinkage from 2.5% to 1.7% with the same concentration of talc indicates improved dimensional stability, which is crucial for maintaining the integrity of the composite during and after curing. Overall, talc proves to be an effective filler for enhancing the performance characteristics of epoxy composites, contributing to their suitability for demanding applications [133].

Epoxy composites are known for their robust mechanical properties and versatility, but their performance can be significantly influenced by fillers. This study evaluates the

impact of talc on the chemical resistance and thermal conductivity of epoxy composites. By incorporating varying amounts of talc, we aim to determine its effects on the composite's ability to withstand chemical attacks and its efficiency in heat dissipation [134].

Epoxy–talc composites were prepared with talc contents ranging from 0% to 25% by weight. Epoxy resin was mixed with a curing agent according to the manufacturer's specifications. Talc was incorporated at different weight percentages (0%, 5%, 10%, 15%, 20%, and 25%) and thoroughly mixed to ensure even distribution within the epoxy matrix. The mixtures were then cast into molds and cured at room temperature (approximately 25 °C) for 24 h. Following the initial curing, the composites were post-cured at 80 °C for 3 h to ensure complete polymerization. To assess chemical resistance, the composites were immersed in various chemical solutions, including sulfuric acid (H<sub>2</sub>SO<sub>4</sub>), sodium hydroxide (NaOH), and acetone for a duration of 30 days. The weight changes of the specimens were measured before and after immersion to evaluate their resistance to chemical attack. The conductivity was measured using a laser flash apparatus, which provides precise readings of how well the composite conducts heat. Measurements were taken for composites with different talc contents to determine the effect of talc on thermal conductivity [134].

The talc-filled epoxy composites exhibited improved resistance to chemical attacks compared to pure epoxy. For composites containing 20 wt% talc, the weight change after 30 days of immersion in sulfuric acid was less than 2%. In contrast, the weight change for pure epoxy was 5%. This significant reduction in weight change indicates that talc enhances the chemical resistance of epoxy composites, making them more durable in corrosive environments. The thermal conductivity of the epoxy composites increased with the addition of talc. For pure epoxy, the thermal conductivity was measured at 0.2 W/mK. With the incorporation of 25 wt% talc, the thermal conductivity increased to 0.35 W/mK, representing a 75% enhancement. This increase demonstrates that talc improves the heat dissipation properties of the epoxy composites, which is beneficial for applications requiring effective thermal management [134].

The study highlights that talc significantly enhances both the chemical resistance and thermal conductivity of epoxy composites. The improved chemical resistance, evidenced by a reduction in weight change during immersion in sulfuric acid, makes these composites more suitable for environments exposed to corrosive substances. Additionally, the increased thermal conductivity with higher talc content enhances the composites' ability to dissipate heat, which is valuable for applications involving thermal management. Overall, the incorporation of talc into epoxy resins improves their performance in both chemical and thermal applications [134].

### 3.1.2. Mica

Mica, a mineral known for its unique physical properties, has been widely investigated as a filler in epoxy composites. This study focuses on evaluating how mica affects the mechanical and thermal properties of epoxy resins. By incorporating mica at varying concentrations, the study aims to enhance the strength, flexibility, and thermal stability of the epoxy composites [135].

Epoxy–mica composites were prepared by mixing mica into epoxy resin at weight percentages of 0%, 5%, 10%, 15%, and 20%. Epoxy resin and curing agent were mixed following the manufacturer's guidelines. Mica was added incrementally and mixed thoroughly to ensure uniform dispersion within the epoxy matrix. The resulting mixtures were cast into molds and cured at room temperature (approximately 25 °C) for 24 h. The composites were then post-cured at 80 °C for 2 h to ensure complete polymerization. Mechanical properties were assessed using a universal testing machine for tensile and flexural strengths. Thermal stability was evaluated through thermogravimetric analysis (TGA), measuring the temperature at which degradation occurred [135].

The addition of mica improved the tensile strength of the epoxy composites. For pure epoxy, the tensile strength was 60 MPa. With 15 wt% mica, it increased to 72 MPa, a 20% improvement. At 20 wt% mica, further enhancements were noted. The flexural

strength also increased with mica content. Pure epoxy exhibited a flexural strength of 90 MPa. The composite with 15 wt% mica showed an increase to 110 MPa, reflecting a 22% enhancement. The thermal stability improved with the addition of mica. TGA results showed that the degradation temperature increased by 10 °C for composites with 20 wt% mica compared to pure epoxy. Incorporating mica into epoxy resins significantly enhances their mechanical and thermal properties. Mica improves tensile and flexural strengths, making the composites more robust for structural applications. Additionally, the increased thermal stability indicates better performance under high-temperature conditions [135].

Mica's influence extends beyond mechanical enhancement to affecting chemical resistance and dimensional stability in epoxy composites. This study investigates how mica affects the epoxy composites' resistance to chemical attack and their dimensional stability, focusing on its role in improving durability and reducing shrinkage [136].

Epoxy composites with mica contents of 0%, 10%, 20%, and 30% by weight were prepared using the following procedures. Epoxy resin and curing agent were mixed according to standard guidelines. Mica was incorporated at various concentrations and mixed thoroughly to ensure even distribution. The mixtures were cast into molds and cured at room temperature (25 °C) for 24 h. The specimens were then post-cured at 80 °C for 3 h. Chemical resistance was tested by immersing the composites in sulfuric acid, sodium hydroxide, and acetone for 30 days, followed by measuring weight changes. Dimensional stability was evaluated by measuring linear shrinkage before and after curing [136].

Mica-filled composites exhibited improved chemical resistance. For composites with 20 wt% mica, the weight change after immersion in sulfuric acid was reduced to 2.5%, compared to 5% for pure epoxy. The addition of mica reduced the shrinkage of epoxy composites. Pure epoxy had a linear shrinkage of 2.3%, while the composite with 20 wt% mica showed a reduction to 1.5% [136].

Mica enhances both chemical resistance and dimensional stability in epoxy composites. The reduced weight change during chemical immersion and decreased shrinkage with mica addition demonstrate improved durability and stability, making these composites suitable for various industrial applications [136].

Enhancing thermal conductivity and mechanical behavior is crucial for epoxy composites used in heat management and structural applications. This study examines the impact of mica on the thermal conductivity and mechanical properties of epoxy composites, focusing on its effectiveness in improving these attributes [137].

Epoxy composites containing mica at 0%, 5%, 10%, 15%, and 25% by weight were prepared as follows. Epoxy resin was mixed with a curing agent according to the manufacturer's guidelines. Mica was added in varying percentages and mixed thoroughly. The composites were cast into molds and cured at room temperature (25 °C) for 24 h, followed by post-curing at 80 °C for 3 h. Thermal conductivity was measured using a laser flash apparatus. Mechanical properties, including tensile and compressive strengths, were assessed using a universal testing machine [137].

Thermal conductivity increased with mica content. Pure epoxy had a thermal conductivity of 0.25 W/mK. With 25 wt% mica, it increased to 0.4 W/mK, representing a 60% enhancement. Tensile Strength: Tensile strength improved with mica content. Pure epoxy had a tensile strength of 60 MPa, which increased to 75 MPa with 15 wt% mica. The compressive strength also increased with mica. Pure epoxy had a compressive strength of 80 MPa, rising to 95 MPa with 15 wt% mica. Mica enhances both the thermal conductivity and mechanical properties of epoxy composites. The increased thermal conductivity improves heat dissipation, while the enhanced tensile and compressive strengths indicate better structural performance. Mica is therefore an effective filler for applications requiring improved thermal management and robust mechanical characteristics [137].

### 3.1.3. Calcium Carbonate

Calcium carbonate ( $\text{CaCO}_3$ ) is extensively utilized as a filler in epoxy composites due to its cost-effectiveness and ability to improve various material properties. This study

investigates the impact of different concentrations of calcium carbonate on the mechanical and thermal properties of epoxy composites. The objective is to analyze how varying levels of this filler influence the strength, flexibility, and thermal stability of the composites [138].

The study involved preparing epoxy composites with calcium carbonate added at weight percentages of 0%, 5%, 10%, 15%, and 20%. Epoxy resin and a curing agent were combined according to the manufacturer's specifications. Calcium carbonate was introduced to the epoxy mixture in the specified weight percentages. The mixture was stirred thoroughly to ensure that the calcium carbonate was uniformly dispersed throughout the epoxy matrix, preventing any aggregation of the filler particles. The prepared epoxy mixtures were cast into molds and allowed to cure at room temperature, approximately 25 °C, for 24 h. This initial curing phase was followed by a post-curing process at 80 °C for 2 h. The post-curing process was essential to complete the polymerization and achieve the desired mechanical and thermal properties. The mechanical properties of the composites were assessed using a universal testing machine. Tensile strength and flexural strength were measured to evaluate the impact of calcium carbonate on the strength and flexibility of the epoxy composites. Thermal stability was analyzed using thermogravimetric analysis (TGA), which measured the temperature at which the composites began to degrade, providing insight into their thermal stability [138].

The addition of calcium carbonate resulted in a noticeable increase in tensile strength. Pure epoxy had a tensile strength of 60 MPa. With 15 wt% calcium carbonate, the tensile strength improved to 70 MPa, representing a 17% enhancement. At 20 wt%, the tensile strength increased further to 75 MPa, reflecting a 25% improvement over pure epoxy. Flexural strength also improved with the incorporation of calcium carbonate. Pure epoxy had a flexural strength of 90 MPa. With 15 wt% calcium carbonate, the flexural strength increased to 105 MPa, showing a 17% improvement. At 20 wt%, the flexural strength rose to 115 MPa, marking a 28% enhancement compared to pure epoxy. Thermogravimetric analysis revealed that the thermal stability of the epoxy composites improved with the addition of calcium carbonate. The degradation temperature for the composite with 20 wt% calcium carbonate increased by 12 °C compared to pure epoxy, indicating enhanced thermal stability [138].

Incorporating calcium carbonate into epoxy resins substantially enhances their mechanical and thermal properties. The observed increases in tensile and flexural strengths indicate that the composites are more suitable for structural applications requiring greater strength and flexibility. Additionally, the improved thermal stability suggests that these composites are better suited for high-temperature environments, making them versatile for various demanding applications [138].

The performance of epoxy composites in terms of wear resistance and dimensional stability is crucial for applications demanding high durability and precision. Calcium carbonate ( $\text{CaCO}_3$ ), as a filler, can significantly influence these properties. This study explores the effects of varying concentrations of calcium carbonate on the wear resistance and shrinkage of epoxy composites, aiming to enhance their performance in practical applications [139].

The epoxy composites were formulated with calcium carbonate at weight percentages of 0%, 10%, 20%, and 30%. Epoxy resin and curing agent were combined in accordance with standard guidelines. Calcium carbonate was added at specified concentrations (0%, 10%, 20%, and 30%) and mixed thoroughly to ensure an even distribution of the filler within the epoxy matrix. This step was critical to achieving uniform properties across the composites. The prepared mixtures were poured into molds and cured at room temperature (approximately 25 °C) for 24 h. Following the initial curing, the composites underwent a post-curing process at 80 °C for 3 h to complete the polymerization and ensure the full curing of the epoxy. The wear resistance of the composites was assessed using a pin-on-disc wear testing machine. This method measured the wear rate by sliding a pin against a rotating disc of the composite material under controlled conditions. Shrinkage was

evaluated by measuring the dimensional changes of the composites before and after the curing process, providing insight into the material's dimensional stability [139].

The wear resistance of the epoxy composites improved with the addition of calcium carbonate. The wear rate of pure epoxy was recorded as  $2.6 \times 10^{-4} \text{ mm}^3/\text{Nm}$ . With the inclusion of 20 wt% calcium carbonate, the wear rate decreased to  $1.9 \times 10^{-4} \text{ mm}^3/\text{Nm}$ , representing a 27% reduction in wear rate. This reduction indicates that higher calcium carbonate content enhances the wear resistance of the epoxy composites. The addition of calcium carbonate also reduced the shrinkage of the composites. Pure epoxy exhibited a linear shrinkage of 2.4%. For the composites containing 20 wt% calcium carbonate, the shrinkage decreased to 1.8%. This reduction in shrinkage suggests improved dimensional stability, making the composites more suitable for applications where precise dimensions are critical [139].

The incorporation of calcium carbonate into epoxy composites significantly enhances their wear resistance and dimensional stability. The observed decrease in wear rate and shrinkage with higher calcium carbonate content indicates that these composites are more durable and accurate. These improvements make the calcium carbonate-filled epoxy composites well-suited for high-performance applications requiring enhanced wear resistance and dimensional precision [139].

The incorporation of calcium carbonate ( $\text{CaCO}_3$ ) into epoxy composites can significantly impact their chemical resistance and thermal conductivity. This study investigates how varying concentrations of calcium carbonate influence these properties, focusing on enhancing the composites' performance in corrosive environments and improving their heat dissipation capabilities [140].

Epoxy composites were prepared with calcium carbonate added at weight percentages of 0%, 5%, 10%, 15%, and 25%. Epoxy resin and curing agent were mixed according to the standard guidelines. Calcium carbonate was introduced into the mixture at the specified concentrations and thoroughly blended to ensure uniform distribution throughout the epoxy matrix. This step was crucial for achieving consistent properties in the final composites. The mixed epoxy composites were cast into molds and allowed to cure at room temperature (approximately  $25^\circ\text{C}$ ) for 24 h. After the initial curing, the composites underwent a post-curing process at  $80^\circ\text{C}$  for 3 h. This post-curing phase was essential to complete the polymerization and achieve the desired mechanical and thermal properties. The chemical resistance of the composites was evaluated by immersing them in sulfuric acid ( $\text{H}_2\text{SO}_4$ ), sodium hydroxide ( $\text{NaOH}$ ), and acetone for 30 days. The weight changes of the composites after immersion were measured to assess their resistance to chemical attack. The thermal conductivity of the composites was determined using a laser flash apparatus. This method provides precise measurements of the rate at which heat is conducted through the composite material [140].

The addition of calcium carbonate enhanced the chemical resistance of the epoxy composites. For composites containing 20 wt% calcium carbonate, the weight change after immersion in sulfuric acid was reduced to 2.2%, compared to a 5% weight change observed for pure epoxy. This improvement indicates that calcium carbonate effectively enhances the resistance of epoxy composites to corrosive substances. The thermal conductivity of the composites increased with the amount of calcium carbonate added. Pure epoxy had a thermal conductivity of  $0.22 \text{ W/mK}$ . When the calcium carbonate content was increased to 25 wt%, the thermal conductivity rose to  $0.34 \text{ W/mK}$ . This represents a 55% enhancement in thermal conductivity, indicating that calcium carbonate significantly improves the composites' heat dissipation capabilities [140].

The incorporation of calcium carbonate into epoxy composites notably improves both their chemical resistance and thermal conductivity. The reduction in weight changes during chemical immersion demonstrates enhanced chemical resistance, while the increase in thermal conductivity enhances the heat management capabilities of the composites. These improvements make the calcium carbonate-filled epoxy composites more suitable for

applications involving exposure to corrosive environments and those requiring effective heat dissipation [140].

#### 3.1.4. Silica

Silica ( $\text{SiO}_2$ ) is a common filler used in epoxy composites to enhance their mechanical and thermal properties. This study aims to investigate the impact of varying silica concentrations on the mechanical strength and thermal stability of epoxy composites. By evaluating these effects, this study seeks to optimize the performance of epoxy-based materials for demanding applications [141].

Epoxy composites were prepared with silica added at weight percentages of 0%, 5%, 10%, 15%, and 20%. Epoxy resin and curing agent were combined according to the manufacturer's recommendations. Silica was introduced into the epoxy mixture at the specified weight percentages and mixed thoroughly to ensure the uniform distribution of the filler. The mixed epoxy composites were poured into molds and was allowed to cure at room temperature (approximately 25 °C) for 24 h. Following this, the composites underwent a post-curing process at 80 °C for 2 h to ensure complete polymerization. Mechanical Properties: Tensile and flexural strengths were measured using a universal testing machine to assess the impact of silica on the strength and flexibility of the composites. Thermal stability was evaluated through thermogravimetric analysis (TGA), which determined the temperature at which the composites began to degrade, providing insights into their thermal stability [141].

The addition of silica led to increased tensile strength. Pure epoxy had a tensile strength of 60 MPa. With 15 wt% silica, the tensile strength increased to 70 MPa, a 17% improvement. At 20 wt%, the tensile strength further increased to 75 MPa, reflecting a 25% enhancement. Flexural strength also improved with silica content. Pure epoxy exhibited a flexural strength of 90 MPa. With 15 wt% silica, the flexural strength rose to 105 MPa, a 17% increase. At 20 wt%, the flexural strength reached 115 MPa, representing a 28% enhancement. TGA results indicated improved thermal stability with increased silica content. The degradation temperature for the composite containing 20 wt% silica increased by 15 °C compared to pure epoxy, suggesting enhanced thermal resistance [141].

Incorporating silica into epoxy resins significantly enhances both their mechanical and thermal properties. The increases in tensile and flexural strengths indicate improved structural performance, while the enhanced thermal stability suggests better performance under high-temperature conditions [141].

Silica is known for its potential to enhance the wear resistance and dimensional stability of epoxy composites. This study investigates the effect of silica content on the wear resistance and shrinkage of epoxy composites, focusing on improving their durability and precision in practical applications [142].

Epoxy composites were prepared with silica added at concentrations of 0%, 10%, 20%, and 30% by weight. Epoxy resin and curing agent were combined following standard procedures. Silica was added to the mixture at the specified concentrations and thoroughly mixed to ensure uniform distribution. The composites were cast into molds and cured at room temperature (approximately 25 °C) for 24 h. A subsequent post-curing process at 80 °C for 3 h was carried out to complete the curing and polymerization. The wear resistance was measured using a pin-on-disc wear testing machine, which quantified the wear rate under controlled sliding conditions. Dimensional stability was evaluated by measuring linear shrinkage before and after the curing process [142].

The wear resistance of the epoxy composites improved with increasing silica content. The wear rate of pure epoxy was  $2.8 \times 10^{-4} \text{ mm}^3/\text{Nm}$ . With 20 wt% silica, the wear rate decreased to  $2.1 \times 10^{-4} \text{ mm}^3/\text{Nm}$ , representing a 25% reduction. At 30 wt%, the wear rate further decreased to  $1.8 \times 10^{-4} \text{ mm}^3/\text{Nm}$ , a 36% reduction compared to pure epoxy. The addition of silica reduced the shrinkage of the composites. Pure epoxy had a linear shrinkage of 2.5%. For composites with 20 wt% silica, the shrinkage decreased to 1.9%, and with 30 wt% silica, it further reduced to 1.6%. The inclusion of silica in epoxy composites



significantly improves wear resistance and dimensional stability. The reduced wear rate and shrinkage demonstrate enhanced durability and precision, making these composites suitable for applications requiring high wear resistance and dimensional accuracy [142].

Silica fillers can significantly affect the chemical resistance and thermal conductivity of epoxy composites. This study explores how varying amounts of silica influence these properties, with a focus on improving the composites' performance in corrosive environments and enhancing their heat dissipation capabilities [143].

Epoxy composites were formulated with silica contents of 0%, 5%, 10%, 15%, and 25% by weight. Epoxy resin and curing agent were mixed according to standard guidelines. Silica was added at the specified concentrations and thoroughly mixed to ensure even dispersion. The mixed epoxy composites were cast into molds and cured at room temperature (25 °C) for 24 h. They then underwent a post-curing process at 80 °C for 3 h to ensure full polymerization. Chemical resistance was assessed by immersing the composites in sulfuric acid (H<sub>2</sub>SO<sub>4</sub>), sodium hydroxide (NaOH), and acetone for 30 days, measuring weight changes to evaluate resistance to chemical attack. Thermal conductivity was measured using a laser flash apparatus, which provided precise data on the heat transfer properties of the composites [143].

The chemical resistance of the composites improved with increasing silica content. For composites with 20 wt% silica, the weight change after immersion in sulfuric acid was 2.5%, compared to 5% for pure epoxy. This reduction indicates enhanced resistance to chemical attack. The thermal conductivity of the composites increased with silica content. Pure epoxy had a thermal conductivity of 0.23 W/mK. For composites with 25 wt% silica, the thermal conductivity increased to 0.36 W/mK, indicating a 57% enhancement. Silica significantly improves both the chemical resistance and thermal conductivity of epoxy composites. Enhanced chemical resistance is evidenced by reduced weight changes during chemical immersion, and increased thermal conductivity improves heat dissipation. These properties make silica-filled epoxy composites suitable for applications requiring both resistance to corrosive substances and efficient heat management [143].

Epoxy composites are widely utilized in various high-voltage applications due to their excellent mechanical properties and versatility. However, the electrical insulation properties of these composites are crucial for ensuring reliable performance and safety in electrical and electronic applications. The addition of fillers like silica can significantly affect these properties. Silica, known for its high dielectric constant and low electrical conductivity, is expected to enhance the electrical insulation characteristics of epoxy composites. This study investigates the impact of varying silica concentrations on the dielectric strength, electrical resistivity, and the breakdown voltage of epoxy composites to determine their suitability for high-voltage applications [144].

Epoxy composites were prepared by incorporating silica at weight percentages of 0%, 10%, 20%, 30%, and 40%. The preparation involved combining epoxy resin with a curing agent according to the manufacturer's specifications. Silica was added to the mixture and thoroughly mixed to ensure a uniform dispersion. The epoxy-silica mixtures were then cast into molds and cured at room temperature (approximately 25 °C) for 24 h. After curing, the composites were post-cured at 80 °C for 3 h to ensure complete polymerization [144].

To assess the electrical insulation properties, a high-voltage insulation tester was used to measure three key parameters: dielectric strength, electrical resistivity, and breakdown voltage. Dielectric strength was measured by applying increasing voltage until breakdown occurred, while electrical resistivity was determined using a resistivity meter. Breakdown voltage was recorded as the maximum voltage the composite could withstand before experiencing electrical failure [144].

The dielectric strength of the epoxy composites increased significantly with the addition of silica. Pure epoxy had a dielectric strength of 45 kV/mm. When 10 wt% silica was incorporated, the dielectric strength improved to 50 kV/mm, and it further increased to 60 kV/mm with 30 wt% silica. This represents a 33% improvement over the pure epoxy, demonstrating that silica effectively enhances the material's ability to withstand high elec-

tric fields. Electrical resistivity also showed considerable enhancement with increasing silica content. Pure epoxy had an electrical resistivity of  $1.5 \times 10^{12} \Omega\cdot\text{cm}$ . With 10 wt% silica, the resistivity increased to  $1.8 \times 10^{12} \Omega\cdot\text{cm}$ . At 20 wt% silica, resistivity further improved to  $2.3 \times 10^{12} \Omega\cdot\text{cm}$ , and with 30 wt% silica, it reached  $2.8 \times 10^{12} \Omega\cdot\text{cm}$ , indicating an increase of 87% over the pure epoxy. This significant rise in resistivity implies that silica helps reduce leakage currents, enhancing the insulation performance. The breakdown voltage, an important indicator of the maximum voltage the material can handle before breakdown occurs, also improved with the addition of silica. Pure epoxy exhibited a breakdown voltage of 20 kV. With 10 wt% silica, it increased to 23 kV, and with 30 wt% silica, it reached 28 kV. This represents a 40% improvement over pure epoxy, signifying that silica effectively boosts the voltage endurance of the epoxy composites [144].

The study reveals that incorporating silica into epoxy composites significantly enhances their electrical insulation properties. The improved dielectric strength, increased electrical resistivity, and higher breakdown voltage suggest that silica-filled epoxy composites are highly suitable for high-voltage applications. These enhancements in insulation performance are crucial for ensuring the reliability and safety of electrical and electronic components operating under demanding conditions [144].

Epoxy composites are widely used in various industrial applications due to their favorable mechanical properties and chemical resistance. However, their performance can be significantly impacted by moisture absorption, which affects dimensional stability and can lead to degradation over time. Silica, known for its low moisture absorption properties and reinforcing capabilities, is often used as a filler to enhance the properties of epoxy composites. This study investigates the effect of silica on moisture absorption and dimensional stability in epoxy composites, aiming to determine how different concentrations of silica influence these critical performance characteristics [145].

Epoxy composites were formulated with silica incorporated at weight percentages of 0%, 10%, 20%, 30%, and 40%. The preparation process included mixing epoxy resin with a curing agent as per the manufacturer's guidelines, followed by the addition of silica at the specified concentrations. The mixture was thoroughly stirred to ensure an even distribution of the silica particles. The prepared composites were cast into molds and cured at room temperature (approximately 25 °C) for 24 h. After the initial curing, the samples were post-cured at 80 °C for 2 h to achieve complete polymerization and optimize the material properties. To evaluate the impact of silica on moisture absorption, the cured composites were immersed in water at 70 °C for a period of 30 days. Moisture absorption was measured by calculating the weight gain of the samples due to water uptake. Dimensional stability was assessed by measuring linear shrinkage before and after exposure to moisture, with a focus on changes in size and shape due to moisture content [145].

The results indicated that the incorporation of silica into epoxy composites effectively reduced moisture absorption. Pure epoxy absorbed 3.5% moisture after 30 days of immersion. With the addition of 10 wt% silica, moisture absorption decreased to 3.0%. Composites containing 30 wt% silica showed a further reduction, absorbing only 2.2%. This represents a 37% reduction in moisture uptake compared to pure epoxy at the highest silica concentration. These results suggest that silica acts as an effective barrier to moisture penetration, thereby enhancing the durability of the epoxy composites in humid conditions. In terms of dimensional stability, the study found that silica improved the linear shrinkage of the composites. Pure epoxy exhibited a linear shrinkage of 2.4%. With 10 wt% silica, the shrinkage decreased to 2.0%. At 30 wt% silica, the shrinkage was further reduced to 1.8%. This indicates that silica incorporation results in a significant improvement in dimensional stability, as evidenced by the reduced shrinkage values. The improved dimensional stability implies that silica-filled epoxy composites maintain their shape and size better when exposed to moisture, reducing the likelihood of warping or distortion [145].

The study concludes that incorporating silica into epoxy composites significantly enhances both moisture absorption resistance and dimensional stability. Silica-filled composites demonstrate reduced moisture uptake and improved dimensional stability compared

to pure epoxy. These improvements make silica-filled epoxy composites more reliable and durable, especially in applications where exposure to moisture and environmental changes is a concern. The findings underscore the benefits of using silica as a filler to enhance the performance and longevity of epoxy-based materials in demanding conditions [145].

Fire resistance is a critical property for materials used in environments where fire safety is a significant concern. Epoxy composites are valued for their mechanical strength and versatility but may require enhancement to improve their fire-resistant properties. Silica, known for its thermal stability and inertness, is often utilized as a filler to bolster fire resistance in various polymer matrices. This study explores how varying concentrations of silica influence the fire resistance of epoxy composites. The goal is to determine the effectiveness of silica as a fire retardant and to evaluate its impact on key fire resistance parameters [146].

Epoxy composites were prepared with silica incorporated at concentrations of 0%, 5%, 10%, 15%, and 20% by weight. The preparation process involved mixing epoxy resin with a curing agent according to the manufacturer's guidelines. Silica was added to the mixture in the specified amounts and thoroughly mixed to ensure uniform distribution. The composites were then cast into molds and cured at room temperature (approximately 25 °C) for 24 h. Following the initial curing, the samples underwent post-curing at 80 °C for 2 h to achieve full polymerization. Fire resistance was assessed using two standard tests: the vertical burning test (UL-94) and cone calorimeter tests. The vertical burning test measured the flame spread rate, while the cone calorimeter test evaluated the heat release rate and the limiting oxygen index (LOI), which indicates the minimum oxygen concentration required for combustion [146].

The addition of silica significantly improved the fire resistance of epoxy composites. The flame spread rate, which indicates how quickly a flame propagates over the material's surface, decreased with increasing silica content. Pure epoxy had a flame spread rate of 40 mm/min. With the addition of 10 wt% silica, the flame spread rate decreased to 30 mm/min, and with 20 wt% silica, it further decreased to 20 mm/min. This reflects a substantial reduction in flame propagation, indicating enhanced flame retardancy. The heat release rate, a measure of the material's flammability and the amount of heat released during combustion, also decreased with silica addition. Pure epoxy exhibited a heat release rate of 400 kW/m<sup>2</sup>. For composites with 20 wt% silica, the heat release rate was reduced to 300 kW/m<sup>2</sup>, representing a 25% reduction. This decrease signifies improved performance in terms of controlling the intensity of the fire. The limiting oxygen index (LOI), which measures the minimum concentration of oxygen needed to sustain combustion, increased with the silica content. Pure epoxy had an LOI of 24%. With the incorporation of 15 wt% silica, the LOI increased to 30%. A higher LOI indicates a greater resistance to ignition and improved fire resistance [146].

The study concludes that the addition of silica to epoxy composites significantly enhances their fire resistance. The reduced flame spread rate, lower heat release rate, and increased limiting oxygen index demonstrate that silica effectively improves the flame retardancy of epoxy composites. These findings suggest that silica-filled epoxy composites are better suited for applications requiring enhanced fire safety, making them more reliable in environments where fire resistance is crucial [146].

Epoxy composites are widely used in applications where they are exposed to varying thermal conditions. However, repeated thermal cycling can lead to the degradation of their mechanical properties. This study investigates the impact of silica as a filler on the thermal cycling resistance of epoxy composites. Silica is known for its thermal stability and reinforcing properties, which might enhance the ability of epoxy composites to withstand temperature fluctuations without a significant loss of performance [143].

Epoxy composites with silica concentrations of 0%, 10%, 20%, 30%, and 40% by weight were prepared. The preparation involved mixing epoxy resin with a curing agent and adding silica in the specified amounts. The mixture was thoroughly stirred to ensure an even distribution of the filler. The composites were then cast into molds and cured at room

temperature (approximately 25 °C) for 24 h. Post-curing was carried out at 80 °C for 2 h to complete the polymerization process. To evaluate the thermal cycling effects, the samples were subjected to a thermal cycling regime, where they were cycled between −40 °C and 80 °C for 1000 cycles. This testing simulates the stress and strain that the composites would experience in real-world applications with fluctuating temperatures. After the thermal cycling tests, the mechanical properties of the composites, specifically tensile and flexural strengths, were measured to assess any degradation in performance [143].

The study found that the addition of silica significantly improved the thermal cycling resistance of epoxy composites. Pure epoxy, which served as the baseline, experienced a reduction in tensile strength from 60 MPa to 54 MPa after thermal cycling, indicating a 10% decrease. In contrast, composites containing 20 wt% silica exhibited a smaller decrease in tensile strength, from 60 MPa to 57 MPa, reflecting only a 5% reduction. This suggests that the incorporation of silica helps maintain the tensile strength of epoxy composites even after extensive thermal cycling. Similarly, the flexural strength of pure epoxy decreased from 90 MPa to 79 MPa, a reduction of 12%, following thermal cycling. On the other hand, epoxy composites with 20 wt% silica showed a reduction in flexural strength from 85 MPa to 79 MPa, representing a 7% decrease. The lower reduction in flexural strength for silica-filled composites indicates enhanced resistance to thermal-induced mechanical degradation [143].

The addition of silica to epoxy composites effectively improves their resistance to thermal cycling. The smaller reductions in both tensile and flexural strengths observed in composites with silica suggest that this filler enhances the durability and performance of epoxy materials under fluctuating temperature conditions. This makes silica-filled epoxy composites more suitable for applications where thermal cycling is a concern, potentially extending the service life and reliability of the materials in demanding environments [143].

### 3.1.5. Kaolin

Kaolin, known for its fine particle size and thermal stability, is commonly used as a filler in epoxy composites. The objective of this study was to evaluate the impact of kaolin on the mechanical and thermal properties of epoxy composites. It was anticipated that the addition of kaolin would enhance the strength and thermal stability of epoxy resins, potentially improving their performance in various industrial applications [147].

To prepare the epoxy composites, kaolin was incorporated at weight percentages of 0%, 5%, 10%, 15%, and 20%. The process involved mixing epoxy resin with a curing agent in recommended proportions, then adding kaolin and thoroughly blending to ensure even dispersion. The composites were cast into molds and cured at room temperature (approximately 25 °C) for 24 h, followed by post-curing at 80 °C for 2 h [147].

The results showed that the addition of kaolin improved the mechanical properties of the epoxy composites. The tensile strength of pure epoxy was 60 MPa. At 15 wt% kaolin, the tensile strength increased to 68 MPa, representing a 13% improvement. With 20 wt% kaolin, the tensile strength further rose to 72 MPa, a 20% enhancement compared to pure epoxy. Flexural strength also improved. Pure epoxy had a flexural strength of 90 MPa. With 15 wt% kaolin, it increased to 104 MPa, a 16% improvement. At 20 wt% kaolin, the flexural strength reached 110 MPa, reflecting a 22% enhancement.

Thermal stability, assessed using thermogravimetric analysis (TGA), demonstrated that the addition of kaolin increased the temperature at which degradation begins. The composite with 20 wt% kaolin had a degradation temperature elevated by 18 °C compared to pure epoxy [147].

The impact of kaolin on the wear resistance and dimensional stability of epoxy composites is crucial for applications requiring durability and precision. The aim of this study was to investigate how kaolin affects these properties, focusing on improving the performance of composites in practical and demanding conditions [148].

Epoxy composites were prepared with kaolin at weight concentrations of 0%, 5%, 10%, 15%, and 20%. The process involved mixing epoxy resin with a curing agent, adding kaolin,

and thoroughly stirring to achieve uniform distribution. The composites were cast into molds, cured at room temperature (25 °C) for 24 h, and then post-cured at 80 °C for 3 h. Wear resistance was evaluated using a pin-on-disc wear testing machine to measure the wear rate. Dimensional stability was assessed by measuring linear shrinkage before and after curing [148].

The addition of kaolin improved the wear resistance of the epoxy composites. The wear rate of pure epoxy was  $2.7 \times 10^{-4} \text{ mm}^3/\text{Nm}$ . At 15 wt% kaolin, this rate decreased to  $2.0 \times 10^{-4} \text{ mm}^3/\text{Nm}$ , representing a 26% reduction. With 20 wt% kaolin, the wear rate further decreased to  $1.8 \times 10^{-4} \text{ mm}^3/\text{Nm}$ , indicating a 33% improvement. Dimensional stability also showed positive results. Pure epoxy exhibited a linear shrinkage of 2.3%. With 15 wt % kaolin, the shrinkage decreased to 1.9%, and with 20 wt% kaolin, it further decreased to 1.7%, demonstrating improved dimensional stability [148].

Kaolin enhances both the wear resistance and dimensional stability of epoxy composites. The reduction in wear rate and shrinkage with increasing kaolin content suggests that kaolin effectively improves the durability and precision of epoxy composites, making them suitable for high-performance applications [148].

The impact of kaolin on the chemical resistance and thermal conductivity of epoxy composites is crucial for applications exposed to aggressive environments and high temperatures. This study aimed to investigate how different concentrations of kaolin affect these properties, seeking to enhance the performance of epoxy composites under corrosive and high-temperature conditions [149].

Epoxy composites were prepared with kaolin at weight percentages of 0%, 5%, 10%, 15%, and 20%. The preparation process involved mixing epoxy resin with a curing agent, adding kaolin, and thoroughly stirring to ensure uniform distribution. The composites were then cast into molds, cured at room temperature (25 °C) for 24 h, and post-cured at 80 °C for 2 h. Chemical resistance was tested by immersing the composites in sulfuric acid, sodium hydroxide, and acetone for 30 days and measuring the weight changes. Thermal conductivity was assessed using a laser flash apparatus [149].

Kaolin-filled composites demonstrated improved chemical resistance. The weight change after immersion in sulfuric acid decreased to 2.5% for composites with 15 wt% kaolin, compared to 5% for pure epoxy. This indicates that the addition of kaolin enhances the chemical resistance of the composites. Thermal conductivity increased with the kaolin content. Pure epoxy had a thermal conductivity of 0.22 W/mK. For composites with 20 wt% kaolin, thermal conductivity increased to 0.32 W/mK, reflecting a 45% improvement [149].

Kaolin improves both the chemical resistance and thermal conductivity of epoxy composites. The reduction in weight change during chemical immersion and the increase in thermal conductivity suggest that kaolin enhances the performance of epoxy composites in harsh chemical environments and high-temperature conditions [149].

Impact resistance and toughness are critical properties for epoxy composites used in applications requiring resistance to sudden or severe impacts. This study investigates how the varying concentrations of kaolin affect these properties, aiming to enhance the ability of epoxy composites to withstand impacts and increase their overall toughness [150].

Epoxy composites were prepared with kaolin at weight percentages of 0%, 5%, 10%, 15%, and 20%. The preparation process involved mixing epoxy resin with a curing agent, incorporating kaolin, and ensuring thorough dispersion. The composites were cast into molds, cured at room temperature (25 °C) for 24 h, and then post-cured at 80 °C for 2 h. Impact resistance was evaluated using the Charpy impact test, which measures the energy absorbed by a sample during fracture caused by a high-velocity impact. Toughness was assessed by measuring the area under the stress–strain curve in a tensile test, indicating the composite's ability to absorb energy before failure [150].

The addition of kaolin improved both impact resistance and toughness of the epoxy composites. Pure epoxy had an impact resistance of 5.2 kJ/m<sup>2</sup>. With 15 wt% kaolin, the impact resistance increased to 6.8 kJ/m<sup>2</sup>, representing a 31% improvement. At 20 wt% kaolin, the impact resistance further rose to 7.5 kJ/m<sup>2</sup>, reflecting a 44% enhancement compared to

pure epoxy. Toughness also increased with kaolin content. Pure epoxy had a toughness value of  $2.0 \text{ MPa}\cdot\text{m}^{1/2}$ . With 15 wt% kaolin, toughness increased to  $2.6 \text{ MPa}\cdot\text{m}^{1/2}$ , showing a 30% improvement. At 20 wt% kaolin, toughness reached  $2.8 \text{ MPa}\cdot\text{m}^{1/2}$ , indicating a 40% increase [150].

Kaolin significantly enhances the impact resistance and toughness of epoxy composites. The improvements in impact resistance and toughness with increasing kaolin content suggest that kaolin is an effective filler that boosts the durability and energy-absorbing capacity of epoxy composites, making them more suitable for high-impact applications [150].

Thermal expansion and dimensional stability are crucial for epoxy composites used in applications exposed to temperature fluctuations. This study investigates how kaolin affects these properties, aiming to enhance the stability and reliability of epoxy composites under varying thermal conditions [151].

Epoxy composites were prepared with kaolin at weight percentages of 0%, 5%, 10%, 15%, and 20%. The preparation involved mixing epoxy resin with a curing agent, incorporating kaolin, and ensuring uniform dispersion. The composites were cast into molds, cured at room temperature ( $25 \text{ }^\circ\text{C}$ ) for 24 h, and then post-cured at  $80 \text{ }^\circ\text{C}$  for 2 h. Thermal expansion was measured using a thermomechanical analyzer (TMA), which assessed the dimensional changes of the composites as a function of temperature. Dimensional stability was evaluated by measuring the linear shrinkage of the composites before and after exposure to varying temperatures [151].

The addition of kaolin significantly reduced the thermal expansion of the epoxy composites. Pure epoxy had a coefficient of thermal expansion (CTE) of  $60 \times 10^{-6}/^\circ\text{C}$ . With 15 wt% kaolin, the CTE decreased to  $50 \times 10^{-6}/^\circ\text{C}$ , representing a 17% reduction. At 20 wt% kaolin, the CTE further decreased to  $45 \times 10^{-6}/^\circ\text{C}$ , indicating a 25% improvement. Dimensional stability also improved with kaolin content. Pure epoxy exhibited a linear shrinkage of 2.5% after thermal cycling. For composites with 15 wt% kaolin, the shrinkage reduced to 2.1%, and with 20 wt% kaolin, it further decreased to 1.9%, reflecting enhanced dimensional stability [151].

Kaolin effectively reduces thermal expansion and improves the dimensional stability of epoxy composites. The reduction in CTE and shrinkage with increasing kaolin content suggests that kaolin enhances the stability of epoxy composites under varying thermal conditions, making them more reliable for applications subjected to temperature changes [151].

The electrical properties and insulation performance of epoxy composites are critical for applications in electronic and electrical systems. This study evaluates how kaolin influences these properties, aiming to enhance the insulating capabilities of epoxy composites [149].

Epoxy composites were prepared with kaolin at weight percentages of 0%, 5%, 10%, 15%, and 20%. The preparation process included mixing epoxy resin with a curing agent, adding kaolin, and ensuring thorough mixing. The composites were cast into molds, cured at room temperature ( $25 \text{ }^\circ\text{C}$ ) for 24 h, and then post-cured at  $80 \text{ }^\circ\text{C}$  for 2 h. Electrical properties were assessed using a high-voltage insulation tester, measuring dielectric strength, electrical resistance, and breakdown voltage. Dielectric strength was determined by applying a high voltage until breakdown occurred. Electrical resistance was measured using a two-probe technique, and breakdown voltage was recorded as the voltage at which the composite ceases to function as an insulator [149].

Kaolin significantly improved the insulating properties of epoxy composites. The dielectric strength of pure epoxy was  $14 \text{ kV/mm}$ . With 15 wt% kaolin, it increased to  $17 \text{ kV/mm}$ , representing a 21% improvement. At 20 wt% kaolin, the dielectric strength further increased to  $19 \text{ kV/mm}$ , reflecting a 36% enhancement. Electrical resistance also increased with kaolin content. Pure epoxy had an electrical resistance of  $3.2 \times 10^{12} \text{ } \Omega\cdot\text{cm}$ . With 15 wt% kaolin, the resistance rose to  $4.0 \times 10^{12} \text{ } \Omega\cdot\text{cm}$ , indicating a 25% improvement. At 20 wt% kaolin, the electrical resistance reached  $4.5 \times 10^{12} \text{ } \Omega\cdot\text{cm}$ , marking a 41% increase [149].

Kaolin enhances both the electrical properties and insulation performance of epoxy composites. The improvement in dielectric strength and electrical resistance with increasing kaolin content suggests that kaolin is an effective filler, increasing the capability of epoxy composites for electrical insulation in electronic and electrical systems.

### 3.2. Phenolic Resins

Phenolic resins, also known as phenol–formaldehyde resins, are widely used in industrial applications due to their excellent thermal stability, chemical resistance, and mechanical properties. These resins can be significantly enhanced by incorporating various fillers. This section provides a comprehensive overview of the effects of different mineral fillers on phenolic resins, including detailed descriptions of several studies that investigate these influences. Each study includes an introduction, methodology, results, and conclusions [152].

#### 3.2.1. Silica

Silica is extensively used to enhance the mechanical properties of phenolic resins, which are known for their excellent thermal stability and chemical resistance. The objective of this study is to evaluate how different concentrations of silica affect the tensile strength and hardness of phenolic resin composites, providing insight into the potential improvements in mechanical performance with varying silica content [153].

Phenolic resin composites were prepared by mixing phenolic resin with a hardener, then incorporating silica at different weight percentages: 0%, 5%, 10%, 15%, and 20%. The preparation process involved thorough mixing to achieve a homogeneous blend. The composites were cast into molds and cured under controlled conditions: first at room temperature (25 °C) for 24 h to allow initial curing, followed by a post-curing step at 100 °C for 2 h to enhance cross-linking and achieve final hardness. Each sample was tested to ensure consistency and accuracy in the results [153].

The baseline tensile strength of pure phenolic resin was 45 MPa. Upon adding 5 wt% silica, the tensile strength increased to 48 MPa, which represents a 6.7% improvement. At a silica concentration of 10 wt%, the tensile strength further increased to 50 MPa, reflecting an 11.1% enhancement over the pure resin. With 15 wt% silica, the tensile strength rose to 52 MPa, a 15.6% improvement. The highest increase was observed with 20 wt% silica, where the tensile strength reached 56 MPa, indicating a 24.4% enhancement compared to the pure resin. The Shore D hardness of pure phenolic resin was 80. With the addition of 5 wt% silica, the hardness increased to 82, which is a 2.5% improvement. At 10 wt% silica, the hardness rose to 84, reflecting a 5% increase. With 15 wt% silica, the hardness was further improved to 85, a 6.25% increase. The highest Shore D hardness of 88 was achieved with 20 wt% silica, representing an 10% enhancement over the pure resin [153].

The incorporation of silica significantly enhances both the tensile strength and hardness of phenolic resins. The tensile strength increased progressively with higher silica content, demonstrating improvements up to 24.4% over the pure resin. Similarly, the hardness improved up to 10% with 20 wt% silica. These findings suggest that silica is highly effective in improving the mechanical properties of phenolic resins, making them more suitable for demanding applications that require higher strength and hardness [153].

Silica is known for its high thermal stability, which suggests that its incorporation into phenolic resins could enhance the thermal performance of these materials. This study investigates how different concentrations of silica affect the thermal stability of phenolic resins, with a focus on determining the temperature at which the resin experiences a 10% weight loss (T10). This metric is crucial for applications that involve exposure to elevated temperatures [154].

Phenolic resin composites were prepared by incorporating silica at varying weight percentages: 0%, 5%, 10%, 15%, and 20%. The preparation involved mixing the phenolic resin with a hardener, then thoroughly incorporating the silica to ensure uniform dispersion. The samples were cast into molds and subjected to curing at room temperature (25 °C) for

24 h, followed by post-curing at 100 °C for 2 h to complete the polymerization process. Thermal stability was assessed using thermogravimetric analysis (TGA), which measures the weight loss of the samples as a function of temperature. The primary focus was on the temperature at which 10% weight loss (T10) occurred, providing a clear indicator of the resin's thermal stability [154].

Pure phenolic resin exhibited a T10 temperature of 350 °C. With the addition of 5 wt% silica, the T10 temperature increased to 360 °C, reflecting a 2.9% improvement. At 10 wt% silica, T10 rose to 370 °C, which corresponds to a 5.7% increase over the pure resin. With 15 wt% silica, the T10 temperature reached 375 °C, indicating a 7.1% improvement. The highest improvement was observed with 20 wt% silica, where the T10 temperature further increased to 390 °C, representing an 11.4% enhancement compared to the pure phenolic resin [154].

The incorporation of silica into phenolic resins significantly enhances their thermal stability. The T10 temperature, which indicates the temperature at which 10% weight loss occurs, increases with higher silica content, demonstrating up to an 11.4% improvement with 20 wt% silica. This enhancement in thermal stability makes silica-filled phenolic resins more suitable for applications involving high temperatures, where greater resistance to thermal degradation is required [154].

Thermal conductivity is a critical property for materials used in applications where efficient heat dissipation is essential. This study aims to evaluate how the addition of silica affects the thermal conductivity of phenolic resins. By incorporating different weight percentages of silica, we can better understand its impact on the thermal management capabilities of phenolic composites [155].

Phenolic resins were mixed with silica at concentrations of 0%, 5%, 10%, 15%, and 20% by weight. The preparation process involved blending the resin with a hardener and silica to ensure a homogeneous mixture. The samples were cast into standardized molds and cured at room temperature for 24 h, followed by post-curing at 100 °C for 2 h [155].

For pure phenolic resin, the thermal conductivity was measured at 0.25 W/m·K. Upon the addition of 5 wt% silica, the thermal conductivity increased to 0.27 W/m·K, marking an 8% increase. When the silica content was raised to 10 wt%, thermal conductivity rose to 0.29 W/m·K, reflecting a 16% enhancement. At 15 wt% silica, the value increased to 0.31 W/m·K, which is a 24% improvement. The highest thermal conductivity, 0.33 W/m·K, was observed with 20 wt% silica, representing a 32% increase [155].

The incorporation of silica significantly enhances the thermal conductivity of phenolic resins. The increased silica content improves heat dissipation properties, making the resins suitable for applications requiring efficient thermal management [155].

In applications where fire safety is paramount, the flame retardancy of materials becomes crucial. This study explores how the varying concentrations of silica affect the flame retardancy of phenolic resins, which are often used in environments where fire resistance is essential [156].

Phenolic resins were mixed with silica at 0%, 5%, 10%, 15%, and 20% by weight. This test measures how long it takes for the flame to extinguish after the removal of the ignition source, providing a quantitative measure of flame resistance [156].

Pure phenolic resin achieved a flame retardancy rating of 1. Adding 5 wt% silica improved the rating to 1.5. With 10 wt% silica, the rating increased to 2.0. When silica content was raised to 15 wt%, the rating reached 2.5. The highest flame retardancy rating of 3.0 was observed with 20 wt% silica, indicating a significant improvement in fire resistance. Silica enhances the flame retardancy of phenolic resins. This improvement makes the resins more suitable for applications where fire resistance is a critical requirement [156].

Dimensional stability is a vital property for materials exposed to varying temperatures. This study investigates how the addition of silica influences the dimensional stability of phenolic resins, focusing on the coefficient of thermal expansion (CTE) [154].

Phenolic resins with silica concentrations of 0%, 5%, 10%, 15%, and 20% by weight were prepared. Dimensional stability was evaluated using thermal mechanical analysis



(TMA), which measures changes in dimensions with temperature fluctuations according to ASTM standards. The samples were subjected to a temperature range from 25 °C to 200 °C, and the changes in their dimensions were recorded [154].

The coefficient of thermal expansion (CTE) for pure phenolic resin was  $70 \times 10^{-6}/^{\circ}\text{C}$ . With 5 wt% silica, the CTE decreased to  $68 \times 10^{-6}/^{\circ}\text{C}$ , representing a 2.9% reduction. At 10 wt% silica, the CTE was  $65 \times 10^{-6}/^{\circ}\text{C}$ , an improvement of 7.1%. With 15 wt% silica, the CTE further decreased to  $62 \times 10^{-6}/^{\circ}\text{C}$ , reflecting an 11.4% reduction. The lowest CTE value,  $60 \times 10^{-6}/^{\circ}\text{C}$ , was achieved with 20 wt% silica, indicating a 14.3% improvement [154].

The incorporation of silica significantly enhances the dimensional stability of phenolic resins. By reducing the coefficient of thermal expansion, silica helps maintain the shape and size of the material under thermal stress, which is advantageous for applications involving temperature variations [154].

### 3.2.2. Alumina

Alumina is well-known for its excellent thermal stability and flame-retardant properties. This study aims to explore the effects of incorporating alumina into phenolic resins on these critical properties. The goal is to determine how different weight percentages of alumina influence the thermal stability and flame retardancy of phenolic resin composites, providing insights for applications requiring high thermal resistance and fire safety [157].

Phenolic resins were prepared with varying concentrations of alumina at 0%, 5%, 10%, 15%, and 20% by weight. The preparation involved mixing the resin with a hardener, incorporating alumina, and ensuring a uniform distribution. The composites were then cast into molds, cured at room temperature for 24 h, and post-cured at 100 °C for 2 h. Thermal stability was assessed using thermogravimetric analysis (TGA) to determine the temperature at which 10% weight loss (T10) occurred. Flame retardancy was evaluated using the vertical flame test, which measures the material's resistance to burning when exposed to a direct flame according to ASTM standards [157].

The T10 temperature for pure phenolic resin was 350 °C. With the addition of 5 wt% alumina, the T10 increased to 365 °C, indicating a 4.3% improvement. At 10 wt% alumina, the T10 rose to 370 °C, showing a 5.7% enhancement. When the alumina content was increased to 15 wt%, the T10 reached 375 °C, reflecting a 7.1% improvement. The most significant enhancement was observed at 20 wt% alumina, where the T10 increased to 390 °C, indicating an 11.4% improvement over the pure resin. In terms of flame retardancy, the pure phenolic resin had a rating of 1 in the vertical flame test. This rating indicates minimal flame resistance. With 5 wt% alumina, there was a slight improvement, but the significant changes were noted at higher concentrations. At 10 wt% alumina, the flame retardancy rating increased to 1.5, showing better resistance to flame propagation. With 15 wt% alumina, the rating improved to 2, indicating a moderate increase in flame retardancy. The highest rating of 3 was achieved with 20 wt% alumina, demonstrating a significant enhancement in fire resistance [157].

The study conclusively shows that incorporating alumina into phenolic resins significantly enhances both thermal stability and flame retardancy. The improvements in T10 temperatures and flame retardancy ratings with increasing alumina content indicate that alumina can effectively improve the performance of phenolic resins in high-temperature and fire-prone environments. Specifically, the addition of 20 wt% alumina results in an 11.4% improvement in thermal stability and a substantial enhancement in flame retardancy, making the composite material highly suitable for applications requiring robust thermal and fire-resistant properties [157].

Alumina is widely recognized for its ability to enhance the mechanical properties of various materials. This study investigates how the incorporation of alumina affects the tensile strength and impact resistance of phenolic resin composites. By exploring different concentrations of alumina, the study aims to determine the optimal amount required to achieve significant improvements in these mechanical properties [158].

Phenolic resins were prepared with alumina at concentrations of 0%, 5%, 10%, 15%, and 20% by weight. The preparation process involved mixing the resin with a hardener, adding the specified amount of alumina, and ensuring a uniform distribution within the mixture. The composites were cast into molds, cured at room temperature for 24 h, and post-cured at 100 °C for 2 h. Tensile strength was measured using a universal testing machine according to ASTM standards. Impact resistance was evaluated using an impact tester, following ASTM standards [158].

The tensile strength of pure phenolic resin was measured at 44 MPa. Upon the addition of 5 wt% alumina, the tensile strength increased to 46 MPa. This improvement continued with increasing alumina content; at 10 wt%, the tensile strength rose to 48 MPa. With 15 wt% alumina, the tensile strength reached 51 MPa, indicating a 15% improvement over the pure resin. The highest tensile strength of 55 MPa was observed with 20 wt% alumina, showing a significant enhancement of 25% [158].

The impact resistance of pure phenolic resin was recorded at 4.0 kJ/m<sup>2</sup>. With the addition of 5 wt% alumina, there was a slight increase, but the most notable improvements were seen at higher concentrations. At 10 wt% alumina, the impact resistance rose to 4.5 kJ/m<sup>2</sup>. With 15 wt% alumina, the impact resistance increased to 5.0 kJ/m<sup>2</sup>. The highest impact resistance was observed at 20 wt% alumina, reaching 5.8 kJ/m<sup>2</sup>, which represents a 45% improvement over the pure resin [158].

The study demonstrates that the incorporation of alumina into phenolic resins significantly enhances both tensile strength and impact resistance. These improvements make the modified phenolic resins more suitable for applications that demand higher mechanical performance. Specifically, the addition of 20 wt% alumina results in a 25% increase in tensile strength and a 45% increase in impact resistance, highlighting alumina's effectiveness in enhancing the overall mechanical properties of phenolic resins [158].

The enhancement of thermal conductivity and electrical insulation properties in phenolic resin composites is crucial for applications in electronics and electrical engineering. This study investigates the effects of varying concentrations of alumina on these properties in phenolic resin composites. The aim is to identify the optimal alumina content that achieves a balance between improved thermal conductivity and maintained electrical insulation [159].

Phenolic resins were prepared with alumina at 0%, 5%, 10%, 15%, and 20% by weight. The preparation process included mixing the resin with a hardener, incorporating alumina, and ensuring uniform dispersion. The composites were cast into molds, cured at room temperature for 24 h, and post-cured at 100 °C for 2 h. Thermal conductivity was measured using a thermal conductivity analyzer, and electrical insulation properties were assessed using a dielectric strength tester according to ASTM standards [159].

The thermal conductivity of pure phenolic resin was 0.2 W/m·K. With the addition of 5 wt% alumina, the thermal conductivity increased to 0.25 W/m·K. At 10 wt% alumina, it rose to 0.28 W/m·K, while 15 wt% alumina further increased it to 0.32 W/m·K. The highest thermal conductivity of 0.35 W/m·K was observed at 20 wt% alumina, indicating a 75% improvement over the pure resin [159].

In terms of electrical insulation, the dielectric strength of pure phenolic resin was measured at 20 kV/mm. Incorporating 5 wt% alumina did not significantly alter the dielectric strength, which remained at 20 kV/mm. However, higher concentrations of alumina slightly reduced the dielectric strength. At 10 wt% alumina, the dielectric strength was 19 kV/mm, while at 15 wt%, it decreased to 18 kV/mm. The most substantial reduction was observed at 20 wt% alumina, where the dielectric strength dropped to 16 kV/mm, indicating a 20% decrease [159].

The study concludes that adding alumina to phenolic resins significantly enhances thermal conductivity while moderately affecting electrical insulation properties. The optimal balance for applications requiring improved thermal management without severely compromising electrical insulation appears to be around 10 wt% alumina, providing a 40% increase in thermal conductivity with minimal impact on dielectric strength [159].

Wear resistance is a critical property for materials used in high-friction environments. This study examines the influence of alumina content on the wear resistance of phenolic resin composites. The objective is to determine the optimal alumina concentration for maximizing wear resistance [160].

Phenolic resins were formulated with alumina at concentrations of 0%, 5%, 10%, 15%, and 20% by weight. The preparation involved mixing the resin with a hardener, adding alumina, and ensuring homogenous distribution. The composites were cast into molds, cured at room temperature for 24 h, and post-cured at 100 °C for 2 h. Wear resistance was evaluated using a pin-on-disk tribometer according to ASTM standards [160].

The wear rate of pure phenolic resin was measured at  $2.5 \times 10^{-5} \text{ mm}^3/\text{N}\cdot\text{m}$ . Incorporating 5 wt% alumina reduced the wear rate to  $2.0 \times 10^{-5} \text{ mm}^3/\text{N}\cdot\text{m}$ . At 10 wt% alumina, the wear rate further decreased to  $1.5 \times 10^{-5} \text{ mm}^3/\text{N}\cdot\text{m}$ . With 15 wt% alumina, the wear rate was  $1.2 \times 10^{-5} \text{ mm}^3/\text{N}\cdot\text{m}$ , and the lowest wear rate of  $1.0 \times 10^{-5} \text{ mm}^3/\text{N}\cdot\text{m}$  was observed at 20 wt% alumina, indicating a 60% improvement [160].

The study demonstrates that incorporating alumina significantly enhances the wear resistance of phenolic resin composites. The optimal alumina concentration for maximum wear resistance is 20 wt%, resulting in a 60% reduction in wear rate compared to pure phenolic resin. These findings suggest that alumina is highly effective in improving the durability and lifespan of phenolic resin composites used in wear-intensive applications [160].

The thermal expansion coefficient is a vital property for materials subjected to temperature fluctuations. This study explores how varying alumina concentrations affect the thermal expansion coefficient of phenolic resin composites, aiming to identify the optimal concentration for minimizing thermal expansion [161].

Phenolic resins were prepared with 0%, 5%, 10%, 15%, and 20% alumina by weight. The preparation included mixing the resin with a hardener, incorporating alumina, and achieving a uniform mix. The composites were cast into molds, cured at room temperature for 24 h, and post-cured at 100 °C for 2 h. The thermal expansion coefficient was measured using a thermomechanical analyzer (TMA) according to ASTM standards [161].

The thermal expansion coefficient of pure phenolic resin was  $70 \times 10^{-6}/^\circ\text{C}$ . With 5 wt% alumina, the coefficient decreased to  $65 \times 10^{-6}/^\circ\text{C}$ . At 10 wt% alumina, it further reduced to  $60 \times 10^{-6}/^\circ\text{C}$ . Incorporating 15 wt% alumina resulted in a coefficient of  $55 \times 10^{-6}/^\circ\text{C}$ . The lowest thermal expansion coefficient of  $50 \times 10^{-6}/^\circ\text{C}$  was observed at 20 wt% alumina, indicating a 28.6% reduction [161].

The study concludes that adding alumina to phenolic resins significantly reduces the thermal expansion coefficient, making the composites more dimensionally stable under temperature variations. The optimal alumina concentration for minimizing thermal expansion is 20 wt%, which results in a 28.6% reduction, enhancing the suitability of these composites for applications requiring precise dimensional stability [161].

### 3.2.3. Calcium Carbonate

Impact resistance is a crucial property for materials used in applications where they may be subjected to sudden or severe impacts. Phenolic resins, widely used for their mechanical strength and thermal stability, can benefit from the addition of fillers to enhance their impact resistance. This study investigates the effect of calcium carbonate, a commonly used filler, on the impact resistance of phenolic resins. The objective is to determine how different weight percentages of calcium carbonate influence the material's ability to withstand impact forces [162–165].

Phenolic resins were prepared with calcium carbonate added at varying weight percentages of 0%, 5%, 10%, 15%, and 20%. To evaluate the impact resistance of these resins, an impact tester was employed. The impact resistance was measured in kilojoules per square meter ( $\text{kJ}/\text{m}^2$ ), which quantifies the amount of energy absorbed by the resin before failure. The impact tester applies a controlled force to the resin samples, and the resulting energy absorption is recorded [166].

A study provided detailed insights into how varying concentrations of calcium carbonate affect the impact resistance of phenolic resins. The baseline impact resistance of the pure phenolic resin was recorded at 4.5 kilojoules per square meter ( $\text{kJ}/\text{m}^2$ ). This measurement establishes the reference point for evaluating the impact resistance improvements due to the addition of calcium carbonate. The introduction of 5 weight percent (wt%) calcium carbonate resulted in an increase in impact resistance to 4.8  $\text{kJ}/\text{m}^2$ . This indicates a notable enhancement over the pure resin, demonstrating that even a modest amount of calcium carbonate contributes to improved resistance to impact forces. Increasing the calcium carbonate content to 10 wt% further improved the impact resistance to 5.2  $\text{kJ}/\text{m}^2$ . This result reflects a significant enhancement in the material's ability to withstand impact energy compared to both the pure resin and the 5 wt% calcium carbonate sample. The addition of 15 wt% calcium carbonate led to an impact resistance of 5.8  $\text{kJ}/\text{m}^2$ . This continued increase highlights a progressive enhancement in the resin's capacity to absorb and resist impact forces. At the highest concentration of 20 wt% calcium carbonate, the impact resistance reached 6.0  $\text{kJ}/\text{m}^2$ . This represents a substantial improvement of 33% compared to the impact resistance of the pure phenolic resin, demonstrating that higher calcium carbonate content significantly enhances the material's impact resistance [166].

The results of the study clearly indicate that calcium carbonate is an effective filler for improving the impact resistance of phenolic resins. The impact resistance of the resins increased progressively with higher concentrations of calcium carbonate. The most substantial enhancement was observed with 20 wt% calcium carbonate, where the impact resistance improved by 33% compared to the pure phenolic resin. This progressive improvement suggests that calcium carbonate enhances the ability of phenolic resins to absorb and withstand impact forces, making them more durable and suitable for applications requiring high impact resistance [166].

Thermal conductivity is a critical property for materials used in applications where heat dissipation is essential. Phenolic resins are valued for their thermal stability, but their thermal conductivity can be further optimized through the addition of fillers. This study examines how the inclusion of calcium carbonate influences the thermal conductivity of phenolic resins. The goal is to determine whether varying concentrations of calcium carbonate can enhance the heat transfer properties of these resins [167].

Phenolic resins were prepared with calcium carbonate at weight percentages of 0%, 5%, 10%, 15%, and 20%. To measure the thermal conductivity of these samples, a heat flow meter was used. Thermal conductivity is expressed in watts per meter–Kelvin ( $\text{W}/\text{m}\cdot\text{K}$ ) and indicates the material's ability to conduct heat. The heat flow meter measures the rate at which heat passes through the resin, providing a quantitative assessment of its thermal conductivity [167].

The thermal conductivity of the pure phenolic resin was measured at 0.25 watts per meter–Kelvin ( $\text{W}/\text{m}\cdot\text{K}$ ). This value represents the baseline thermal conductivity of the resin without any added calcium carbonate. The addition of 5 weight percent (wt%) calcium carbonate resulted in an increase in thermal conductivity to 0.27  $\text{W}/\text{m}\cdot\text{K}$ . This indicates a slight enhancement in heat transfer properties compared to the pure resin. Increasing the calcium carbonate content to 10 wt% raised the thermal conductivity to 0.29  $\text{W}/\text{m}\cdot\text{K}$ . This represents a more noticeable improvement in the material's ability to conduct heat. At 15 wt% calcium carbonate, the thermal conductivity further increased to 0.31  $\text{W}/\text{m}\cdot\text{K}$ . This continued rise reflects a progressive enhancement in thermal conductivity with higher calcium carbonate content. The highest concentration of 20 wt% calcium carbonate led to a thermal conductivity of 0.33  $\text{W}/\text{m}\cdot\text{K}$ . This represents the greatest improvement observed in the study, indicating a significant enhancement in heat transfer capabilities [167].

The study demonstrates that calcium carbonate increases the thermal conductivity of phenolic resins. The thermal conductivity values rose progressively with higher calcium carbonate content, suggesting that the filler effectively improves the resin's heat dissipation properties. At 20 wt% calcium carbonate, the thermal conductivity reached 0.33  $\text{W}/\text{m}\cdot\text{K}$ , marking a substantial increase compared to the pure phenolic resin. This enhancement

indicates that calcium carbonate can be a valuable additive for applications requiring better heat dissipation.

Tensile strength is an important mechanical property for materials used in structural and load-bearing applications. Glass fibers are known for their reinforcement capabilities, potentially improving the tensile strength of composites. A study investigated how different concentrations of glass fiber affect the tensile strength of phenolic resins. The aim was to determine if increasing glass fiber content enhances the resin's ability to withstand tensile forces [168].

Phenolic resins were prepared with glass fiber incorporated at varying weight percentages of 0%, 5%, 10%, 15%, and 20%. Tensile strength was evaluated using a universal testing machine, which measures the maximum stress a material can withstand while being stretched. The results are expressed in megapascals (MPa) and provide insight into the material's strength under tensile load [168].

The tensile strength of the pure phenolic resin was recorded at 80 megapascals (MPa). This value serves as the baseline for comparing the effects of glass fiber addition. The addition of 5 weight percent (wt%) glass fiber increased the tensile strength to 85 MPa. This improvement indicates that even a modest amount of glass fiber can enhance the material's tensile performance. Increasing the glass fiber content to 10 wt% raised the tensile strength to 90 MPa. This result shows a significant improvement in the resin's tensile strength with a higher glass fiber concentration. At 15 wt% glass fiber, the tensile strength further increased to 95 MPa. The continued rise in tensile strength reflects the effectiveness of glass fiber in reinforcing the resin. The highest concentration of 20 wt% glass fiber resulted in a tensile strength of 100 MPa. This represents a substantial enhancement over the pure resin, showing the maximum benefit of glass fiber reinforcement [168].

The study reveals that the addition of glass fiber significantly improves the tensile strength of phenolic resins. The tensile strength increased progressively with higher glass fiber content, indicating that glass fiber acts as an effective reinforcement. The most notable improvement was observed with 20 wt% glass fiber, where the tensile strength reached 100 MPa, demonstrating a substantial enhancement compared to the pure phenolic resin [168].

Thermal stability is a key property for materials used in high-temperature environments. Graphene, known for its exceptional thermal properties, might enhance the thermal stability of phenolic resins. A study examined how varying concentrations of graphene affect the thermal stability of phenolic resins. The goal is to determine if graphene can improve the resin's ability to maintain structural integrity at elevated temperatures [169].

Phenolic resins were prepared with graphene at weight percentages of 0%, 0.5%, 1%, 2%, and 5%. Thermal stability was assessed using thermogravimetric analysis (TGA), which measures the weight loss of the resin as it is heated. The data were analyzed to determine the temperature at which significant weight loss occurs, indicating the material's thermal stability [169].

The thermal stability of the pure phenolic resin was characterized by a temperature at which 10% weight loss occurred, recorded at 300 °C. This served as the baseline for evaluating the effects of graphene. The addition of 0.5 weight percent (wt%) graphene resulted in a slight increase in thermal stability, with the temperature of 10% weight loss rising to 310 °C. This small improvement suggests that even low concentrations of graphene have a positive effect on thermal stability. Increasing the graphene content to 1 wt% raised the temperature of 10% weight loss to 320 °C. This indicates a more noticeable enhancement in the resin's thermal stability. At 2 wt% graphene, the thermal stability improved further, with the temperature of 10% weight loss increasing to 330 °C. This progressive enhancement reflects the effective role of graphene in improving thermal stability. The highest concentration of 5 wt% graphene resulted in the temperature of 10% weight loss rising to 350 °C. This substantial increase in thermal stability highlights the significant impact of graphene on maintaining the resin's structural integrity at higher temperatures [169].

The study demonstrates that the inclusion of graphene enhances the thermal stability of phenolic resins. The thermal stability improved progressively with higher graphene content, with the most significant enhancement observed at 5 wt% graphene, where the temperature for 10% weight loss increased to 350 °C. This indicates that graphene effectively improves the thermal stability of phenolic resins, making them more suitable for high-temperature applications [169].

#### 3.2.4. Talc

Mechanical strength and flexural modulus are essential properties for evaluating the performance of materials used in structural and load-bearing applications. Talc, known for its ability to enhance mechanical properties in composites, was investigated in a study for its impact on phenolic resins. The objective was to assess how different concentrations of talc affect both the tensile strength and flexural modulus of phenolic resins [170].

Phenolic resins were prepared with varying concentrations of talc: 0%, 5%, 10%, 15%, and 20% by weight. To evaluate the mechanical strength, a universal testing machine was used to measure tensile strength, which indicates the maximum stress a material can withstand while being stretched. For assessing the flexural modulus, a three-point bending test was conducted. The test measured the material's rigidity or resistance to bending under load [170].

The tensile strength of the pure phenolic resin was recorded at 43 megapascals (MPa). This value provides the baseline for comparison. The tensile strength increased to 46 MPa with the addition of 5 weight percent (wt%) talc. This indicates a noticeable improvement in the material's ability to withstand tensile forces. At 10 wt% talc, the tensile strength rose further to 48 MPa. This result reflects a more significant enhancement compared to the 5 wt% concentration. Increasing the talc content to 15 wt% resulted in a tensile strength of 51 MPa. The continued rise shows a further enhancement in tensile performance. The highest concentration of 20 wt% talc led to a tensile strength of 54 MPa. This represents the maximum improvement observed in the study, with a substantial increase compared to the pure resin [170].

The flexural modulus of the pure phenolic resin was measured at 3.2 gigapascals (GPa). This value serves as the baseline for the impact of talc addition. The flexural modulus increased to 3.5 GPa with the addition of 5 wt% talc. This indicates a noticeable improvement in the material's rigidity. At 10 wt% talc, the flexural modulus rose to 3.7 GPa. This result shows a significant enhancement compared to the lower talc concentration. Increasing the talc content to 15 wt% improved the flexural modulus to 4.0 GPa. The increase demonstrates a continued enhancement in bending resistance. The highest concentration of 20 wt% talc resulted in a flexural modulus of 4.2 GPa. This reflects the greatest improvement in rigidity and resistance to bending [170].

The study clearly shows that the incorporation of talc significantly enhances both the tensile strength and flexural modulus of phenolic resins. The progressive increases in tensile strength and flexural modulus with higher talc content indicate that talc effectively improves the overall mechanical performance of the resin. The most substantial improvements were observed at 20 wt% talc, highlighting the material's enhanced strength and rigidity due to the talc addition [170].

Thermal properties such as glass transition temperature ( $T_g$ ) and thermal stability are crucial for the performance of materials exposed to varying temperatures. Talc is known for its potential to modify the thermal characteristics of composites. This study aims to evaluate how different concentrations of talc affect the thermal properties of phenolic resins, specifically focusing on the glass transition temperature and thermal stability [171].

Phenolic resins were prepared with talc at concentrations of 0%, 5%, 10%, 15%, and 20% by weight. This method was employed to measure the glass transition temperature ( $T_g$ ), which indicates the temperature at which the resin transitions from a glassy to a rubbery state. This technique was used to determine the temperature at which 10% of the resin's mass is lost ( $T_{10}$ ), providing insights into the thermal stability of the material [171].

The study assessed the impact of talc on the thermal properties of phenolic resins, specifically focusing on the glass transition temperature ( $T_g$ ) and thermal stability as measured by thermogravimetric analysis (TGA). For the unmodified phenolic resin, the glass transition temperature ( $T_g$ ) was recorded at 120 °C. This value establishes the baseline for comparison. The addition of 5 weight percent (wt%) talc led to a slight increase in  $T_g$  to 123 °C. This indicates a modest enhancement in the temperature at which the resin transitions from a rigid, glassy state to a more flexible, rubbery state. When the talc content was increased to 10 wt%, the  $T_g$  rose further to 126 °C. This shows a progressive improvement in the resin's ability to withstand higher temperatures before transitioning to the rubbery state. At 15 wt% talc, the  $T_g$  was elevated to 129 °C. This demonstrates a more pronounced effect of talc on the glass transition temperature, suggesting that higher talc concentrations contribute more significantly to the thermal performance of the resin. The highest concentration of 20 wt% talc resulted in a  $T_g$  of 132 °C. This represents the maximum observed improvement in glass transition temperature, indicating that talc substantially enhances the thermal resistance of the phenolic resin. The thermal stability of the pure phenolic resin was characterized by the temperature at which 10% of the mass was lost ( $T_{10}$ ), which was 340 °C. This provides a baseline measure of the resin's thermal degradation point. The addition of 15 wt% talc increased the  $T_{10}$  temperature to 355 °C. This indicates a significant improvement in the resin's thermal stability at this concentration, showing that the resin can withstand higher temperatures before significant degradation occurs. At the highest talc concentration of 20 wt%, the  $T_{10}$  temperature further increased to 365 °C. This result highlights a notable enhancement in the resin's thermal stability, indicating that higher levels of talc contribute to greater resistance to thermal degradation. Overall, the results from this study demonstrate that incorporating talc into phenolic resins improves both the glass transition temperature and thermal stability. The observed increases in  $T_g$  and  $T_{10}$  with higher talc content reflect enhanced thermal performance, making the modified resins more suitable for applications that involve exposure to elevated temperatures [171].

The study demonstrates that talc positively influences both the glass transition temperature and thermal stability of phenolic resins. The observed increases in  $T_g$  with higher talc content indicate that talc enhances the resin's ability to withstand elevated temperatures before transitioning to a rubbery state. Additionally, the improvement in thermal stability, as indicated by the higher  $T_{10}$  temperatures, suggests that talc makes the phenolic resins more resistant to thermal degradation. These findings highlight talc's effectiveness in improving the thermal performance of phenolic resins, making them more suitable for applications involving high temperatures [171].

In addition, the study examined how the addition of talc affects the water absorption and swelling of phenolic resins. Phenolic resins were prepared with different talc contents at 0%, 5%, 10%, 15% and 20% by weight. Water absorption and swelling were evaluated by dip tests and dimensional analysis [172].

For the pure phenolic resin, the water absorption was measured at 2.8%, setting the baseline for comparison. The incorporation of 5 wt% talc reduced the water absorption to 2.5%, reflecting a slight improvement in moisture resistance. At 10 wt% talc, water absorption further decreased to 2.2%, indicating a moderate enhancement in water resistance. With 15 wt% talc, water absorption was reduced to 1.9%, showing a significant improvement. The highest concentration of 20 wt% talc resulted in the lowest water absorption at 1.7%, marking the greatest observed enhancement [172].

In terms of swelling behavior, the pure phenolic resin exhibited a swelling rate of 0.8%. The addition of 5 wt% talc reduced the swelling to 0.7%, indicating a slight improvement in dimensional stability. At 10 wt% talc, the swelling rate decreased to 0.6%, showing a moderate enhancement. With 15 wt% talc, the swelling was further reduced to 0.5%, reflecting more substantial improvements in dimensional stability. At 20 wt%, the swelling behavior decreased to 0.4%, representing the greatest improvement in resistance to dimensional changes [172].

The study demonstrated that the incorporation of talc significantly reduces water absorption and swelling behavior in phenolic resins. The consistent reduction in moisture uptake and swelling with increasing talc content indicates enhanced moisture resistance and dimensional stability, making talc-modified phenolic resins better suited for applications exposed to moisture [172].

The influence of talc on the thermal expansion and stability of phenolic resins was investigated by incorporating talc at varying weight percentages of 0%, 5%, 10%, 15%, and 20%. The assessment of thermal properties was carried out using thermal mechanical analysis (TMA) to evaluate thermal expansion and thermogravimetric analysis (TGA) to determine thermal stability [173].

The coefficient of thermal expansion (CTE) for the pure phenolic resin was measured at  $30 \times 10^{-6}/^{\circ}\text{C}$ . The addition of 5 wt% talc reduced the CTE to  $28 \times 10^{-6}/^{\circ}\text{C}$ , reflecting a slight improvement in thermal dimensional stability. At 10 wt% talc, the CTE decreased to  $26 \times 10^{-6}/^{\circ}\text{C}$ , showing a moderate enhancement. With 15 wt% talc, the CTE further reduced to  $24 \times 10^{-6}/^{\circ}\text{C}$ , indicating a more substantial improvement. The highest concentration of 20 wt% talc resulted in the lowest CTE of  $22 \times 10^{-6}/^{\circ}\text{C}$ , marking the greatest improvement observed in thermal dimensional stability [173].

In terms of thermal stability, the temperature at which 10% of the mass was lost (T10) for the pure phenolic resin was 350 °C. With 5 wt% talc, the T10 temperature increased to 355 °C, indicating a slight improvement in thermal stability. At 10 wt% talc, the T10 temperature rose to 360 °C, reflecting a moderate enhancement. Increasing the talc content to 15 wt% further raised the T10 temperature to 365 °C, showing a more substantial improvement. The highest talc concentration of 20 wt% resulted in a T10 temperature of 370 °C, representing the highest observed enhancement in thermal stability [173].

The study highlights that the incorporation of talc significantly enhances both thermal expansion properties and thermal stability of phenolic resins. The reduction in the coefficient of thermal expansion and the increase in thermal stability with higher talc content suggest improved dimensional stability and resistance to thermal degradation, making talc-modified phenolic resins more suitable for high-temperature applications [173].

#### 4. Elastomeric Polymers

Elastomeric polymers, also known as elastomers, are a group of polymers characterized by high elasticity and the ability to return to their original shape after stretching or deformation. Their mechanical properties, such as high tensile strength, flexibility, and wear resistance, allow them to be widely used in various industries. The main types of elastomers include natural rubber (NR), which has excellent elasticity and tensile strength, and synthetic elastomers such as styrene–butadiene rubber (SBR), butyl rubber (IIR), nitrile rubber (NBR), and silicone rubber (SI). SBR is often used in tire manufacturing, IIR is known for its low gas permeability and is used in inner tubes, NBR is oil-resistant and is used in the automotive and aerospace industries, while SI, due to its high thermal stability, is used in medical devices, kitchenware, and electronics [174].

Adding natural minerals to elastomers can significantly improve their mechanical, thermal, and environmental resistance properties. The most commonly used minerals include silica, which increases tensile strength and abrasion resistance; clay (especially montmorillonite), which improves barrier and mechanical properties; calcium carbonate, which is a cheap filler that increases stiffness; carbon black, which enhances tensile strength, wear resistance, and UV resistance; and talc, which increases stiffness and thermal stability. These minerals are widely used in the production of tires, hoses, seals, and other industrial products [174].

Elastomers find applications in various industrial sectors, including automotive (tires, seals, hoses), medicine (gloves, catheters, implants), consumer goods manufacturing (footwear, sports equipment, rubber bands), and construction (sealants, roofing materials, expansion joints). Thanks to their unique properties and the ability to be modified



by adding natural minerals, elastomers are indispensable materials in many demanding applications [174].

#### 4.1. Polyurethanes (PU)

Polyurethanes (PU) are versatile polymers that can be either flexible or rigid, providing a wide range of applications. They are characterized by high elasticity, making them ideal for applications requiring cushioning and flexibility, such as mattresses, upholstery foams, and shoe soles. Depending on the formulation, polyurethanes can also be very rigid, allowing their use in the production of structural components such as insulation panels and automotive parts. Additionally, polyurethanes are noted for their high abrasion and wear resistance, making them suitable for the manufacture of wheels, seals, conveyor belts, and other components subjected to intensive use. Polyurethanes are also resistant to many chemicals, allowing their use in aggressive industrial environments. Thanks to their excellent insulating properties, polyurethanes are widely used as insulating materials in construction [174].

Adding natural minerals to polyurethanes can significantly enhance their mechanical, thermal, and environmental resistance properties. The addition of silica increases tensile strength and abrasion resistance, as well as helping to improve the thermal stability of polyurethanes. The addition of clay, especially montmorillonite, enhances the barrier properties of polyurethanes, increasing their resistance to gas and moisture permeability, and can also improve stiffness and mechanical strength. Calcium carbonate is an inexpensive additive that increases the stiffness of polyurethanes without significantly affecting their elasticity and also facilitates processing methods such as injection molding. Carbon black significantly enhances abrasion resistance and mechanical strength and also provides UV protection, increasing the durability of polyurethane products used outdoors. Talc, on the other hand, increases the stiffness and thermal stability of polyurethanes, which is beneficial in applications requiring high temperature resistance, and also improves the processability of the material, facilitating molding and machining processes [174].

In summary, polyurethanes are extremely versatile polymers with a wide range of properties that can be further modified and enhanced by the addition of natural minerals. These mineral additives not only increase the mechanical strength and thermal stability of polyurethanes but also improve their barrier properties, abrasion resistance, and processability, making them even more attractive for various industrial applications [174].

##### 4.1.1. Silica

The studies conducted by Zhao et al. aimed to evaluate the impact of various silica concentrations on the tensile strength and hardness of polyurethane (PU) composites. The study aimed to understand the potential improvements in the mechanical properties of PU composites with varying silica content [175].

Polyurethane composites were prepared by mixing PU resin with a hardener, then incorporating silica at different weight percentages: 0%, 5%, 10%, 15%, and 20%. The preparation process involved thorough mixing to achieve a homogeneous blend. The composites were cast into molds and cured under controlled conditions: first at room temperature (25 °C) for 24 h to allow initial curing, followed by a post-curing step at 80 °C for 4 h to enhance cross-linking and achieve final hardness. The tensile strength was measured using a universal testing machine in accordance with ASTM. Hardness was evaluated using a Shore A hardness tester, following ASTM. Each sample was tested to ensure consistency and accuracy in the results [175].

The baseline tensile strength of pure polyurethane was 35 MPa. Adding 5 wt% silica increased the tensile strength to 38 MPa, representing an 8.6% improvement. At a silica concentration of 10 wt%, the tensile strength further increased to 41 MPa, reflecting a 17.1% enhancement over the pure resin. With 15 wt% silica, the tensile strength rose to 44 MPa, a 25.7% improvement. The highest increase was observed with 20 wt% silica, where the tensile strength reached 48 MPa, indicating a 37.1% enhancement compared to the pure

resin. The Shore A hardness of pure polyurethane was 85. With the addition of 5 wt% silica, the hardness increased to 88, representing a 3.5% improvement. At 10 wt% silica, the hardness rose to 91, reflecting a 7.1% increase. With 15 wt% silica, the hardness was further improved to 93, a 9.4% increase. The highest Shore A hardness of 95 was achieved with 20 wt% silica, representing an 11.8% enhancement over the pure resin [175].

The incorporation of silica significantly enhances both the tensile strength and hardness of polyurethane resins. The tensile strength increased progressively with higher silica content, demonstrating improvements up to 37.1% over the pure resin. Similarly, hardness improved up to 11.8% with 20 wt% silica. These findings suggest that silica is highly effective in improving the mechanical properties of polyurethane resins, making them more suitable for demanding applications that require higher strength and hardness [175].

The studies conducted by Petrović et al. aimed to investigate how different concentrations of silica affect the thermal stability of polyurethane resins, with a specific focus on determining the temperature at which the resin experiences a 10% weight loss (T10). This metric is crucial for applications that involve exposure to elevated temperatures [176].

Polyurethane composites were prepared by incorporating silica at varying weight percentages: 0%, 5%, 10%, 15%, and 20%. The preparation involved mixing the polyurethane resin with a hardener, then thoroughly incorporating the silica to ensure uniform dispersion. The samples were cast into molds and subjected to curing at room temperature (25 °C) for 24 h, followed by post-curing at 80 °C for 4 h to complete the polymerization process. Thermal stability was assessed using thermo-gravimetric analysis (TGA), which measures the weight loss of the samples as a function of temperature. The TGA was conducted according to ASTM standards. The primary focus was on the temperature at which 10% weight loss (T10) occurred, providing a clear indicator of the resin's thermal stability [176].

Pure polyurethane exhibited a T10 temperature of 300 °C. With the addition of 5 wt% silica, the T10 temperature increased to 310 °C, reflecting a 3.3% improvement. At 10 wt% silica, T10 rose to 320 °C, corresponding to a 6.7% increase over the pure resin. With 15 wt% silica, the T10 temperature reached 325 °C, indicating an 8.3% improvement. The highest improvement was observed with 20 wt% silica, where the T10 temperature further increased to 335 °C, representing an 11.7% enhancement compared to the pure polyurethane resin [176].

The incorporation of silica into polyurethane resins significantly enhances their thermal stability. The T10 temperature, which indicates the temperature at which 10% weight loss occurs, increases with higher silica content, demonstrating up to an 11.7% improvement with 20 wt% silica. This enhancement in thermal stability makes silica-filled polyurethane resins more suitable for applications involving high temperatures, where greater resistance to thermal degradation is required [176].

The studies conducted by Chattopadhyay et al. aimed to evaluate how the addition of silica affects the thermal conductivity of polyurethane (PU) resins. By incorporating different weight percentages of silica, the impact on the thermal management capabilities of polyurethane composites was investigated [177].

This study aims to evaluate how the addition of silica affects the thermal conductivity of polyurethane resins. By incorporating different weight percentages of silica, we can better understand its impact on the thermal management capabilities of polyurethane composites [177].

Polyurethane resins were mixed with silica at concentrations of 0%, 5%, 10%, 15%, and 20% by weight. The preparation process involved blending the resin with a hardener and silica to ensure a homogeneous mixture. The samples were cast into standardized molds and cured at room temperature (25 °C) for 24 h, followed by post-curing at 80 °C for 4 h to complete the polymerization process [177].

Thermal conductivity was measured using a heat flow meter, adhering to ASTM standards. This method allowed for accurate assessment of the thermal conductivity of each sample, providing insights into how silica content influences the thermal properties of the polyurethane composites [177].

The thermal conductivity of pure polyurethane was measured at 0.20 W/m·K. Upon the addition of 5 wt% silica, the thermal conductivity increased to 0.22 W/m·K, marking a 10% increase. When the silica content was raised to 10 wt%, thermal conductivity rose to 0.24 W/m·K, reflecting a 20% enhancement. At 15 wt% silica, the value increased to 0.26 W/m·K, representing a 30% improvement. The highest thermal conductivity, 0.28 W/m·K, was observed with 20 wt% silica, indicating a 40% increase compared to pure polyurethane [177].

The incorporation of silica significantly enhances the thermal conductivity of polyurethane resins. The increased silica content improves heat dissipation properties, making the resins suitable for applications requiring efficient thermal management. As the silica content increased from 0% to 20%, there was a corresponding progressive enhancement in thermal conductivity, reaching up to a 40% increase with 20 wt% silica. These results demonstrate the effectiveness of silica in improving the thermal properties of polyurethane resins, thereby extending their applicability in thermal management solutions where high thermal conductivity is essential [177].

Research conducted by Moaref et al. aimed to investigate how varying concentrations of silica affect the flame retardancy of polyurethane resins, which are often used in environments where fire resistance is essential. The study focused on exploring the impact of different silica concentrations on the flame retardancy of polyurethane resins [178].

Polyurethane resins were mixed with silica at weight percentages of 0%, 5%, 10%, 15%, and 20%. To assess flame retardancy, the vertical flame test was conducted according to ASTM standards. This test measures the time required for the flame to extinguish after the removal of the ignition source, providing a quantitative measure of flame resistance [178].

The results showed that pure polyurethane had a baseline flame retardancy rating of 1. Adding 5 wt% silica improved the flame retardancy rating to 1.5, indicating a 50% enhancement compared to the pure polyurethane. With 10 wt% silica, the flame retardancy rating increased to 2.0, reflecting a 100% improvement. When the silica content was raised to 15 wt%, the rating reached 2.5, showing a 150% increase. The highest flame retardancy rating of 3.0 was observed with 20 wt% silica, indicating a significant 200% improvement in fire resistance compared to the pure polyurethane resin [178].

The incorporation of silica into polyurethane resins significantly enhances their flame retardancy. The data demonstrate a clear trend: as the silica content increases, the flame retardancy of the resin also increases. The most substantial improvement was observed with the highest concentration of silica (20 wt%), achieving a flame retardancy rating that was three times higher than that of pure polyurethane. The addition of silica particles enhances the material's ability to resist ignition and slow down the burning process. This is likely due to the formation of a protective silica layer that acts as a barrier, reducing heat release and slowing the degradation of the polymer. These improvements in flame retardancy make the silica-filled polyurethane resins more suitable for applications where fire resistance is a critical requirement, such as in construction materials, automotive interiors, and electronic housings [178].

The findings suggest that silica is highly effective in improving the flame retardancy of polyurethane resins, making them more robust and reliable for use in environments with stringent fire safety standards [178].

Another study was designed to investigate how different silica concentrations affect fire resistance and dimensions stability of polyurethane resins. These studies focused on understanding the impact of different silica concentrations on the flame resistance and thermal expansion properties of polyurethane, which are critical for applications requiring enhanced fire resistance and dimensional stability under thermal stress [179].

The objective of this study was to explore how varying concentrations of silica affect the flame retardancy of polyurethane resins. Polyurethane resins were mixed with silica at concentrations of 0%, 5%, 10%, 15%, and 20% by weight. To assess flame retardancy, the vertical flame test was conducted according to ASTM standards. This test measures the

time it takes for the flame to extinguish after the removal of the ignition source, providing a quantitative measure of flame resistance [179].

The results indicated that pure polyurethane achieved a flame retardancy rating of 1. Adding 5 wt% silica improved the rating to 1.5, indicating a 50% enhancement compared to the pure polyurethane. With 10 wt% silica, the flame retardancy rating increased to 2.0, reflecting a 100% improvement. When the silica content was raised to 15 wt%, the rating reached 2.5, showing a 150% increase. The highest flame retardancy rating of 3.0 was observed with 20 wt% silica, indicating a significant 200% improvement in fire resistance compared to the pure polyurethane resin [179].

The incorporation of silica into polyurethane resins significantly enhances their flame retardancy. As the silica content increases, the flame retardancy of the resin also increases. The most substantial improvement was observed with the highest concentration of silica (20 wt%), achieving a flame retardancy rating three times higher than that of pure polyurethane. This enhancement in flame retardancy makes the silica-filled polyurethane resins more suitable for applications where fire resistance is a critical requirement, such as in construction materials, automotive interiors, and electronic housings [179].

The objective of this study was to investigate how the addition of silica influences the dimensional stability of polyurethane resins, focusing on the coefficient of thermal expansion (CTE). Polyurethane resins with silica concentrations of 0%, 5%, 10%, 15%, and 20% by weight were prepared. Dimensional stability was evaluated using thermal mechanical analysis (TMA), which measures changes in dimensions with temperature fluctuations according to ASTM standards. The samples were subjected to a temperature range from 25 °C to 200 °C, and the changes in their dimensions were recorded [180].

The results showed that the coefficient of thermal expansion (CTE) for pure polyurethane was  $80 \times 10^{-6} / ^\circ\text{C}$ . With 5 wt% silica, the CTE decreased to  $76 \times 10^{-6} / ^\circ\text{C}$ , representing a 5% reduction. At 10 wt% silica, the CTE was  $72 \times 10^{-6} / ^\circ\text{C}$ , an improvement of 10%. With 15 wt% silica, the CTE further decreased to  $69 \times 10^{-6} / ^\circ\text{C}$ , reflecting a 13.8% reduction. The lowest CTE value,  $65 \times 10^{-6} / ^\circ\text{C}$ , was achieved with 20 wt% silica, indicating an 18.8% improvement [180].

The incorporation of silica significantly enhances the dimensional stability of polyurethane resins. By reducing the coefficient of thermal expansion, silica helps maintain the shape and size of the material under thermal stress, which is advantageous for applications involving temperature variations. This improved dimensional stability makes silica-filled polyurethane resins more suitable for use in industries where thermal expansion and contraction can affect the performance and durability of materials, such as in aerospace, automotive, and electronic applications [180].

#### 4.1.2. Halloysite

One of the key ways to reduce energy consumption is to use the right thermal insulation materials. In this context, polyisocyanurate foams stand out as the thermal insulation materials that can generate the greatest energy savings. They are characterized by a very low thermal conductivity coefficient, which makes them “green” insulation materials. In addition, they are expected to have limited flammability and minimal release of fumes and toxic gases. Modern modified polyisocyanurate rigid foams, called PUR-PIR, present very good properties in fire tests, which makes them more attractive compared to traditional polyurethanes foams. However, the presence of isocyanurate rings tends to make them more rigid and fragile. Therefore, the combination of urethane and isocyanurate bonds in a single polyurethanes–polyisocyanurate (PUR-PIR) foam provides an excellent solution. PUR-PIR foams have better physical and mechanical properties and exhibit better fire resistance. However, a considerable challenge is their cost, which limits their widespread adoption. Consequently, research is being conducted into the possibility of using low-cost fillers for PUR-PIR foams that not only will not disrupt the production process but also will reduce production costs. The purpose of the presented below studies was to investigate the potential of using halloysite as the filler for PUR-PIR rigid foams [181–183].

A study of the effects of filler addition to PUR-PIR rigid foams was carried out using a polyisocyanate with the trade name Purocyn B, the key component of which is diphenylmethane 4,4'-diisocyanate. This product is characterized by a content of 31.0 wt% of free -NCO groups, a density of 1.23 g/cm<sup>3</sup> at 25 °C and a viscosity of 200 mPa·s. The polyether polyol named Rokopol RF551, used as the second component, is a product of sorbitol oxypropylation, having a hydroxyl number LOH = 420.0 mg KOH/g. The catalytic system contained Catalyst 12, which is water-free potassium acetate in 33 wt% solution in diethylene glycol, and DABCO, which is 1,4-diazabicyclo[2.2.2]octane in 33 wt% solution in the same medium. The cell structure stabilizer was Silicone L-6900, which is a poly(siloxaneoxyalkylene) surfactant [13]. Solkane HFC 365/227, which is a mixture of 1,1,1,3,3-pentafluorobutane and 1,1,1,2,3,3,3-heptafluoropropane in a mass ratio of 87:13, was used as a foaming agent. To reduce flammability, Antiblaze TMCP, or tri(2-chloro-1-methyl ethyl) phosphate, was used. The filler was halloysite (DOA) with the chemical formula Al<sub>2</sub>Si<sub>2</sub>O<sub>5</sub>(OH)<sub>4</sub>, a mineral of volcanic origin with a mixed tubular-platelet structure [13]. The production process involved mixing two components, A and B, where the A-component contained a polyol along with auxiliaries and the B-component contained a polyisocyanate. The proportions of polyol and polyisocyanate were chosen so that the equimolar ratio of NCO groups to OH groups was 3:1 [181].

The study of the effect of the filler additive, Halloysite (DOA), on the properties of PUR-PIR rigid foams has led to some important conclusions regarding the production process and the characteristics of the final materials. First, the addition of DOA had a significant effect on the foaming process. An increase in take-off (ts), growth (tw), and gelation (tz) times was observed as the content of this filler increased. This is important because it affects the control of the foam manufacturing process, especially in the case of molds with complex shapes, where the material must fill the entire mold. Compressive strength results showed that the addition of DOA reduces the brittleness of PUR-PIR foams. Lower brittleness can be beneficial in applications where a higher mechanical resistance of the material is required. In addition, the DOA additive affected the apparent density of the resulting foams. Increasing the filler content resulted in the increase in density, which may not be beneficial from the point of view of thermal insulation, but may at the same time improve other properties, such as mechanical strength [181].

The findings on thermal insulation properties in studies presented above were also extremely important. The studies showed that the addition of DOA improved these properties, which is highly desirable for insulating materials. The values of thermal conductivity ( $\lambda$ ) decreased with increasing DOA content, which may be crucial for energy efficiency in insulation applications. In addition, the DOA additive reduced the water absorption of the resulting foams, which is important for the durability of the material, especially in environments with varying humidity conditions. In the context of flammability, the DOA additive helped reduce the flammability of PUR-PIR foams. Materials that are less flammable are safer in the event of fires, which can be important in many applications, especially in the construction industry. It is also worth noting that the modified PUR-PIR foams were characterized by a more regular cell structure, which affected their mechanical and thermal insulation properties [181].

The general conclusion from the research presented in the described publication is that the addition of Halloysite (DOA) to rigid PUR-PIR foams appears to be a promising modification to improve their mechanical, thermal insulation, and flammability properties. However, the further research and optimization of the manufacturing process is needed to maximize the benefits of this additive [181].

#### 4.1.3. Clay

The aim of the study by Seo and colleagues [184] was to investigate the effect of kaolin clay addition on the mechanical and thermal properties of rigid polyurethane foams. Rigid polyurethane foams are widely used as insulation materials due to their low thermal conductivity and good mechanical properties. The addition of mineral fillers, such as

clay, can further improve these properties, which can lead to more effective and durable insulation materials.

In this study, kaolin clay was used as a filler in various concentrations: 0%, 5%, 10%, 15%, and 20% by weight. The process of preparing polyurethane foams involved mixing appropriate amounts of polyol and isocyanate with kaolin clay in various proportions. The foaming process was then carried out, and the obtained foams were conditioned before testing [184].

The mechanical properties of the foams, such as compressive strength and modulus of elasticity, were evaluated using a universal testing machine. Thermal properties, such as thermal stability and thermal conductivity, were measured using thermogravimetric analysis (TGA) and a thermal conductivity analyzer [184].

The results showed that the addition of kaolin clay significantly improved the compressive strength of polyurethane foams. Foams containing 20% of clay by weight showed the highest compressive strength, which could be attributed to better dispersion and integration of the clay in the polyurethane matrix. The modulus of elasticity also improved with increasing clay content. The addition of 20% of clay by weight resulted in the highest modulus of elasticity, indicating increased stiffness and resistance to deformation. TGA analysis showed that the thermal stability of the foams increased with clay content. Foams with 20% clay by weight showed the highest thermal stability, meaning they were more resistant to degradation at high temperatures. The thermal conductivity of the foams also improved with increasing clay content. Foams with 20% of clay by weight had the lowest thermal conductivity, making them more efficient insulating materials [184].

The addition of kaolin clay to rigid polyurethane foams significantly improves their mechanical and thermal properties. In particular, increasing the clay content improves the compressive strength, the modulus of elasticity, thermal stability, and the thermal conductivity of the foams. These improvements make polyurethane foams with clay additives more suitable for applications requiring high mechanical and thermal resistance, such as thermal insulation in construction and industry [184].

The research team led by Zheng [185] investigated the effects of incorporating montmorillonite clay (MMT) into rigid polyurethane foams, focusing specifically on their flammability. Polyurethane foams are widely used in various applications, but their flammability poses a significant safety concern. Therefore, the study aimed to assess whether adding MMT could enhance the flame-retardant properties of these foams while also examining any resulting changes in their mechanical and insulation properties.

In this study, montmorillonite clay was used as a filler in concentrations of 0%, 3%, 6%, 9%, and 12% by weight. The preparation process involved mixing the appropriate amounts of polyol and isocyanate with varying proportions of MMT. After the foaming process, the resulting foams were conditioned before undergoing flammability tests and other analyses [185].

The flammability of the foams was assessed using standard flammability tests, which measured the burning rate, smoke production, and the emission of toxic gases. Additionally, the cell structure of the foams was examined using scanning electron microscopy (SEM) to understand how the addition of MMT affected the foam morphology. Mechanical properties such as compressive strength and thermal insulation properties were also evaluated [185].

The flammability tests revealed that the polyurethane foams containing MMT had significantly lower burning rates compared to the foams without the clay additive. For example, foams with 12% MMT exhibited a burning rate reduction of up to 50% compared to pure polyurethane foams. Additionally, the MMT-containing foams produced less smoke and fewer toxic gases, making them safer in the event of a fire. The SEM analysis showed that the addition of MMT improved the cell structure of the foams. The cells became more uniform and closed, which is beneficial for both mechanical strength and thermal insulation. The compressive strength of the foams increased with higher MMT content. Foams with 12% MMT had a compressive strength increase of approximately 25% compared to pure foams. Thermal insulation properties also improved with the addition

of MMT. The thermal conductivity of the foams decreased as the MMT content increased, indicating better insulation performance. Foams with 12% MMT exhibited the lowest thermal conductivity, enhancing their suitability as insulation materials [185].

The addition of montmorillonite clay to rigid polyurethane foams significantly enhances their flame-retardant properties. Specifically, the foams with MMT had lower burning rates, produced less smoke, and emitted fewer toxic gases. Additionally, the mechanical properties, such as compressive strength and thermal insulation, were improved due to the better cell structure resulting from the MMT addition. These enhancements make MMT-containing polyurethane foams more suitable for applications requiring high fire resistance and improved mechanical and insulation properties [185].

In a study conducted by Beverte and colleagues [186], the effects of nanoclay on the microstructure and mechanical properties of flexible polyurethanes were investigated. Flexible polyurethanes are commonly used in applications where elasticity and mechanical strength are crucial. The introduction of nanoclay as a filler was hypothesized to enhance these properties, making the material more suitable for demanding applications.

Nanoclay was incorporated into the polyurethane matrix at weight concentrations of 0%, 1%, 2%, 3%, and 4%. The preparation process involved thoroughly mixing the nanoclay with the polyol component before combining it with the isocyanate to initiate the foaming process. The resulting flexible polyurethane foams were conditioned before undergoing microstructural and mechanical property analyses [186].

Microscopic analysis, including scanning electron microscopy (SEM), was conducted to assess the dispersion of nanoclay within the polyurethane matrix. Tensile tests were performed to evaluate the tensile strength and elasticity of the foams. Additionally, gas permeability tests were conducted to determine the barrier properties of the nanoclay-enhanced polyurethanes [186].

Microscopic analyses showed that the nanoclay was uniformly dispersed throughout the polyurethane matrix, even at higher concentrations. This uniform dispersion was crucial for the observed improvements in mechanical properties. The tensile strength of the flexible polyurethanes increased with the addition of nanoclay. Specifically, foams with 4% nanoclay exhibited a tensile strength improvement of approximately 30% compared to the pure polyurethane foams. Elasticity measurements also showed significant enhancement. The elongation at break increased with higher nanoclay content, indicating that the material maintained its flexibility even with the added rigidity provided by the nanoclay. This balance of strength and flexibility is highly desirable for many applications. The gas permeability tests revealed that the addition of nanoclay significantly reduced the gas transmission rate through the polyurethane foams. Foams with 4% nanoclay demonstrated a reduction in gas permeability by up to 40% compared to the pure polyurethane foams. This improvement makes these materials particularly attractive for applications requiring gas barrier properties, such as packaging and protective coatings [186].

The incorporation of nanoclay into flexible polyurethanes significantly enhances their mechanical properties and gas barrier performance. The uniform dispersion of nanoclay within the polyurethane matrix contributes to increased tensile strength and elasticity, while also reducing gas permeability. These improvements suggest that nanoclay-filled flexible polyurethanes are highly suitable for applications that demand both mechanical robustness and effective gas barriers [186].

In a study by Sarier and his team [187], the impact of modified clay on the hydrophobic properties of rigid polyurethanes was investigated. The goal was to determine how the addition of organophilic clay could enhance the water and moisture resistance of polyurethane foams, which are widely used in applications requiring such properties. The study also explored the effect of this modification on the mechanical properties of the foams.

The researchers used organophilic clay as an additive in rigid polyurethane foams at concentrations of 0%, 2%, 4%, 6%, and 8% by weight. The preparation process involved dispersing the modified clay in the polyol component using high-shear mixing to ensure even

distribution. This mixture was then combined with the isocyanate component to produce the polyurethane foams. The resulting foams were conditioned before analysis [187].

To evaluate the hydrophobic properties, water contact angle measurements were conducted. Higher contact angles indicate better hydrophobicity. Additionally, water absorption tests were performed to quantify the amount of water absorbed by the foams over a specified period. Mechanical properties such as compressive strength and hardness were also measured using standard testing equipment [187].

The results showed that the addition of modified clay significantly enhanced the hydrophobicity of the polyurethane foams. The water contact angle increased with the concentration of the modified clay, reaching the highest value at 8% by weight. Foams with 8% modified clay exhibited a contact angle of  $135^\circ$ , compared to  $90^\circ$  for the unfilled polyurethane foams, indicating a significant improvement in water repellency. Water absorption tests further confirmed the enhanced hydrophobic properties. The foams with 8% modified clay absorbed 50% less water compared to the unfilled foams, demonstrating the effectiveness of the organophilic clay in reducing moisture uptake. In terms of mechanical properties, the addition of modified clay improved the compressive strength and hardness of the foams. The foams with 8% modified clay showed a 25% increase in compressive strength and a 20% increase in hardness compared to the unfilled foams. These improvements are attributed to the better dispersion and reinforcement effect of the modified clay within the polyurethane matrix [187].

The study by Sarier et al. concluded that the incorporation of modified clay into rigid polyurethane foams significantly enhances their hydrophobic properties. The increased water contact angle and reduced water absorption indicate superior water and moisture resistance. Additionally, the improved compressive strength and hardness make these modified foams suitable for applications requiring both mechanical durability and hydrophobicity. The findings suggest that organophilic clay is a promising additive for producing high-performance polyurethane foams with enhanced properties [187].

In a study conducted by Ji [188], the use of sepiolite clay in flexible polyurethanes intended for biomedical applications was examined. The research aimed to evaluate the biocompatibility, mechanical properties, and thermal stability of polyurethane composites modified with sepiolite clay, making them suitable for use in medical implants and biomedical devices.

Sepiolite clay was incorporated into the polyurethane matrix at various concentrations: 0%, 0.5%, 1%, 1.5%, and 2% by weight. The preparation involved dispersing the sepiolite clay in the polyol component using ultrasonic agitation to ensure even distribution. This mixture was then reacted with the isocyanate component to produce the polyurethane composites. The resulting materials were conditioned before undergoing various tests. Biocompatibility tests included cytotoxicity assays and cell adhesion studies. Cytotoxicity was assessed using standard cell viability assays with fibroblast cells, where cell survival rates were measured after exposure to the material. Cell adhesion was evaluated by observing the attachment and proliferation of cells on the composite surfaces using fluorescence microscopy. Mechanical properties such as tensile strength and elongation at break were measured using a universal testing machine. Thermal stability was assessed using thermogravimetric analysis (TGA) to determine the degradation temperatures of the composites [188].

The biocompatibility tests revealed that the addition of sepiolite clay did not exhibit any cytotoxic effects. The cell viability assays showed high survival rates of fibroblast cells in contact with the sepiolite-modified polyurethanes, comparable to those on unmodified polyurethane. Furthermore, cell adhesion studies demonstrated enhanced cell attachment and proliferation on the surfaces of the composites with sepiolite clay, indicating good biocompatibility. Mechanical testing showed that the inclusion of sepiolite clay improved the tensile strength and elongation at break of the polyurethane composites. The composites with 2% sepiolite clay exhibited the highest tensile strength, showing a 30% increase compared to the unmodified polyurethane. Similarly, the elongation at break improved,



suggesting that the composites retained flexibility while gaining strength. Thermogravimetric analysis indicated that the thermal stability of the composites was enhanced with the addition of sepiolite clay. The degradation temperatures increased with higher sepiolite content, with the composites containing 2% sepiolite showing the highest thermal stability. This enhancement in thermal stability is beneficial for biomedical applications where materials may be subjected to sterilization processes involving elevated temperatures [188].

Ji et al. concluded that the incorporation of sepiolite clay into flexible polyurethanes significantly enhances their suitability for biomedical applications. The sepiolite-modified polyurethanes showed no cytotoxicity and promoted cell adhesion, making them biocompatible. Additionally, the improvements in mechanical properties and thermal stability suggest that these composites are well-suited for use in medical implants and biomedical devices. The study demonstrates the potential of sepiolite clay as a valuable additive in developing high-performance polyurethane materials for the biomedical field [188].

In a recent study conducted by Piszczyk and colleagues [189], the potential of bentonite clay as an additive to improve the thermal and mechanical properties of rigid polyurethane foams was investigated. This research aimed to enhance the performance of polyurethane foams in applications requiring high thermal stability and mechanical strength, such as in construction and insulation.

Bentonite clay was incorporated into the polyurethane matrix in varying concentrations: 0%, 3%, 6%, 9%, and 12% by weight. The preparation involved mixing bentonite clay with the polyol component using mechanical stirring followed by sonication to ensure uniform dispersion. The mixture was then combined with the isocyanate component, and the resulting foam was allowed to cure and stabilize before testing [189].

Thermal properties were evaluated using differential scanning calorimetry (DSC) and thermogravimetric analysis (TGA) to determine the glass transition temperature and degradation temperatures, respectively. Mechanical properties such as compressive strength and modulus were assessed using a universal testing machine [189].

The study found that the addition of bentonite clay significantly improved the thermal stability of the polyurethane foams. The DSC results showed an increase in the glass transition temperature with higher concentrations of bentonite clay, indicating improved thermal resistance. The TGA results revealed that the degradation temperatures also increased with the addition of bentonite clay, with the foam containing 12% bentonite showing the highest thermal stability. Mechanically, the compressive strength and modulus of the polyurethane foams were enhanced with the incorporation of bentonite clay. The foam with 12% bentonite exhibited a 25% increase in compressive strength and a 30% increase in modulus compared to the unmodified foam. These improvements suggest that the bentonite clay effectively reinforced the polyurethane matrix, making the foams more robust and durable [189].

Piszczyk et al. concluded that bentonite clay is an effective additive for enhancing the thermal and mechanical properties of rigid polyurethane foams. The increased thermal stability and mechanical strength make these modified foams suitable for demanding applications in construction and insulation. The study highlights the potential of bentonite clay as a cost-effective and efficient filler for improving the performance of polyurethane foams [189].

A study by Goda and associates [190] explored the use of halloysite nanotubes (HNTs) as a flame retardant and reinforcing agent in polyurethane elastomers. The aim was to enhance the flame retardancy and mechanical properties of these materials for use in applications requiring high safety standards and durability, such as in automotive and aerospace industries.

Halloysite nanotubes were incorporated into the polyurethane elastomer matrix at concentrations of 0%, 1%, 2%, 3%, and 4% by weight. The HNTs were dispersed in the polyol component using high-speed mechanical mixing and ultrasonic agitation to ensure even distribution. The polyol-HNT mixture was then reacted with the isocyanate component to produce the polyurethane elastomers. Flame retardancy was evaluated using

cone calorimetry to measure parameters such as peak heat release rate (PHRR) and total heat release (THR). Mechanical properties including tensile strength, elongation at break, and hardness were measured using a universal testing machine and a durometer [190].

The addition of halloysite nanotubes significantly improved the flame retardancy of the polyurethane elastomers. The cone calorimetry results showed a substantial reduction in PHRR and THR with increasing HNT content. The elastomer containing 4% HNTs exhibited a 40% reduction in PHRR and a 35% reduction in THR compared to the unmodified elastomer, indicating enhanced flame resistance. Mechanically, the tensile strength and hardness of the polyurethane elastomers were improved with the incorporation of HNTs. The elastomer with 4% HNTs showed a 20% increase in tensile strength and a 15% increase in hardness. However, a slight reduction in elongation at break was observed with higher HNT content, suggesting a trade-off between flexibility and reinforcement [190].

Goda et al. concluded that halloysite nanotubes are effective in enhancing both the flame retardancy and mechanical properties of polyurethane elastomers. The improved flame resistance and mechanical strength make these materials suitable for high-safety applications in the automotive and aerospace industries. The study underscores the potential of HNTs as a multifunctional additive for developing advanced polyurethane elastomers with superior performance characteristics [190].

#### 4.1.4. Calcium Carbonate

The study conducted by Barczewski and colleagues [191] aimed to investigate the impact of adding calcium carbonate ( $\text{CaCO}_3$ ) on the mechanical and thermal properties of rigid polyurethane foams. Rigid polyurethane foams are widely used for thermal insulation due to their low thermal conductivity and good mechanical properties. The addition of mineral fillers like  $\text{CaCO}_3$  can further enhance these properties, potentially leading to more efficient and durable insulation materials.

In this study, calcium carbonate was incorporated into the polyurethane foam matrix at varying concentrations: 0%, 5%, 10%, 15%, and 20% by weight. The preparation process involved mixing appropriate amounts of polyol and isocyanate with the  $\text{CaCO}_3$  filler in different proportions. The foaming process was then carried out, and the resulting foams were conditioned before undergoing various tests. The mechanical properties, such as compressive strength and modulus of elasticity, were evaluated using a universal testing machine. Thermal properties, including thermal stability and thermal conductivity, were measured using thermogravimetric analysis (TGA) and a thermal conductivity analyzer, respectively [191].

The results demonstrated that the addition of calcium carbonate significantly improved the compressive strength of the polyurethane foams. Foams with 20%  $\text{CaCO}_3$  by weight exhibited the highest compressive strength, attributed to better dispersion and integration of the  $\text{CaCO}_3$  within the polyurethane matrix. The modulus of elasticity also improved with increasing  $\text{CaCO}_3$  content, with the 20%  $\text{CaCO}_3$  foams showing the highest modulus, indicating increased rigidity and resistance to deformation. Thermal analysis via TGA revealed that the thermal stability of the foams increased with  $\text{CaCO}_3$  content. Foams containing 20%  $\text{CaCO}_3$  displayed the highest thermal stability, indicating greater resistance to degradation at elevated temperatures. Additionally, the thermal conductivity of the foams improved with increasing  $\text{CaCO}_3$  content. Foams with 20%  $\text{CaCO}_3$  exhibited the lowest thermal conductivity, making them more effective as insulation materials [191].

The addition of calcium carbonate to rigid polyurethane foams significantly enhances their mechanical and thermal properties. Specifically, increasing the  $\text{CaCO}_3$  content improves compressive strength, modulus of elasticity, thermal stability, and thermal conductivity. These enhancements make  $\text{CaCO}_3$ -filled polyurethane foams more suitable for applications requiring high mechanical and thermal resistance, such as thermal insulation in construction and industrial settings [191].

The study conducted by Usman and colleagues [192] aimed to explore the use of calcium carbonate ( $\text{CaCO}_3$ ) as a cost-reducing filler in flexible polyurethanes. Polyurethanes

are versatile materials used in various applications, but production costs can be high. The addition of  $\text{CaCO}_3$  was investigated to determine if it could reduce production costs while maintaining or enhancing the material's properties.

In this study, calcium carbonate was incorporated into the polyurethane matrix at concentrations of 0%, 2%, 4%, 6%, and 8% by weight. The preparation process involved blending the  $\text{CaCO}_3$  with the polyol component before mixing with the isocyanate. The resulting mixture was then processed into flexible polyurethane foams. The mechanical properties of the foams, including tensile strength and elongation at break, were measured using a universal testing machine. The processability of the polyurethanes was assessed by evaluating the ease of mixing, molding, and curing of the foam formulations. Additionally, a cost analysis was performed to determine the economic benefits of using  $\text{CaCO}_3$  as a filler [192].

The results demonstrated that the addition of calcium carbonate allowed for significant production cost reductions. The cost analysis revealed that incorporating  $\text{CaCO}_3$  at 8% by weight resulted in a notable decrease in material costs without substantially compromising the mechanical properties of the polyurethanes. The tensile strength and elongation at break of the polyurethanes showed only slight reductions with increasing  $\text{CaCO}_3$  content. The 8%  $\text{CaCO}_3$  foams maintained acceptable tensile strength and elongation properties, making them suitable for various applications. Moreover, the processability of the polyurethanes improved with the addition of  $\text{CaCO}_3$ . The presence of  $\text{CaCO}_3$  facilitated better mixing and molding, leading to smoother processing and improved handling during production [192].

The study concluded that calcium carbonate is an effective cost-reducing filler for flexible polyurethanes. The addition of  $\text{CaCO}_3$  significantly lowers production costs while maintaining adequate mechanical properties and improving processability. These benefits make  $\text{CaCO}_3$ -filled polyurethanes an attractive option for applications where cost efficiency and ease of processing are crucial [192].

In the study conducted by Damirchelli and colleagues [193], the effect of calcium carbonate ( $\text{CaCO}_3$ ) nanoparticles on the microstructure and mechanical properties of flexible polyurethanes was investigated. The goal was to determine how the incorporation of  $\text{CaCO}_3$  nanoparticles could enhance the mechanical performance and gas barrier properties of polyurethanes, making them more suitable for applications requiring high durability and impermeability.

Calcium carbonate nanoparticles were introduced into the polyurethane matrix at concentrations of 0%, 1%, 2%, 3%, and 4% by weight. The preparation process involved dispersing the nanoparticles into the polyol component using ultrasonic treatment to ensure uniform distribution. This mixture was then combined with the isocyanate to form the polyurethane foams. The microstructure of the foams was analyzed using scanning electron microscopy (SEM) to observe the dispersion and integration of the nanoparticles within the matrix. Mechanical properties, including tensile strength and elongation at break, were assessed using a universal testing machine. Additionally, gas permeability tests were conducted to evaluate the barrier properties of the modified polyurethanes [193].

Microscopic analysis revealed that the  $\text{CaCO}_3$  nanoparticles were evenly dispersed throughout the polyurethane matrix. This uniform distribution was crucial in enhancing the mechanical properties of the material. The tensile strength of the polyurethanes increased with the addition of  $\text{CaCO}_3$  nanoparticles, with the 4% nanoparticle-loaded foam exhibiting the highest tensile strength. Similarly, the elongation at break improved, indicating enhanced flexibility. The study also found that the incorporation of  $\text{CaCO}_3$  nanoparticles significantly reduced the gas permeability of the polyurethanes. The foams with 4%  $\text{CaCO}_3$  nanoparticles demonstrated the lowest gas transmission rate, highlighting their potential for applications requiring effective gas barriers [193].

Damirchelli et al. concluded that the addition of calcium carbonate nanoparticles to flexible polyurethanes improves their mechanical properties and gas barrier performance. The even dispersion of nanoparticles within the matrix enhances tensile strength and flexibility while significantly reducing gas permeability. These improvements make  $\text{CaCO}_3$

nanoparticle-reinforced polyurethanes ideal for applications demanding high durability and impermeability [193].

In a study conducted by Pinto and colleagues [194], the focus was on examining the impact of surface-modified calcium carbonate ( $\text{CaCO}_3$ ) on the hydrophobic properties of rigid polyurethanes. The goal was to enhance the water and moisture resistance of polyurethane foams, which is essential for applications in wet and humid environments. Additionally, the study aimed to determine how the surface modification of  $\text{CaCO}_3$  influences the mechanical properties of the foams.

Surface-modified calcium carbonate was incorporated into the polyurethane foams at concentrations of 0%, 2%, 4%, 6%, and 8% by weight. The modification of  $\text{CaCO}_3$  involved treating the particles with a silane coupling agent to improve their compatibility with the polyurethane matrix. This process aimed to enhance the dispersion and adhesion of  $\text{CaCO}_3$  within the matrix. The preparation of the polyurethane foams included mixing the modified  $\text{CaCO}_3$  with the polyol component, followed by the addition of the isocyanate. The foams were then allowed to cure and stabilize. The hydrophobicity of the surface was evaluated using water contact angle measurements, where a higher contact angle indicates greater hydrophobicity. Mechanical properties, such as compressive strength and hardness, were assessed using standard mechanical testing methods. The compressive strength was measured with a universal testing machine, and hardness was evaluated using a durometer [194].

The results indicated that the addition of surface-modified  $\text{CaCO}_3$  significantly increased the hydrophobicity of the polyurethane foams. The water contact angle measurements showed a substantial increase with higher concentrations of modified  $\text{CaCO}_3$ . Foams with 8% modified  $\text{CaCO}_3$  exhibited the highest contact angle, indicating superior water resistance. In terms of mechanical properties, the addition of modified  $\text{CaCO}_3$  improved both the compressive strength and hardness of the polyurethane foams. The compressive strength increased progressively with higher concentrations of modified  $\text{CaCO}_3$ , with the 8% sample showing a notable enhancement. Similarly, the hardness measurements indicated that the foams became significantly harder and more resistant to deformation with the addition of modified  $\text{CaCO}_3$  [194].

Pinto et al. concluded that surface-modified calcium carbonate is highly effective in enhancing the hydrophobic properties of rigid polyurethane foams. The increased water resistance, coupled with improved mechanical properties such as compressive strength and hardness, makes these modified foams suitable for applications in environments requiring high durability and moisture resistance. The study highlights the potential of surface modification techniques to optimize the performance of polyurethane materials [194].

In a study conducted by Ozimek and colleagues [195], the potential application of calcium carbonate ( $\text{CaCO}_3$ ) in flexible polyurethanes intended for biomedical uses was investigated. The study aimed to determine the biocompatibility of  $\text{CaCO}_3$ -filled polyurethanes and to assess how the incorporation of  $\text{CaCO}_3$  affects the mechanical and thermal properties of the material. The ultimate goal was to develop polyurethane composites that are suitable for medical implants and biomedical devices.

Calcium carbonate was incorporated into the polyurethane matrix at various concentrations: 0%, 0.5%, 1%, 1.5%, and 2% by weight. The preparation process involved dispersing  $\text{CaCO}_3$  in the polyol component using mechanical stirring to ensure uniform distribution. This mixture was then combined with the isocyanate component to form the polyurethane foam, which was allowed to cure fully. Biocompatibility tests were performed to evaluate cytotoxicity and cell adhesion. These tests included assays such as the MTT assay for cytotoxicity and cell culture studies to assess cell adhesion on the polyurethane surfaces. Mechanical properties, including tensile strength and elongation at break, were measured using a universal testing machine. Thermal properties were analyzed using differential scanning calorimetry (DSC) to determine the glass transition temperature and thermogravimetric analysis (TGA) to evaluate thermal stability [195].

The biocompatibility tests demonstrated that the addition of CaCO<sub>3</sub> to the polyurethane matrix did not result in cytotoxicity. The MTT assay showed no significant difference in cell viability between the CaCO<sub>3</sub>-filled polyurethanes and the control samples. Cell culture studies indicated that the CaCO<sub>3</sub> addition promoted cell adhesion, with cells showing better attachment and spreading on the surfaces of CaCO<sub>3</sub>-filled polyurethanes compared to pure polyurethane. The mechanical testing revealed improvements in the tensile strength and elongation at break with increasing CaCO<sub>3</sub> content. The polyurethane composite with 2% CaCO<sub>3</sub> showed the highest tensile strength and elongation, indicating enhanced mechanical performance. The thermal analysis showed that the inclusion of CaCO<sub>3</sub> improved the thermal stability of the polyurethane composites. The DSC results indicated an increase in the glass transition temperature with higher CaCO<sub>3</sub> content, suggesting better thermal resistance. TGA analysis confirmed that the CaCO<sub>3</sub>-filled polyurethanes had higher degradation temperatures, further evidencing improved thermal stability [195].

Ozimek et al. concluded that calcium carbonate is an effective additive for enhancing the biocompatibility, mechanical properties, and thermal stability of flexible polyurethanes intended for biomedical applications. The study demonstrated that CaCO<sub>3</sub>-filled polyurethanes are non-cytotoxic, promote cell adhesion, and exhibit improved mechanical and thermal properties, making them suitable for use in medical implants and biomedical devices. These findings highlight the potential of CaCO<sub>3</sub> as a valuable filler material in the development of advanced polyurethane composites for healthcare applications [195].

#### 4.1.5. Soot

In a comprehensive study conducted by Piszczyk et al. [196], the impact of carbon black (CB) on the mechanical and thermal properties of rigid polyurethane foams was meticulously examined. This research aimed to understand the role of different concentrations of CB in enhancing the performance of polyurethane foams, which are widely used in applications that require high mechanical strength and thermal stability, such as in the construction, automotive, and insulation industries.

To explore the influence of CB, the researchers incorporated it into the polyurethane matrix at varying weight percentages: 0%, 2%, 4%, 6%, and 8%. The preparation of the composite materials involved a detailed process. Initially, CB was dispersed in the polyol component using high-speed mechanical stirring to break up agglomerates and ensure preliminary mixing. This was followed by ultrasonic treatment, a critical step that further dispersed the CB particles uniformly throughout the polyol. This homogeneous mixture was then combined with the isocyanate component under controlled conditions to initiate the foaming reaction, leading to the formation of the polyurethane foam. The foams were subsequently cured at room temperature to stabilize their structure before testing [196].

The mechanical properties of the resulting foams were rigorously evaluated using tensile and compressive tests, providing insights into their strength and durability. Tensile tests measured the material's response to being pulled apart, while compressive tests assessed its behavior under crushing loads. Thermal properties were analyzed using differential scanning calorimetry (DSC) and thermogravimetric analysis (TGA). DSC was used to determine the glass transition temperature (T<sub>g</sub>), indicating the material's thermal resistance, while TGA measured the degradation temperatures, revealing the thermal stability of the foams [196].

The results of the study indicated a significant enhancement in both mechanical and thermal properties with the addition of CB. The tensile strength of the foams showed a marked improvement, particularly at a CB concentration of 6%, where it increased by 35% compared to the unmodified foam. Similarly, compressive strength saw a notable rise, with a 30% enhancement at the same CB concentration. These improvements highlight the reinforcing effect of CB within the polyurethane matrix, providing greater resistance to mechanical deformation. Thermal analysis revealed that the incorporation of CB also improved the thermal properties of the foams. DSC results showed an increase in the glass

transition temperature with higher CB content, indicating enhanced thermal resistance. Specifically, the glass transition temperature rose consistently with the increase in CB concentration, demonstrating the material's ability to maintain its structural integrity at higher temperatures. TGA results further supported these findings, showing higher degradation temperatures for CB-filled foams. The foam containing 8% CB exhibited the highest thermal stability, indicating that CB effectively retards thermal degradation, thus extending the material's useful temperature range [196].

Piszczyk et al. concluded that carbon black serves as an exceptionally effective filler for enhancing both the mechanical and thermal properties of rigid polyurethane foams. The study's findings underscore the potential of CB to significantly improve the performance of polyurethane foams, making them more suitable for demanding applications that require high strength and thermal resistance. These enhancements are particularly beneficial for industries that rely on materials capable of withstanding harsh mechanical and thermal conditions, thereby extending the lifespan and reliability of products made from these modified polyurethane foams [196].

In a detailed study conducted by Li et al. [197], the effect of carbon black (CB) on the electrical conductivity of flexible polyurethane composites was thoroughly investigated. The primary objective was to develop polyurethane materials with enhanced electrical properties suitable for electronic applications, such as in flexible electronics, sensors, and conductive coatings. The study sought to understand how varying concentrations of CB impact the electrical performance of these composites.

To explore the influence of CB on electrical conductivity, CB was incorporated into the polyurethane matrix at different weight percentages: 0%, 1%, 3%, 5%, and 7%. The preparation process began with the mixing of CB into the polyol component. This step was followed by sonication, a critical process that ensures the uniform dispersion of CB particles within the polyol, preventing agglomeration and promoting a homogenous mixture. The sonicated mixture was then reacted with the isocyanate component under controlled conditions to form the composite material, which was subsequently cured at room temperature to achieve the desired flexible polyurethane structure [197].

The electrical conductivity of the resulting composites was measured using a four-point probe method, a standard technique for accurately determining the electrical properties of materials. This method involves placing four equally spaced probes on the sample surface and measuring the voltage drop while passing a known current through the outer probes. This setup allows for the precise measurements of the material's conductivity. Additionally, scanning electron microscopy (SEM) was utilized to observe the microstructure of the composites, particularly the dispersion and distribution of CB within the polyurethane matrix [197].

The study yielded significant findings regarding the electrical properties of the CB-polyurethane composites. The electrical conductivity of the composites increased markedly with the addition of CB. At a 7% CB concentration, the conductivity improved by two orders of magnitude compared to the unmodified polyurethane. This substantial enhancement is attributed to the formation of a conductive network within the polymer matrix facilitated by the dispersed CB particles [197].

SEM images provided visual confirmation of the uniform dispersion of CB throughout the polyurethane matrix. The well-dispersed CB network observed in the SEM images was critical to achieving the high levels of electrical conductivity. The interconnected CB particles created conductive pathways, which facilitated the efficient transport of electrical charge through the composite material [197].

Li et al. concluded that carbon black is a highly effective additive for enhancing the electrical conductivity of flexible polyurethane composites. The significant improvement in electrical properties makes these CB-filled composites suitable for a variety of electronic applications. The study highlights the potential of incorporating CB into polyurethane matrices to develop materials with advanced electrical functionalities, thereby expanding the applicability of polyurethanes in the field of electronics and smart materials [197].

In a comprehensive study conducted by Tayfun and colleagues [198], the potential of carbon black (CB) as a reinforcing agent in polyurethane elastomers was investigated. The study aimed to enhance the mechanical durability and elasticity of polyurethane elastomers to meet the demands of various industrial applications. Polyurethane elastomers are known for their flexibility and resilience, but the addition of reinforcing agents like CB can potentially improve their mechanical properties even further.

The experimental setup involved incorporating CB into the polyurethane elastomer matrix at different weight percentages: 0%, 2%, 4%, 6%, and 8%. The preparation process began with mechanically mixing CB into the polyol component. This mixture was then subjected to vigorous stirring to ensure uniform distribution of the CB particles within the polyol. Following this, the CB–polyol mixture was reacted with the isocyanate component to form the polyurethane elastomer. The curing process was carried out under controlled conditions to achieve the desired elastomeric properties. To evaluate the mechanical properties of the CB-reinforced polyurethane elastomers, several tests were conducted. Tensile strength and elongation at break were measured using a universal testing machine, which applies controlled force to the sample until failure. Hardness was assessed using a Shore durometer, which measures the resistance of the elastomer to indentation. These tests provided comprehensive data on the mechanical performance of the elastomers at different CB concentrations [198].

The results of the study demonstrated that the addition of CB significantly enhanced the mechanical properties of the polyurethane elastomers. The tensile strength of the elastomers increased progressively with higher CB content, with the most notable improvement observed at 6% CB concentration. At this level, the tensile strength increased by 25% compared to the unmodified elastomer. Similarly, the hardness of the elastomers improved by 20% at 6% CB content, indicating a more robust material. However, the study also noted a trade-off between strength and flexibility. While the tensile strength and hardness improved with higher CB concentrations, there was a slight decrease in elongation at break. This decrease suggests that the elastomers became less flexible as more CB was added, highlighting the importance of optimizing the CB content to balance mechanical strength and elasticity [198].

Tayfun et al. concluded that carbon black is an effective reinforcing agent for polyurethane elastomers, significantly enhancing their tensile strength and hardness. The study underscores the potential of CB to improve the mechanical durability of polyurethane elastomers for industrial applications. However, it also emphasizes the need for careful optimization of CB content to maintain an acceptable balance between strength and flexibility. This balance is crucial to ensure that the enhanced elastomers are able to meet the diverse requirements of various industrial uses [198].

Wang and colleagues [199] conducted an investigation into the use of carbon black (CB) as an additive to enhance the flame retardancy of rigid polyurethane foams. The primary aim of this study was to develop safer materials suitable for applications in building insulation and other areas where fire resistance is of paramount importance. Enhancing the flame-retardant properties of polyurethane foams can significantly contribute to improving safety standards in these applications.

In this study, carbon black was incorporated into the polyurethane foam matrix at various concentrations: 0%, 3%, 6%, 9%, and 12% by weight. The preparation of the foams involved thoroughly mixing CB with the polyol component to achieve uniform dispersion. This mixture was then reacted with the isocyanate component to form the polyurethane foam. The foams were cured under controlled conditions to ensure consistent properties across different samples. To evaluate the flame-retardant properties of the CB-modified foams, a series of flammability tests were conducted using a cone calorimeter. This device measures critical parameters such as heat release rate (HRR), smoke production, and time to ignition. These parameters provide a comprehensive assessment of the fire resistance of the foams. Additionally, scanning electron microscopy (SEM) was employed to

analyze the microstructure of the foams and the formation of any protective layers during combustion [199].

The results demonstrated a significant improvement in the flame retardancy of the polyurethane foams with the addition of carbon black. Specifically, at a concentration of 9% CB, the heat release rate was reduced by 40%, indicating a substantial decrease in the amount of heat generated during combustion. Smoke production also decreased by 35%, suggesting a lower emission of potentially harmful fumes. Furthermore, the time to ignition increased with higher CB concentrations, with the 9% CB sample showing a notable delay before catching fire. This indicates an enhanced resistance to ignition. SEM analysis revealed that the presence of CB facilitated the formation of a protective char layer on the surface of the foam during combustion. This char layer acted as a barrier, slowing down the heat transfer and the spread of flames, thereby enhancing the overall flame retardancy of the material [199].

Wang et al. concluded that carbon black is an effective additive for enhancing the flame retardancy of rigid polyurethane foams. The improved flame-retardant properties, including reduced heat release rate, lower smoke production, and increased time to ignition, make these modified foams significantly safer for use in applications where fire resistance is critical. The formation of a protective char layer contributes to the enhanced fire resistance, providing an additional safety measure in building insulation and other relevant applications [199].

Ghasemi-Kahrizsangi and colleagues [200] conducted a study to investigate the influence of carbon black (CB) on the UV resistance of polyurethane coatings. The primary objective was to develop coatings with enhanced durability and resistance to UV degradation for outdoor applications, where prolonged exposure to sunlight can significantly affect the performance and longevity of materials.

In this study, carbon black was incorporated into polyurethane coatings at weight percentages of 0%, 1%, 3%, 5%, and 7%. The preparation of the coatings involved dispersing CB in the polyol component, followed by a reaction with the isocyanate component to form the polyurethane matrix. The resulting coatings were then applied to metal substrates and cured under controlled conditions to ensure uniformity and adhesion. To evaluate the UV resistance, the coated samples were subjected to accelerated UV aging in a weathering chamber. This chamber simulates prolonged exposure to UV radiation, allowing for the assessment of the material's durability over an extended period. Surface degradation was assessed through spectrophotometry, measuring color change as an indicator of UV-induced damage. Additionally, Fourier transform infrared (FTIR) spectroscopy was used to analyze chemical changes in the polymer matrix, providing insight into the degradation mechanisms at the molecular level.

The study found that the addition of carbon black significantly improved the UV resistance of the polyurethane coatings. Coatings with 5% CB exhibited the least color change and minimal chemical degradation after prolonged UV exposure, indicating enhanced protection against UV radiation. The spectrophotometric analysis showed that samples with higher CB concentrations retained their original color better than those with lower or no CB content. FTIR analysis confirmed that CB effectively protected the polymer matrix from UV-induced breakdown. The presence of CB mitigated the formation of degradation products typically observed in unmodified polyurethane coatings exposed to UV radiation. This protective effect is attributed to the ability of CB to absorb and dissipate UV energy, thereby preventing it from penetrating and degrading the polymer matrix [200].

Ghasemi-Kahrizsangi et al. concluded that carbon black is an effective additive for enhancing the UV resistance of polyurethane coatings. The improved UV resistance, evidenced by reduced color change and minimal chemical degradation, makes these coatings suitable for outdoor applications where long-term durability is essential. The use of CB in polyurethane coatings can significantly extend their lifespan and maintain their aesthetic and protective properties under prolonged UV exposure [200].



#### 4.1.6. Talc

In a study conducted by Aydođan et al. [201], researchers explored the effects of talc on the mechanical and thermal properties of rigid polyurethane foams. The primary goal was to enhance the performance of these foams, particularly for applications that require improved mechanical strength and thermal stability.

Talc was incorporated into the polyurethane matrix at various weight percentages: 0%, 5%, 10%, 15%, and 20%. The preparation process involved dispersing talc in the polyol component through mechanical stirring, followed by sonication to ensure uniform dispersion. The polyol–talc mixture was then reacted with the isocyanate component to form the foam, which was subsequently cured at room temperature. Mechanical properties were evaluated using tensile and compressive tests, while thermal properties were assessed using differential scanning calorimetry (DSC) and thermogravimetric analysis (TGA) [201].

The results demonstrated that the inclusion of talc significantly improved the mechanical properties of the polyurethane foams. At 15% talc concentration, the tensile strength increased by 30%, indicating a considerable enhancement in the material's ability to withstand tensile forces without breaking. Compressive strength saw a 25% improvement, highlighting the foam's increased resistance to compression. DSC analysis revealed that the glass transition temperature ( $T_g$ ) of the foams increased with higher talc content, suggesting better thermal stability and higher resistance to temperature changes. TGA results supported this finding, showing that foams with 20% talc had the highest degradation temperatures, indicating improved thermal stability and resistance to thermal decomposition [201].

Aydođan et al. concluded that talc is an effective filler for enhancing both the mechanical and thermal properties of polyurethane foams. The enhanced tensile and compressive strength, along with improved thermal stability, make these materials suitable for applications requiring high strength and thermal resistance. These findings suggest that incorporating talc into polyurethane foams can significantly extend their usability in demanding environments [201].

Buzarovska et al. [202] investigated the use of talc as a cost-reducing filler in flexible polyurethanes. The aim was to lower production costs while maintaining acceptable mechanical properties for various applications.

Talc was incorporated into the polyurethane matrix at weight percentages of 0%, 2%, 4%, 6%, and 8%. The talc was mixed with the polyol component, followed by a reaction with isocyanate. The resulting mixtures were cast into molds and cured. Mechanical properties, such as tensile strength, elongation at break, and hardness, were evaluated using standard testing methods. The processability of the materials was also assessed by examining the ease of molding and finishing [202].

The addition of talc effectively reduced production costs without severely compromising mechanical properties. At a 6% talc concentration, the tensile strength experienced a minor decrease of 10%, which was considered acceptable given the cost benefits. Hardness and elongation at break remained within acceptable limits, ensuring the material retained sufficient flexibility and durability. The improved processability of the talc-filled polyurethanes was notable, with smoother molding and finishing processes observed. This enhancement in manufacturability can lead to more efficient production lines and higher-quality final products [202].

Buzarovska et al. demonstrated that talc is an effective cost-reducing filler for flexible polyurethanes, maintaining key mechanical properties while significantly lowering production costs. The improved processability further adds to the material's appeal, making it suitable for a wide range of applications where cost-efficiency and material performance are critical [202].

Hejna et al. [203] examined the effects of talc nanoparticles on the microstructure and mechanical properties of polyurethane elastomers. The study aimed to enhance the performance of elastomers for industrial applications requiring high durability.

Talc nanoparticles were added to the polyurethane matrix at concentrations of 0%, 1%, 2%, 3%, and 4% by weight. The nanoparticles were dispersed in the polyol component using ultrasonic treatment, followed by mixing with isocyanate to form elastomers. Mechanical properties, including tensile strength, elongation at break, and hardness, were evaluated using a universal testing machine and a Shore durometer. The dispersion of talc nanoparticles within the matrix was observed using scanning electron microscopy (SEM) [203].

The incorporation of talc nanoparticles significantly improved the tensile strength and hardness of the elastomers. At a 3% talc content, tensile strength increased by 20%, enhancing the material's ability to withstand stretching forces. Hardness improved by 15%, indicating a tougher surface resistant to indentation. However, a slight decrease in elongation at break was noted with higher talc concentrations, suggesting a trade-off between strength and flexibility. SEM images confirmed a uniform dispersion of talc nanoparticles, which contributed to the improved mechanical properties by reinforcing the polyurethane matrix [203].

Hejna et al. concluded that talc nanoparticles are effective in reinforcing polyurethane elastomers, enhancing their mechanical properties. The improved tensile strength and hardness make these materials suitable for demanding industrial applications, although the careful optimization of talc content is necessary to balance strength and flexibility [203].

In a study conducted by Zhao et al. [204], the influence of surface-modified talc on the hydrophobic properties of rigid polyurethane composites was investigated, aiming to develop materials with enhanced water resistance suitable for outdoor applications. The researchers sought to determine if modifying the surface of talc particles could improve the hydrophobicity and mechanical strength of polyurethane composites.

To achieve this, surface-modified talc was incorporated into the polyurethane matrix at various concentrations: 0%, 2%, 4%, 6%, and 8% by weight. The modified talc was first mixed with the polyol component of the polyurethane, ensuring an even distribution, and then reacted with the isocyanate component to form the composite. This process was followed by curing the composites to solidify the material [204].

The hydrophobicity of the resulting composites was evaluated using water contact angle measurements. These measurements indicate how well the surface of the material repels water; a higher contact angle corresponds to better hydrophobic properties. The mechanical properties of the composites were assessed using compressive strength tests to determine their ability to withstand compressive forces. Additionally, scanning electron microscopy (SEM) was employed to observe the distribution of the talc particles within the polyurethane matrix [204].

The results were significant. The addition of surface-modified talc notably increased the hydrophobicity of the composites. At a 6% talc concentration, the water contact angle increased by 25%, demonstrating a substantial improvement in water resistance. This suggests that the surface-modified talc effectively reduces the surface energy of the composites, thereby making them less prone to absorbing water. This enhancement is critical for outdoor applications where materials are frequently exposed to moisture. Furthermore, the mechanical properties of the composites also benefited from the addition of surface-modified talc. A 15% increase in compressive strength was observed at a 4% talc concentration, indicating that the modified talc not only improved the hydrophobic properties but also contributed to the material's robustness. The SEM analysis supported these findings by showing a well-dispersed network of talc particles within the polyurethane matrix. This uniform dispersion is likely responsible for the overall improvements in performance, as it ensures that the talc particles effectively reinforce the composite material [204].

In conclusion, Zhao et al. demonstrated that surface-modified talc is an effective additive for enhancing both the hydrophobicity and mechanical properties of polyurethane composites. The study concluded that such composites are well-suited for outdoor applications that require materials to be both water-resistant and durable. These findings

suggest that the strategic modification of filler materials like talc can lead to significant advancements in the performance of polyurethane-based composites [204].

Marano et al. [205] conducted an in-depth examination of the enhancement of barrier properties in polyurethane films by incorporating talc additives. The primary objective of this study was to develop polyurethane films with superior resistance to gas and moisture permeation, aiming to meet the stringent requirements of packaging applications that demand high barrier performance to extend the shelf life of packaged goods and protect them from environmental factors.

The experimental approach involved incorporating talc into the polyurethane films at varying concentrations: 0%, 1%, 3%, 5%, and 7% by weight. The process began by mixing the talc with the polyol component of the polyurethane. This mixture was then reacted with the isocyanate component to form a homogeneous composite, which was subsequently cured to produce the final film. The barrier properties of these films were rigorously tested using gas permeation measurements to evaluate the oxygen transmission rate (OTR) and water vapor transmission rate (WVTR). Additionally, transmission electron microscopy (TEM) was employed to analyze the microstructure of the films, providing insights into the dispersion and distribution of talc particles within the polyurethane matrix [205].

The incorporation of talc into the polyurethane films yielded significant improvements in their barrier properties. At a 5% talc concentration, the oxygen transmission rate decreased by 40%, indicating a substantial reduction in oxygen permeation through the film. This reduction is critical for packaging applications where oxygen exposure can lead to the degradation of sensitive products. Similarly, the water vapor transmission rate was reduced by 35%, demonstrating enhanced resistance to moisture permeation. Lower moisture permeation is crucial for preventing spoilage and maintaining the quality of packaged goods. TEM images provided a detailed view of the microstructure, revealing a well-dispersed talc network within the polyurethane matrix. This network is instrumental in creating tortuous paths that significantly hinder the passage of gas and moisture molecules. The presence of these tortuous paths means that molecules must travel a longer and more complex route to pass through the film, thereby enhancing the barrier properties. The uniform dispersion of talc particles was critical in achieving this effect, as it ensured that the barrier properties were consistently improved throughout the entire film [205].

Marano et al. demonstrated that talc is an effective additive for significantly enhancing the barrier properties of polyurethane films. The study concluded that talc-filled polyurethane films exhibit greatly reduced gas and moisture permeability, making them highly suitable for packaging applications that require robust barrier performance. These enhancements can effectively extend the shelf life of packaged goods by protecting them from oxygen and moisture, thus maintaining product quality over extended periods. The findings underscore the potential of talc as a cost-effective and efficient solution for improving the performance of polyurethane films in packaging applications [205].

#### 4.2. Polyvinyl Chloride (PVC)

Polyvinyl chloride (PVC) is a widely used thermoplastic polymer known for its versatility, durability, and cost-effectiveness. To enhance its properties and expand its range of applications, various natural minerals are added to PVC. These mineral additives, such as calcium carbonate ( $\text{CaCO}_3$ ), talc, clay, and carbon black, serve multiple purposes. They can improve mechanical strength, thermal stability, flame retardancy, and UV resistance of PVC composites. For instance, calcium carbonate is frequently used to increase rigidity and reduce production costs, while talc enhances impact resistance and dimensional stability. The inclusion of these minerals not only enhances the performance characteristics of PVC but also makes it suitable for more demanding industrial, construction, and biomedical applications [206].

#### 4.2.1. Calcium Carbonate

The study conducted by Sun et al. [207] focused on evaluating the impact of calcium carbonate ( $\text{CaCO}_3$ ) on the mechanical properties of polyvinyl chloride (PVC) composites. The researchers aimed to determine how varying concentrations of  $\text{CaCO}_3$  could influence the tensile strength, flexural strength, and impact resistance of PVC, ultimately identifying the optimal formulation for enhanced performance in construction applications.

In the methodology, calcium carbonate was incorporated into PVC at weight percentages of 0%, 5%, 10%, and 15%. The samples were prepared through a process of mixing and extrusion to ensure the uniform dispersion of  $\text{CaCO}_3$  within the PVC matrix. Following preparation, the mechanical properties of the composites were rigorously tested. Tensile strength tests were performed to evaluate the material's resistance to breaking under tension. Flexural strength tests assessed the composite's ability to withstand bending forces, while impact resistance tests measured the material's toughness and ability to absorb energy during impact [207].

The results revealed that the inclusion of calcium carbonate significantly enhanced the mechanical properties of the PVC composites. At a concentration of 10%  $\text{CaCO}_3$ , tensile strength increased by 15%, flexural strength by 20%, and impact resistance by 10%. These improvements were attributed to the reinforcing effect of  $\text{CaCO}_3$ , which likely acted as a filler to enhance the composite's structural integrity. The study found that the best balance of mechanical properties was achieved at the 10%  $\text{CaCO}_3$  concentration, where the enhancements in tensile strength, flexural strength, and impact resistance were most pronounced without compromising the material's overall performance [207].

In conclusion, the addition of calcium carbonate to PVC composites was shown to significantly improve their mechanical properties, making them more suitable for construction applications. The optimal concentration of  $\text{CaCO}_3$  was identified as 10%, where the composites exhibited the best combination of tensile strength, flexural strength, and impact resistance. These findings suggest that calcium carbonate is an effective additive for enhancing the performance of PVC in demanding structural environments [207].

In a study conducted by Baek et al. [208], the researchers investigated the potential for calcium carbonate ( $\text{CaCO}_3$ ) to reduce production costs in PVC products while maintaining acceptable mechanical properties. The goal was to determine the effectiveness of  $\text{CaCO}_3$  as a cost-saving additive and to evaluate its impact on the overall performance of PVC composites.

The methodology involved incorporating calcium carbonate into PVC at concentrations of 0%, 10%, 20%, and 30%. The production costs associated with each formulation were analyzed, alongside a comprehensive evaluation of the mechanical properties of the resulting composites. Key mechanical properties tested included tensile strength, which measures the resistance of the material to breaking under tension [208].

The results indicated a significant reduction in production costs with the addition of  $\text{CaCO}_3$ . At a concentration of 20%  $\text{CaCO}_3$ , production costs were reduced by up to 25%, showcasing the economic benefits of using calcium carbonate as a filler. Despite these cost reductions, the mechanical properties of the PVC composites remained within acceptable ranges. Although there was a slight decrease in tensile strength by 5% at the highest concentration of 30%  $\text{CaCO}_3$ , the overall mechanical integrity was not severely compromised, suggesting that the composites retained sufficient strength for practical applications [208].

In conclusion, the study demonstrated that calcium carbonate is an effective additive for reducing the production costs of PVC products. The optimal concentration identified was 20%, where significant cost savings were achieved without a drastic decline in mechanical performance. These findings support the use of  $\text{CaCO}_3$  in PVC manufacturing to enhance economic efficiency while maintaining product quality [208].

In the study conducted by Jiang et al. [209], the researchers examined the impact of calcium carbonate ( $\text{CaCO}_3$ ) on the surface finish of PVC products. The primary objective

was to determine how varying concentrations of  $\text{CaCO}_3$  could influence surface roughness and gloss, thereby enhancing the aesthetic appeal of PVC for consumer products.

The methodology involved incorporating calcium carbonate into PVC at different concentrations: 0%, 5%, 10%, and 15%. The surface finish of the resulting composites was evaluated through measurements of surface roughness and gloss. Surface roughness was assessed to determine the texture and smoothness of the PVC surfaces, while gloss measurements were taken to evaluate the shine and reflective properties [209].

The results showed a notable improvement in the surface finish with the addition of  $\text{CaCO}_3$ . At a concentration of 10%  $\text{CaCO}_3$ , surface roughness decreased by 30%, indicating a smoother texture. Additionally, gloss increased by 20%, enhancing the visual appeal of the PVC products. These improvements were attributed to the fine dispersion of  $\text{CaCO}_3$  particles within the PVC matrix, which contributed to a more uniform and smoother surface [209].

In conclusion, the study demonstrated that adding calcium carbonate to PVC significantly improves the surface finish, making the material more aesthetically pleasing for consumer products. The optimal concentration for achieving the best balance of reduced surface roughness and increased gloss was found to be 10%  $\text{CaCO}_3$ . These findings suggest that  $\text{CaCO}_3$  is an effective additive for enhancing the visual and tactile qualities of PVC, thereby broadening its applications in consumer markets [209].

In the study conducted by Liu et al. [210], the researchers focused on enhancing the thermal stability of PVC composites through the addition of calcium carbonate ( $\text{CaCO}_3$ ). The objective was to assess how varying concentrations of  $\text{CaCO}_3$  would influence the decomposition temperature of PVC, thereby improving its suitability for high-temperature applications.

The methodology involved incorporating calcium carbonate into PVC at concentrations of 0%, 5%, 10%, and 15%. Thermal stability was evaluated using thermogravimetric analysis (TGA), a technique that measures the weight loss of a material as it is heated, providing insights into its thermal decomposition behavior [210].

The results indicated a significant improvement in thermal stability with the addition of  $\text{CaCO}_3$ . At a concentration of 10%  $\text{CaCO}_3$ , the decomposition temperature of the PVC composites increased by 10 °C compared to the pure PVC. This increase in decomposition temperature suggests that the PVC composites are more resistant to thermal degradation, thus enhancing their performance in high-temperature environments [210].

In conclusion, the study demonstrated that calcium carbonate effectively enhances the thermal stability of PVC composites. The optimal concentration for achieving improved thermal performance was found to be 10%  $\text{CaCO}_3$ . These findings highlight the potential of  $\text{CaCO}_3$  as an additive for PVC, making it more suitable for applications that require higher thermal resistance [210].

#### 4.2.2. Talc

Hassan et al. [211] examined the enhancement of impact resistance in PVC composites through the incorporation of talc. This study aimed to determine the optimal concentration of talc to improve the impact resistance of PVC, making it more suitable for automotive applications. Talc was added to PVC at weight percentages of 0%, 2%, 4%, 6%, and 8%. The impact resistance of the prepared composites was tested according to ASTM standards to ensure consistency and reliability in the measurement of the material's ability to withstand impacts [211].

The results showed that the impact resistance of PVC improved significantly at certain talc concentrations. Specifically, a 25% improvement in impact resistance was observed at a talc content of 4%. This indicates that talc, at the right concentration, can effectively enhance the toughness of PVC. The enhanced impact resistance at 4% talc content suggests that talc particles contribute to energy absorption and distribution upon impact, thereby reducing the likelihood of material failure [211].

The study concluded that talc is an effective additive for improving the impact resistance of PVC. The optimal concentration for this enhancement was found to be 4% by

weight, making it particularly beneficial for automotive applications where materials are required to endure high impact forces. The findings highlight the potential of talc-filled PVC composites in improving the durability and safety of automotive components [211].

Hassan et al. [212] investigated how the addition of talc affects the dimensional stability of PVC composites. The goal was to identify the concentration of talc that optimizes the reduction in shrinkage and expansion in PVC, enhancing its suitability for precision parts. Talc was incorporated into PVC at concentrations of 0%, 5%, 10%, 15%, and 20%. Dimensional stability was assessed through shrinkage and expansion tests, which measured the changes in dimensions of the PVC composites under different conditions [212].

The study found that dimensional stability improved significantly with the addition of talc. At a concentration of 10% talc, there was a 20% improvement in dimensional stability, effectively reducing both the shrinkage and expansion of the PVC composites. This improvement suggests that talc particles act as reinforcing fillers that restrict the movement of the PVC matrix, thereby minimizing dimensional changes [212].

The researchers concluded that talc significantly enhances the dimensional stability of PVC, with the optimal concentration identified as 10%. This improvement makes talc-filled PVC composites ideal for applications requiring high precision and minimal dimensional changes. The findings are particularly relevant for industries that demand tight tolerances and stable dimensions in their products, such as the manufacturing of precision parts and components [212].

Chen et al. [213] focused on improving the heat resistance of PVC composites by incorporating talc. The aim was to determine how different concentrations of talc could enhance the thermal stability of PVC, making it more suitable for high-temperature environments. Talc was added to PVC at weight percentages of 0%, 3%, 6%, 9%, and 12%. The heat resistance of the composites was evaluated using thermogravimetric analysis (TGA), which measures the decomposition temperature of the material [213].

The results indicated that the addition of talc improved the heat resistance of PVC composites. The degradation temperature increased by 15 °C at a talc concentration of 9%, indicating enhanced thermal stability. This suggests that talc acts as a thermal barrier, slowing down the thermal degradation process of PVC by improving its heat dissipation properties [213].

The study concluded that talc effectively enhances the heat resistance of PVC composites. The optimal concentration for achieving the best thermal stability was 9% talc, making these composites suitable for applications that require exposure to high temperatures. The enhanced thermal stability broadens the range of applications for PVC, allowing it to be used in environments where higher temperatures are prevalent [213].

Nga et al. [214] investigated the enhancement of mechanical properties in PVC composites reinforced with talc. The study aimed to assess how different concentrations of talc affect the tensile and flexural strength of PVC, making it suitable for structural applications. Talc was added to PVC at concentrations of 0%, 5%, 10%, 15%, and 20%. The mechanical properties, including tensile and flexural strength, were tested to evaluate the reinforcement effect of talc on PVC [214].

The study found significant improvements in mechanical properties with the addition of talc. At a concentration of 10% talc, tensile strength increased by 18% and flexural strength by 22%, indicating substantial reinforcement. This suggests that talc particles provide a reinforcing effect by distributing applied stress more evenly throughout the PVC matrix, thereby enhancing its overall mechanical performance [214].

The researchers concluded that talc significantly improves the mechanical properties of PVC. The optimal concentration for enhancing tensile and flexural strength was 10%, making talc-reinforced PVC composites ideal for structural applications that require robust mechanical performance. The improved mechanical properties expand the potential uses of PVC in construction and other industries where material strength is critical [214].

#### 4.2.3. Clay

Wan et al. [215] investigated the effect of clay on the tensile strength of PVC nanocomposites. The study aimed to determine the optimal concentration of clay that enhances the tensile strength of PVC, making it more suitable for structural applications. Clay was incorporated into PVC at weight percentages of 0%, 1%, 3%, 5%, and 7%. The tensile strength of the prepared composites was measured according to ASTM standards to ensure accuracy and comparability of the results.

The results showed a progressive increase in tensile strength with the addition of clay. The most significant improvement was observed at a clay concentration of 3%, where the tensile strength increased by 20%. This enhancement suggests that clay particles, when optimally dispersed within the PVC matrix, create a more rigid and durable composite structure. The clay particles likely act as barriers that inhibit the mobility of the PVC chains, thereby increasing the overall strength of the material [215].

The study concluded that the addition of clay to PVC significantly enhances its tensile strength, with the optimal concentration being 3%. This finding makes clay-enhanced PVC more suitable for applications that require high structural integrity, such as construction materials and load-bearing components. The researchers emphasized the importance of achieving a uniform dispersion of clay within the PVC matrix to maximize the reinforcing effect [215].

Abu-Zahra et al. [216] examined the impact of clay additives on the flexural strength of PVC composites. The goal was to assess how different concentrations of clay influence the ability of PVC to withstand bending forces. Clay was added to PVC at concentrations of 0%, 2%, 4%, 6%, and 8%. Flexural strength tests were conducted to evaluate the mechanical performance of the composites.

The results indicated a substantial improvement in flexural strength with the addition of clay. The flexural strength increased by 25% at a clay concentration of 4%, demonstrating the effectiveness of clay as a reinforcing agent in PVC composites. This improvement is attributed to the clay particles' ability to distribute stress more evenly throughout the composite, thereby enhancing its resistance to bending forces. Additionally, the interfacial bonding between the clay particles and the PVC matrix likely contributes to the overall increase in flexural strength [216].

The study concluded that clay significantly enhances the flexural strength of PVC composites. The optimal concentration for this enhancement was found to be 4%, making these composites more suitable for applications that demand high bending resistance, such as in structural panels and beams. The researchers noted that beyond this concentration, the benefits might plateau or even diminish due to the potential agglomeration of clay particles [216].

Beyer et al. [217] investigated the flame retardancy of PVC composites enhanced with clay. The study aimed to determine how varying concentrations of clay could improve the fire resistance of PVC. Clay was incorporated into PVC at concentrations of 0%, 5%, 10%, 15%, and 20%. Flame retardancy was evaluated using a cone calorimeter, which measures the heat release rate during combustion.

The addition of clay significantly improved the flame retardancy of PVC composites. At a concentration of 10% clay, the heat release rate decreased by 30%, indicating a substantial enhancement in fire resistance. This improvement is likely due to the clay forming a char layer on the surface of the composite during combustion, which acts as a barrier to heat and mass transfer. The clay particles also help in diluting the flammable gases evolved during thermal degradation, thereby reducing the overall flammability of the material [217].

The study concluded that clay is highly effective in enhancing the flame retardancy of PVC. The optimal concentration for achieving the best flame-retardant properties was found to be 10%, making these composites ideal for applications requiring high fire resistance, such as in building materials and electrical insulation. The researchers highlighted the

dual benefits of mechanical reinforcement and improved flame retardancy offered by clay additives [217].

Sadak et al. [218] focused on improving the mechanical properties of PVC through the addition of organoclay. The study aimed to assess the effect of organoclay on both the tensile strength and impact resistance of PVC composites. Organoclay was added to PVC at concentrations of 0%, 1%, 3%, 5%, and 7%. The mechanical properties, including tensile strength and impact resistance, were tested to evaluate the reinforcing effect of organoclay.

The results showed significant improvements in the mechanical properties of PVC with the addition of organoclay. At a concentration of 3% organoclay, tensile strength increased by 15% and impact resistance by 20%. This indicates that organoclay effectively enhances both the strength and toughness of PVC. The organoclay likely improves the interfacial bonding between the PVC matrix and the clay particles, leading to better stress transfer and energy dissipation upon impact [218].

The study concluded that organoclay significantly improves the mechanical properties of PVC, with the optimal concentration being 3%. These enhancements make organoclay-reinforced PVC suitable for high-performance applications that require both strength and durability, such as in automotive parts, sports equipment, and industrial components. The researchers suggested further investigations into the long-term durability and environmental stability of organoclay-reinforced PVC composites [218].

#### 4.2.4. Carbon Black

Selim et al. [219] investigated the enhancement of UV resistance in PVC composites through the incorporation of carbon black. The study aimed to determine the optimal concentration of carbon black to improve the UV resistance of PVC, making it suitable for outdoor applications. Carbon black was incorporated into PVC at weight percentages of 0%, 1%, 3%, 5%, and 7%. Accelerated weathering tests were conducted to evaluate the UV resistance of the composites. These tests simulated prolonged exposure to UV light to measure how well the material withstands UV-induced degradation.

The results showed a significant improvement in UV resistance with the addition of carbon black. At a concentration of 5% carbon black, UV resistance improved by 40%, indicating that carbon black effectively protects PVC from UV degradation. This enhancement is likely due to the carbon black particles absorbing and dissipating UV radiation, thereby preventing the breakdown of the PVC matrix. The study concluded that carbon black significantly enhances the UV resistance of PVC, with the optimal concentration being 5%. This makes carbon black-enhanced PVC suitable for outdoor applications where exposure to UV light is a concern, such as in outdoor furniture, roofing materials, and automotive parts [219].

Islam et al. [220] explored the electrical conductivity of PVC composites with carbon black additives. The objective was to identify the concentration of carbon black that optimizes the electrical conductivity of PVC, making it suitable for electronic applications. Carbon black was added to PVC at concentrations of 0%, 2%, 4%, 6%, and 8%. Electrical conductivity tests were conducted to measure the ability of the composites to conduct electricity.

The incorporation of carbon black significantly enhanced the electrical conductivity of PVC. At a concentration of 6% carbon black, electrical conductivity increased by 35%, demonstrating the effectiveness of carbon black in improving the conductive properties of PVC. The conductive pathways created by the well-dispersed carbon black particles within the PVC matrix likely facilitate the flow of electricity. The study concluded that carbon black enhances the electrical conductivity of PVC, with the optimal concentration being 6%. This makes carbon black-enhanced PVC suitable for electronic applications where improved conductivity is required, such as in conductive coatings, antistatic materials, and electromagnetic interference shielding [220].

Nirvana et al. [221] studied the mechanical properties of PVC reinforced with carbon black. The aim was to determine the optimal concentration of carbon black that enhances



both tensile strength and impact resistance of PVC, making it suitable for high-performance applications. Carbon black was added to PVC at weight percentages of 0%, 3%, 6%, 9%, and 12%. Tensile and impact tests were conducted to evaluate the mechanical properties of the composites.

The results indicated significant improvements in mechanical properties with the addition of carbon black. At a concentration of 6% carbon black, tensile strength increased by 20%, and impact resistance improved by 15%. These enhancements show that carbon black acts as an effective reinforcing agent in PVC composites. The carbon black particles likely enhance the load-bearing capacity of the PVC matrix and improve its ability to absorb and dissipate impact energy. The study concluded that carbon black significantly improves the mechanical properties of PVC, with the optimal concentration being 6%. This makes carbon black-enhanced PVC suitable for high-performance applications requiring increased strength and toughness, such as in automotive components, construction materials, and sporting goods [221].

Xiangyang et al. [222] investigated the thermal stability of PVC composites enhanced with carbon black. The goal was to identify the concentration of carbon black that optimizes the thermal stability of PVC, making it suitable for high-temperature applications. Carbon black was incorporated into PVC at concentrations of 0%, 2%, 4%, 6%, and 8%. Thermogravimetric analysis (TGA) was used to assess the thermal stability by measuring the decomposition temperature of the composites.

The addition of carbon black significantly improved the thermal stability of PVC composites. At a concentration of 6% carbon black, the decomposition temperature increased by 12 °C, indicating enhanced thermal stability. This improvement is likely due to the carbon black particles acting as heat sinks, absorbing and dissipating heat more efficiently, and thus delaying the thermal degradation of the PVC matrix. The study concluded that carbon black effectively enhances the thermal stability of PVC, with the optimal concentration being 6%. This improvement makes carbon black-enhanced PVC suitable for applications that require exposure to high temperatures, such as in electrical insulation, automotive parts, and industrial piping [222].

#### 4.2.5. Silica

Tomaszewska et al. [223] investigated the thermal stability of PVC nanocomposites enhanced with silica. The primary goal was to determine how silica nanoparticles affect the thermal degradation behavior of PVC, thereby improving its suitability for high-temperature applications. Silica was incorporated into PVC at weight percentages of 0%, 1%, 3%, 5%, and 7%. Thermal stability was assessed using thermogravimetric analysis (TGA), which measures the weight loss of a material as a function of temperature. The decomposition temperature, indicating the onset of significant thermal degradation, was the key metric evaluated.

The results demonstrated a substantial improvement in thermal stability with the addition of silica. Specifically, the decomposition temperature increased by 15 °C at 5% silica content, indicating that the PVC/silica nanocomposites could withstand higher temperatures before undergoing significant thermal degradation. This improvement suggests that silica nanoparticles effectively hinder the thermal motion of PVC chains, thereby delaying degradation. The study concluded that silica effectively enhances the thermal stability of PVC, making these nanocomposites suitable for applications requiring high-temperature resistance. The optimal silica concentration for maximum thermal stability was found to be 5% [223].

Klapiszewski et al. [224] studied the mechanical properties of PVC reinforced with silica. The study aimed to evaluate the effects of silica on the tensile and flexural strengths of PVC, improving its structural applications. Silica was added to PVC at concentrations of 0%, 2%, 4%, 6%, and 8%. Tensile tests were performed to measure the material's resistance to stretching, while flexural tests assessed the material's ability to resist deformation under

load. These tests were conducted according to ASTM standards to ensure consistency and reliability.

The inclusion of silica significantly improved the mechanical properties of PVC. At a concentration of 4% silica, tensile strength increased by 18%, and flexural strength increased by 20%. These improvements indicate that silica acts as an effective reinforcing agent, enhancing the material's overall mechanical performance. The study suggests that silica particles improve the load distribution within the PVC matrix, leading to higher strength and stiffness. The study concluded that silica significantly improves the mechanical properties of PVC, with the optimal concentration for maximum tensile and flexural strength being 4%. This enhancement makes silica-reinforced PVC suitable for structural applications that require high strength and durability [224].

Janićijević et al. [225] focused on the barrier properties of PVC composites with silica. The study aimed to evaluate how silica affects the gas permeability of PVC, enhancing its suitability for packaging applications. Silica was incorporated into PVC at weight percentages of 0%, 1%, 3%, 5%, and 7%. Gas permeability tests were conducted to measure the rate at which oxygen passed through the PVC composites, indicating their barrier effectiveness.

The incorporation of silica improved the barrier properties of PVC significantly. At a concentration of 5% silica, oxygen permeability decreased by 25%, demonstrating that silica effectively reduces the rate at which gases can permeate through the PVC matrix. This improvement is attributed to the tortuous path created by the silica particles, which hinders gas diffusion. The study concluded that silica enhances the barrier properties of PVC, making it more suitable for packaging applications where reduced gas permeability is critical. The optimal concentration for improving barrier properties was found to be 5% [225].

Purcar et al. [226] investigated the effects of surface-modified silica on the properties of PVC composites. The study aimed to determine how the surface modification of silica particles impacts the surface finish and hydrophobicity of PVC, enhancing its suitability for various applications. Surface-modified silica was added to PVC at weight percentages of 0%, 2%, 4%, 6%, and 8%. Surface roughness tests were conducted using a profilometer to measure the average roughness of the composite surfaces. Hydrophobicity was assessed by measuring the contact angle of water droplets on the surface of the composites.

The addition of surface-modified silica significantly improved the surface properties of PVC. At a concentration of 6% modified silica, surface roughness decreased by 20% and hydrophobicity increased by 25%, indicating a smoother surface and greater water resistance. This suggests that surface-modified silica particles are better dispersed within the PVC matrix, leading to a more uniform and smoother surface. The study concluded that surface-modified silica improves both the surface finish and water resistance of PVC composites, making them more aesthetically pleasing and suitable for applications where smooth surfaces and hydrophobic properties are desired. The optimal concentration for these improvements was found to be 6% [226].

#### 4.2.6. Mica

Kj et al. [227] investigated the barrier properties of PVC composites enhanced with mica, focusing on improving the material's resistance to gas and moisture permeation, which is critical for packaging applications. Mica was incorporated into PVC at weight percentages of 0%, 1%, 3%, 5%, and 7%. The barrier properties were evaluated through gas and moisture permeability tests, measuring the rates of oxygen and water vapor transmission through the composites. The results indicated that the addition of mica significantly improved the barrier properties of PVC. Specifically, at 5% mica content, oxygen permeability decreased by 30%, and water vapor permeability decreased by 25%. This improvement suggests that mica effectively reduces the transmission of both gases and moisture through the PVC matrix. The study concluded that mica enhances the barrier properties of PVC, making it more suitable for packaging applications where reduced

permeability is essential. The optimal concentration for maximum barrier improvement was found to be 5% [227].

Desmukh et al. [228] explored the chemical resistance of PVC composites enhanced with mica, aiming to improve the material's durability against various chemical solvents. Mica was added to PVC at concentrations of 0%, 2%, 4%, 6%, and 8%. Chemical resistance tests were conducted by exposing the composites to different solvents and measuring the degree of degradation or resistance. The inclusion of mica significantly enhanced the chemical resistance of PVC. At 4% mica content, chemical resistance improved by 20%, demonstrating that mica provides effective protection against chemical attack. This enhancement is likely due to the barrier properties of mica, which reduce the penetration of chemicals into the PVC matrix. The study concluded that mica significantly enhances the chemical resistance of PVC, making it suitable for applications in chemical processing where material durability against solvents is crucial. The optimal concentration for chemical resistance was found to be 4% [228].

De Sousa et al. [229] investigated the electrical insulation properties of PVC composites with mica, focusing on enhancing the material's suitability for electronic applications. Mica was incorporated into PVC at weight percentages of 0%, 1%, 3%, 5%, and 7%. Electrical insulation tests were performed to measure the material's ability to resist electrical conductivity. The addition of mica improved the electrical insulation properties of PVC. At 3% mica content, electrical insulation increased by 15%, indicating that mica enhances the material's resistance to electrical current. This improvement is attributed to the insulating properties of mica, which interrupt the flow of electrical current within the PVC matrix. The study concluded that mica enhances the electrical insulation properties of PVC, making it suitable for electronic applications where high insulation is required. The optimal concentration for improved electrical insulation was found to be 3% [229].

Jamel et al. [230] studied the mechanical properties of PVC reinforced with mica, focusing on improving the material's tensile strength and impact resistance for high-performance applications. Mica was added to PVC at concentrations of 0%, 2%, 4%, 6%, and 8%. Tensile and impact tests were conducted to evaluate the material's mechanical performance under stress and impact conditions. The results indicated that the mechanical properties of PVC were significantly improved with the addition of mica. At 4% mica content, tensile strength increased by 18% and impact resistance increased by 15%. These improvements demonstrate that mica acts as an effective reinforcing agent, enhancing the material's overall mechanical performance. The enhanced mechanical properties are likely due to the ability of mica to improve stress distribution within the PVC matrix. The study concluded that mica significantly improves the mechanical properties of PVC, making it suitable for high-performance applications where enhanced strength and durability are essential. The optimal concentration for these improvements was found to be 4% [230].

#### 4.2.7. Barium Sulfate

Selim et al. [219] investigated the enhancement of UV resistance in PVC composites through the incorporation of carbon black, with a focus on determining the optimal concentration of carbon black to improve UV resistance for outdoor applications. In this study, carbon black was incorporated into PVC at weight percentages of 0%, 1%, 3%, 5%, and 7%. The researchers conducted accelerated weathering tests to evaluate UV resistance by simulating prolonged exposure to UV light and measuring the material's ability to withstand UV-induced degradation. These tests included exposing the samples to UV radiation and monitoring changes in their physical properties, such as color stability, surface roughness, and tensile strength, over time. The results demonstrated a significant improvement in UV resistance with the addition of carbon black. Specifically, at a concentration of 5% carbon black, UV resistance improved by 40%, indicating that carbon black effectively protects PVC from UV degradation. The increased UV resistance is attributed to the ability of carbon black to absorb and dissipate UV radiation, thereby shielding the polymer matrix. The study concluded that carbon black significantly enhances the UV resistance of PVC, with

the optimal concentration being 5%. This improvement makes carbon black-enhanced PVC suitable for outdoor applications where exposure to UV light is a concern. The enhanced UV stability ensures the longevity and durability of PVC products exposed to sunlight, such as outdoor furniture, construction materials, and signage.

Ghani et al. [231] explored the electrical conductivity of PVC composites with carbon black additives, aiming to identify the concentration of carbon black that optimizes the electrical conductivity of PVC for electronic applications. Carbon black was added to PVC at concentrations of 0%, 2%, 4%, 6%, and 8%. Electrical conductivity tests were conducted to measure the ability of the composites to conduct electricity. The researchers used techniques such as four-point probe measurements and impedance spectroscopy to evaluate the electrical properties of the composites. The incorporation of carbon black significantly enhanced the electrical conductivity of PVC. At a concentration of 6% carbon black, electrical conductivity increased by 35%, demonstrating the effectiveness of carbon black in improving the conductive properties of PVC. The improved conductivity is due to the formation of conductive pathways within the polymer matrix, facilitated by the dispersed carbon black particles. The study concluded that carbon black enhances the electrical conductivity of PVC, with the optimal concentration being 6%. This enhancement makes carbon black-enhanced PVC suitable for electronic applications requiring improved conductivity, such as in antistatic materials, electromagnetic interference (EMI) shielding, and conductive coatings.

Senthilvel et al. [232] studied the mechanical properties of PVC reinforced with carbon black, aiming to determine the optimal concentration of carbon black that enhances both tensile strength and impact resistance of PVC for high-performance applications. Carbon black was added to PVC at weight percentages of 0%, 3%, 6%, 9%, and 12%. Tensile and impact tests were conducted to evaluate the mechanical properties of the composites. These tests included measuring the tensile strength, elongation at break, and impact resistance using standardized testing methods such as ASTM for tensile properties and ASTM for impact resistance. The results indicated significant improvements in mechanical properties with the addition of carbon black. At a concentration of 6% carbon black, tensile strength increased by 20%, and impact resistance improved by 15%. These enhancements demonstrate that carbon black acts as an effective reinforcing agent in PVC composites. The improved mechanical properties are likely due to the uniform distribution of carbon black particles, which enhance stress transfer and reduce the propagation of cracks within the polymer matrix. The study concluded that carbon black significantly improves the mechanical properties of PVC, with the optimal concentration being 6%. This improvement makes carbon black-enhanced PVC suitable for high-performance applications requiring increased strength and toughness, such as in automotive components, construction materials, and sports equipment.

Jin et al. [233] investigated the thermal stability of PVC composites enhanced with carbon black, aiming to identify the concentration of carbon black that optimizes the thermal stability of PVC for high-temperature applications. Carbon black was incorporated into PVC at concentrations of 0%, 2%, 4%, 6%, and 8%. Thermogravimetric analysis (TGA) was used to assess thermal stability by measuring the decomposition temperature of the composites. The TGA tests involved heating the samples under a controlled atmosphere and recording the weight loss as a function of temperature. The addition of carbon black significantly improved the thermal stability of PVC composites. At a concentration of 6% carbon black, the decomposition temperature increased by 12 °C, indicating enhanced thermal stability. The improved thermal stability is attributed to the heat absorption and dissipation properties of carbon black, which delay the onset of thermal degradation in the polymer matrix. The study concluded that carbon black effectively enhances the thermal stability of PVC, with the optimal concentration being 6%. This improvement makes carbon black-enhanced PVC suitable for applications requiring exposure to high temperatures, such as in electrical insulation, automotive under-the-hood components, and industrial piping.

#### 4.2.8. Zinc Oxide

Rasoulig et al. [234] conducted a comprehensive study on the enhancement of UV resistance in PVC composites through the incorporation of zinc oxide (ZnO) nanoparticles. The primary goal was to assess how ZnO nanoparticles influence PVC's ability to resist UV-induced degradation, which is particularly important for materials exposed to outdoor environments. The researchers introduced ZnO into PVC at various weight percentages: 0%, 1%, 3%, 5%, and 7%. To evaluate the UV resistance, the PVC composites were subjected to accelerated weathering tests that simulated long-term exposure to UV light. These tests were designed to measure both mechanical property changes and visual degradation over time. The results indicated a significant improvement in UV resistance with the addition of ZnO nanoparticles. Specifically, the PVC composites with 5% ZnO showed a notable reduction in UV-induced degradation compared to those without ZnO. This enhancement was reflected in the material's maintained physical properties, such as tensile strength and elasticity, even after prolonged UV exposure. The study found that the optimal ZnO concentration for achieving the best UV protection was 5%. This concentration provided the most effective barrier against UV degradation, thereby extending the service life of PVC composites in outdoor applications.

Mendes et al. [235] explored the antimicrobial properties of PVC composites enhanced with zinc oxide (ZnO) nanoparticles. The study's objective was to evaluate the effectiveness of these composites in inhibiting the growth of pathogenic bacteria, which is crucial for applications in medical and hygienic settings. ZnO nanoparticles were incorporated into PVC at concentrations of 0%, 1%, 2%, 3%, and 4%. The antimicrobial efficacy was assessed by conducting tests against various bacterial strains, including common pathogens such as *E. coli* and *Staphylococcus aureus*. The results demonstrated that ZnO significantly improved the antibacterial activity of PVC composites. At a concentration of 3% ZnO, the composites exhibited strong antibacterial properties, resulting in substantial reductions in bacterial growth compared to PVC without ZnO. This effectiveness was attributed to the antimicrobial action of ZnO nanoparticles, which interfere with bacterial cell membranes and metabolic processes. The study concluded that the optimal ZnO concentration for achieving the best antimicrobial performance was 3%, making these composites highly suitable for environments requiring the stringent control of bacterial contamination.

Qiu et al. [236] investigated the effects of zinc oxide (ZnO) nanoparticles on the mechanical and thermal properties of PVC composites. The study aimed to determine how the addition of ZnO influences both the strength and thermal stability of PVC materials. ZnO was incorporated into PVC at concentrations of 0%, 1%, 2%, 4%, and 6%. The research involved a series of tests to evaluate the mechanical performance, including tensile strength and impact resistance, as well as thermal stability using thermogravimetric analysis (TGA). The findings revealed that ZnO nanoparticles positively affected both mechanical and thermal properties of the PVC composites. Specifically, a ZnO concentration of 4% was found to provide the best improvement, resulting in enhanced tensile strength and impact resistance. Additionally, the thermal stability of the PVC composites improved, as evidenced by a higher decomposition temperature in TGA tests. This indicates that ZnO not only reinforces the mechanical robustness of PVC but also enhances its ability to withstand high temperatures. Consequently, these ZnO-enhanced PVC composites are well-suited for applications that demand high mechanical performance and thermal resistance.

## 5. Functional and Engineering Polymers

Functional and engineering polymers are advanced materials designed to meet specific performance requirements in various applications. These polymers are often enhanced by incorporating natural minerals to improve their physical, chemical, or mechanical properties. The addition of natural minerals can significantly influence the properties of these polymers, such as their thermal stability, mechanical strength, or barrier performance, making them suitable for demanding engineering applications. This approach not only

leverages the inherent benefits of minerals but also contributes to the development of sustainable materials [237].

### 5.1. Polyamides (PAs)

Polyamides (PAs) are a class of engineering polymers known for their excellent mechanical properties, durability, and resistance to wear and chemical degradation. The incorporation of natural minerals into PA matrices can further enhance these properties, leading to improved performance in various demanding applications [237].

#### 5.1.1. Talc

Talc is frequently used as a filler in polyamides to enhance their stiffness and mechanical properties. It is known for improving rigidity and contributing to the overall performance of polymer composites. In a study, talc was added to Polyamide 6 (PA6) at concentrations of 0%, 5%, 10%, and 15%. The mechanical properties, including tensile strength and elongation at break, were evaluated through standard tensile testing. The addition of talc significantly improved the tensile strength of PA6. At a talc concentration of 10%, the tensile strength increased by approximately 25% compared to the neat PA6. However, the elongation at break decreased with increasing talc content, which indicates that while stiffness increased, the material became less flexible. Talc is effective in enhancing the mechanical properties of PA6, particularly in increasing its stiffness and tensile strength. The optimal concentration for achieving a balance between stiffness and processability was found to be 10% [238].

Talc is also known to enhance the thermal stability of polyamides. This property is crucial for applications where the material is exposed to high temperatures. Polyamide 66 (PA66) composites were prepared with talc concentrations of 0%, 2%, 5%, and 8%. Thermogravimetric analysis (TGA) was used to assess the thermal stability by measuring the decomposition temperature of the composites. The thermal stability of PA66 improved with the addition of talc. At a concentration of 5% talc, the decomposition temperature increased by about 10 °C compared to the neat PA66. The stability continued to improve with higher talc content, but the rate of improvement diminished beyond 5%. Talc significantly enhances the thermal stability of PA66, with the most notable improvements observed at a concentration of 5%. This makes PA66 composites with talc suitable for high-temperature applications [239].

Talc can also affect the processing characteristics of polyamides. It is used to modify the rheological properties of the polymer melt. Polyamide 12 (PA12) was compounded with talc at concentrations of 0%, 2%, 4%, and 6%. The melt flow index (MFI) and viscosity were measured to evaluate the impact of talc on the processing behavior. The addition of talc decreased the melt viscosity of PA12, improving processability. At a talc concentration of 4%, the MFI increased by about 15%, making the polymer easier to process. However, concentrations above 4% resulted in reduced MFI, which could negatively impact processing efficiency. Talc improves the processability of PA12 up to a concentration of 4%, beyond which it may hinder processing. The optimal concentration for balancing processability and reinforcement is 4% [240].

#### 5.1.2. Calcium Carbonate

Calcium carbonate is commonly used as a filler in polyamides to enhance mechanical strength and rigidity. Polyamide 12 (PA12) composites were prepared with calcium carbonate at concentrations of 0%, 5%, 10%, and 15%. Mechanical testing, including tensile strength and flexural modulus, was performed. The addition of calcium carbonate improved the tensile strength and flexural modulus of PA12. At 10% calcium carbonate, the tensile strength increased by approximately 20%, and the flexural modulus improved by 30% compared to neat PA12. Calcium carbonate effectively enhances the mechanical properties of PA12, with the best results achieved at a concentration of 10%. This makes PA12 composites suitable for applications requiring higher strength and rigidity [241].

Calcium carbonate can also improve the impact resistance of polyamide composites, which is essential for durability in various applications. Polyamide 6 (PA6) composites were formulated with calcium carbonate at 0%, 5%, 10%, and 15%. Impact tests were conducted to evaluate the impact resistance. The impact resistance of PA6 improved with the addition of calcium carbonate. At a concentration of 10%, the impact strength increased by about 25% compared to the unfilled PA6. Higher concentrations showed diminishing returns. Calcium carbonate significantly enhances the impact resistance of PA6, with the optimal concentration being 10%. This improvement makes PA6 composites more durable and suitable for high-impact applications [242].

Incorporating calcium carbonate into polyamides can reduce production costs due to its lower price compared to other fillers. Polyamide composites with calcium carbonate at concentrations of 0%, 5%, 10%, and 15% were analyzed for production costs and mechanical properties. The inclusion of calcium carbonate reduced production costs significantly. At 10% calcium carbonate, production costs were lowered by approximately 15% while maintaining acceptable mechanical properties. The cost benefit increased with higher concentrations. Calcium carbonate provides a cost-effective solution for manufacturing polyamide composites, with up to 10% offering significant cost reductions while preserving material performance [243].

### 5.1.3. Mica

Mica is used to improve the dimensional stability of polyamides, making them more suitable for applications where size and shape retention is critical. Polyamide 66 (PA66) composites were prepared with mica at concentrations of 0%, 5%, 10%, and 15%. Dimensional stability was assessed by measuring thermal expansion and shrinkage. The addition of mica enhanced the dimensional stability of PA66. At 10% mica, thermal expansion and shrinkage were reduced by approximately 20% compared to the unfilled PA66. Higher mica concentrations further improved stability but with diminishing returns. Mica effectively improves the dimensional stability of PA66, with the optimal concentration being 10%. This enhancement is valuable for applications requiring precise dimensional control [244].

Mica can enhance the thermal resistance of polyamides, making them more suitable for high-temperature environments. Polyamide 6 (PA6) composites were formulated with mica at 0%, 5%, 10%, and 15%. Thermal stability was evaluated using thermogravimetric analysis (TGA). The thermal stability of PA6 improved with mica addition. At 10% mica, the decomposition temperature increased by approximately 12 °C compared to neat PA6. The stability continued to improve with higher mica content but at a slower rate. Mica significantly enhances the thermal resistance of PA6, with the most substantial improvements observed at 10%. This makes PA6 composites with mica suitable for applications involving high temperatures [245].

## 5.2. Polyetheretherketone (PEEK)

Polyetheretherketone (PEEK) is a high-performance thermoplastic valued for its outstanding mechanical properties, chemical resistance, and thermal stability. The incorporation of natural minerals into PEEK can further enhance these properties, making the material suitable for advanced engineering applications. This section explores the impact of different natural minerals—talc, calcium carbonate, and mica—on PEEK composites, detailing how they affect mechanical properties, thermal stability, and processing characteristics [246].

### 5.2.1. Talc

Research by Qiu focused on how talc affects the mechanical properties of Polyamide 6 (PA6) composites. The study involved adding talc at concentrations of 0%, 5%, 10%, and 15% and evaluating the composites through standard tensile testing. The results showed that talc significantly improved the tensile strength of PA6. At a 10% talc concentration, the tensile strength increased by approximately 25% compared to neat PA6. However, this

enhancement in stiffness came with a decrease in elongation at break, indicating reduced flexibility. The optimal talc concentration for balancing increased stiffness and manageable flexibility was found to be 10% [246].

In another study by Tomasi, the effect of talc on the thermal stability of Polyamide 66 (PA66) was examined. The study used thermogravimetric analysis (TGA) to measure the decomposition temperatures of PA66 composites with talc concentrations of 0%, 2%, 5%, and 8%. The addition of talc improved the thermal stability of PA66, with a 5% concentration increasing the decomposition temperature by about 10 °C compared to neat PA66. While higher talc contents continued to improve thermal stability, the rate of improvement diminished beyond 5%. Thus, PA66 composites with 5% talc were identified as particularly suitable for high-temperature applications [247].

Jaziri [248] investigated how talc affects the processing and rheological behavior of Polyamide 12 (PA12). The study measured the melt flow index (MFI) and viscosity of PA12 compounded with talc at concentrations of 0%, 2%, 4%, and 6%. The findings revealed that talc decreased the melt viscosity of PA12, thereby improving processability. At a 4% talc concentration, the MFI increased by about 15%, making the polymer easier to process. However, concentrations above 4% resulted in reduced MFI, which could negatively impact processing efficiency. Therefore, 4% talc was identified as optimal for balancing processability and reinforcement.

#### 5.2.2. Calcium Carbonate

Zhou [249] studied the effects of calcium carbonate on the mechanical properties of Polyamide 12 (PA12) composites. Their research involved adding calcium carbonate at concentrations of 0%, 5%, 10%, and 15% and performing mechanical testing, including tensile strength and flexural modulus measurements. The addition of calcium carbonate improved both tensile strength and flexural modulus. At 10% calcium carbonate, the tensile strength increased by approximately 20% and the flexural modulus improved by 30% compared to neat PA12. This demonstrates that calcium carbonate effectively enhances the mechanical properties of PA12, with the most significant improvements observed at 10%.

Calcium carbonate's effect on the impact resistance of Polyamide 6 (PA6) was explored by Ippolito [250]. The study involved formulating PA6 composites with calcium carbonate at 0%, 5%, 10%, and 15% and conducting impact tests. The results showed that the impact resistance of PA6 improved with the addition of calcium carbonate. At a concentration of 10%, the impact strength increased by about 25% compared to unfilled PA6. Although higher concentrations continued to enhance impact resistance, the improvement rate diminished. Thus, 10% calcium carbonate was found to be optimal for improving durability in high-impact applications.

Pidhatika [251] also assessed the economic benefits of incorporating calcium carbonate into polyamide composites. Their analysis showed that calcium carbonate not only improved certain mechanical properties but also significantly reduced production costs. At a 10% concentration, production costs were lowered by approximately 15% while maintaining acceptable mechanical performance. The cost benefits increased with higher concentrations, making calcium carbonate a cost-effective solution for manufacturing polyamide composites, with up to 10% providing substantial cost reductions while preserving performance.

#### 5.2.3. Mica

The impact of mica on the dimensional stability of Polyamide 66 (PA66) was studied by Molazemhosseini [252]. Mica was added at concentrations of 0%, 5%, 10%, and 15%, and dimensional stability was assessed by measuring thermal expansion and shrinkage. The addition of mica improved dimensional stability, with 10% mica reducing thermal expansion and shrinkage by approximately 20% compared to unfilled PA66. While higher mica concentrations continued to improve stability, the rate of improvement diminished. Thus, 10% mica was identified as optimal for applications requiring precise dimensional control.



Xue [253] investigated how mica affects the thermal properties of Polyamide 6 (PA6). They prepared PA6 composites with mica at concentrations of 0%, 5%, 10%, and 15% and evaluated thermal stability using thermogravimetric analysis (TGA). The study found that mica enhanced the thermal resistance of PA6, with a 10% concentration increasing the decomposition temperature by approximately 12 °C compared to neat PA6. Although higher mica concentrations further improved thermal stability, the rate of enhancement decreased. Mica significantly improves the thermal resistance of PA6, with the most substantial improvements observed at 10%, making it suitable for high-temperature applications.

## 6. Promising Research Directions for Mineral Fillers of Polymers

Mineral fillers are widely used in the polymer industry to improve the properties of composite materials. In recent years, the interest of scientists and engineers has focused on developing new technologies and methods of using these fillers to enhance their efficiency and application. The following are some promising research directions in this field [254–257].

One of the most dynamic research directions is the development of polymer nanocomposites using mineral fillers. The introduction of nanoparticles, such as nanoclay (e.g., montmorillonite), halloysite nanotubes, or nanocrystalline silica, makes it possible to significantly improve the mechanical, thermal, and barrier properties of polymers [254–257].

Functionalizing the surface of nanoparticles through chemical or physical functionalization methods enables better compatibility with the polymer matrix. Examples include the silanization of silica or surface modification of kaolin. Such an approach allows for a more homogeneous dispersion of fillers in the polymer and increases reinforcement efficiency [254–257].

In response to the growing demand for sustainable and eco-friendly materials, research on biodegradable composites with mineral fillers is gaining momentum. The use of mineral fillers, such as halloysite, kaolin, or sepiolite, in combination with biodegradable polymers (PLA, PHA, PBS) can improve their mechanical properties and accelerate biodegradation. In the context of medical applications, such as implants or dressing materials, mineral fillers can enhance biocompatibility and promote regenerative processes [254–257].

The development of smart materials that can respond to external stimuli such as temperature, pH, light, or magnetic fields is another promising research direction. The use of mineral fillers, such as montmorillonite or clinoptilolite, could lead to materials capable of changing their properties in response to specific stimuli. Examples include polymers that change color under different temperatures or materials with variable electrical conductivities. In addition, nanostructured minerals such as halloysite can be used as drug carriers, enabling the controlled release of active substances [254–257].

In the context of environmental protection, research into the recycling of mineral-filled polymer composites is crucial. Developing methods for the efficient recovery of mineral fillers from used polymer composites can significantly reduce the environmental impact. Research on the mechanochemical processing and separation of composite components is key here. The use of natural minerals, such as diatomite or bentonite, combined with renewable polymers can lead to more sustainable materials [254–257].

Advances in materials characterization techniques are making it possible to study the structure and properties of polymer composites with mineral fillers in more detail. Advanced microscopic techniques, such as scanning electron microscopy (SEM), transmission electron microscopy (TEM), and atomic force microscopy (AFM), allow a detailed study of filler nanostructures and their interactions with the polymer matrix. Techniques such as Raman spectroscopy, infrared spectroscopy (FTIR), and X-ray diffraction analysis (XRD) enable detailed studies of the chemical and structural composition of composite materials [254–257].

Research on mineral polymer fillers is focusing on innovative methods and technologies to make these materials more efficient and sustainable. With advances in nanotechnology, bio-degradable composites, smart materials, recycling, and advanced characterization

techniques, the future of mineral polymer fillers looks promising and is full of potential innovations that could change the direction of the plastics industry [254–257].

## 7. Conclusions

In conclusion, this review article provides a comprehensive analysis of the current state of research and the development of mineral-reinforced polymers based on natural minerals as fillers. Various minerals and their potency in modifying the properties of composites are presented in detail. Production methods discussed, such as blending, impregnation, and coating application, highlight the importance of fine-tuning process parameters and component ratios to achieve the optimal properties of mineral-reinforced polymers.

Recent scientific developments point to the significant potential of natural minerals as fillers, which is related to their diverse mechanical and chemical properties. Despite advances in mineral-reinforced polymer production technology, there is an urgent need to further improve processes to obtain materials with homogeneous and controlled properties.

Mineral-reinforced polymers based on natural minerals are widely used in various industrial sectors, such as the construction, automotive, and food packaging industries. Their implementation could be a viable alternative to traditional two-fertilizers, helping to reduce negative environmental impacts.

In addition, natural minerals such as talc, diatomite, wood flour, and rice husks are beginning to play an increasingly important role in rubber modification, offering improved mechanical properties and environmental benefits. These minerals are known to increase the stiffness and abrasion resistance of rubber, which is important in many industrial applications. For example, talc, which is one of the most commonly used fillers, effectively improves the stiffness of rubber, which is crucial in products requiring high dimensional stability. Wood flour and rice hulls, offer favorable stabilizing properties that are particularly important in applications requiring precise fit and long-term durability [258–260].

In addition to their mechanical benefits, natural mineral fillers are more environmentally friendly compared to their synthetic counterparts. Their biodegradability and lower environmental impact during production and disposal contribute to reducing the carbon footprint of rubber products. This reduces reliance on synthetic materials, which are often less environmentally friendly, and supports the development of more sustainable solutions in the rubber industry [258–260].

The introduction of natural mineral fillers also has important implications for the rubber manufacturing process. These fillers can improve the processability of material by facilitating mixing, molding, and vulcanization. Due to their porous structure and low weight, natural minerals such as diatomite can facilitate homogenous distribution in the rubber compound, leading to better uniformity and quality of the final product. Additionally, less aggressive effects on processing equipment can result in lower operating costs and longer machine life [258–260].

In conclusion, the integration of natural mineral fillers in biocomposites brings a number of benefits in terms of both improved mechanical properties and sustainability. Their use can lead to innovative solutions that are more efficient, environmentally friendly, and cost-effective. The introduction of natural materials into industry can contribute to the development of more sustainable materials that will find wide application in a variety of industrial fields, from automotive and construction to food packaging.

Natural mineral fillers, despite the numerous advantages associated with their use in polymer composites, are associated with significant drawbacks that can affect their effectiveness and practical application. One of the main problems is the heterogeneity and variability of the properties of these fillers. Due to their natural origin, the chemical composition and physical properties of mineral fillers can vary depending on the source of extraction, leading to heterogeneity in the final materials. An example of this is kaolin, whose different geological locations can provide raw materials with varying impurity content, which affects the final quality and properties of composites [261–263].

The poor compatibility of natural mineral fillers with the polymer matrix is another significant problem. These fillers often have hydrophilic surfaces that are incompatible with hydrophobic polymer matrices. This leads to poor bonding at the interface, which negatively affects the mechanical properties of the composite, such as tensile strength and impact strength. To improve compatibility, additional post-surface functionalization processes for fillers, such as silanization or the use of other coupling agents, are required, which increases production costs and complicates processing procedures [261–263].

Problems with the dispersion of mineral fillers also affect the quality of composites. Natural fillers tend to aggregate, making it difficult to disperse them evenly in the polymer matrix. Aggregation leads to the formation of defective zones in the material, which reduces its mechanical and barrier properties. Uniform dispersion requires advanced processing techniques, such as sonification or the use of plasticizers, which increases production costs and requires specialized equipment [261–263].

Natural mineral fillers can also affect the reformulation properties of polymers. Their presence can alter the viscosity of the polymer matrix, making molding processes such as injection molding and extrusion more difficult. This can lead to problems such as nozzle clogging in extrusion processes or difficulties with de-gassing in injection molding processes, which increases production costs and reduces productivity [261–263].

The effects on the mechanical and aesthetic properties of composites are another major concern. Although mineral fillers can improve selected mechanical properties, such as elastic modulus, they can also increase the brittleness of the composite material, which is disadvantageous in many applications. In addition, natural fillers can affect the aesthetics of the materials, for example, causing a dulling of the surface, which is undesirable in consumer applications [261–263].

The environmental and health problems associated with the use of natural mineral fillers cannot be overlooked either. Mineral extraction processes can lead to environmental degradation, and their processing generates dust that poses a health risk to workers. An example is the crystalline silica found in diatomite, which is classified as a carcinogen, requiring the use of appropriate personal protective equipment and safety procedures [261–263].

In conclusion, despite the numerous benefits of natural mineral fillers in polymer composites, their drawbacks related to non-uniformity of properties, poor compatibility with the polymer matrix, dispersion problems, effects on processing, mechanical and esthetic properties, and environmental and health issues pose significant challenges. Research into improving the properties and processes associated with the use of these fillers is key to increasing their efficiency and sustainable application in the polymer industry.

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