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# Enhancing the Mechanical and Thermal Properties of PMMA Composites with Hazelnut Shell Micro-Particles for Potential Dental Applications

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**ABSTRACT**

The objective of this study is to examine the mechanical and thermal properties of polymethyl methacrylate (PMMA)-based composites containing ground hazelnut shell micro-particles (HSMP) to improve their application in the dental sector. HSMP with volume concentrations of 0.25%–1.25% were dispersed into the PMMA matrix, and the resultant composites were characterized through tensile, compressive, impact strength, hardness, and thermal conductivity measurements. The findings show that the incorporation of HSMP enhances both stiffness and hardness of the composites, and the maximum improvement is realized with 0.25%–0.50% of the filler. At such proportions, a trade-off between mechanical strength and toughness was achieved, and further additions of HSMP resulted in rigid and brittle characteristics, which are attributed to the agglomeration effect of the filler. Thermal conductivity was observed to reduce with the addition of HSMP, and this confirmed good insulation characteristics. SEM analysis confirmed uniform dispersion of HSMP at optimal concentration and interfacial debonding and crack path after performing the impact test, which provided evidence of a fracture energy dissipation mechanism. These findings demonstrate the feasibility of HSMP as an eco-friendly and inexpensive reinforcement solution for enhancing the functional properties of PMMA for dental prostheses applications.

## 1. INTRODUCTION

Polymethyl methacrylate (PMMA) is widely used in both biomedical and structural applications because of its biocompatibility, lightweight nature and ease of processing [1]. PMMA is widely used as a main material used in denture bases, artificial teeth, and orthodontic appliances in dentistry owing to its aesthetic appearance, chemical stability and cheapest price [2]. However, despite these advantages, PMMA has inherent drawbacks such as brittleness, low impact strength, and inadequate wear resistance, thereby limiting its long-term durability in demanding applications [3]. To overcome these drawbacks, some modifications in the form of polymer reinforcement with bio-based fillers in PMMA have been made to improve its mechanical and thermal as well as fracture properties [4].

Several reinforcement strategies have been sought to improve PMMA's mechanical and thermal properties [5-9]. Improvements of PMMA's flexural strength, wear resistance and impact resistance of PMMA by the use of synthetic fillers such as aluminum borate whiskers [10], zirconia and boron nitride nanoparticles [11], graphene oxide [12], and hybrid nano-reinforcements [13] have been demonstrated. Nevertheless, synthetic fillers are expensive, and there are concerns over environmental issues, which have prompted increasing interest in bio- based reinforcements [14].

Agricultural waste bio-based fillers, which are a sustainable alternative to available fillers, provide an improvement in PMMA mechanical property along with its easiness of production and material cost [15]. The effects of incorporating natural reinforcements such as microcrystalline cellulose [16], date seed powder [17], ridge gourd fibre [18], and modified cellulose fibres [19] have been investigated. These fillers not only increase stiffness, hardness, and impact resistance but also positively influence thermal conductivity and wear performance.

Up to date, among the natural fillers, hazelnut shell micro-particles (HSMP) have shown a high potential as a reinforcing material, thanks to their rigidity and characterized by high lignin and cellulose content and low weight index [20]. HSMP incorporation in the PMMA matrix could improve the structural integrity and also show environmental sustainability [21]. Additionally, hybrid approaches utilizing waste fillers of basalt fibers [22] and recycled carbon fibers [23] have shown excellent improvements in mechanical properties with enhanced material recyclability.

In comparison to the agricultural byproduct fillers, rice husks, coconut shells, and walnut shells, HSMP has several advantages. These are primarily due to its composition which has approximately 45% cellulose, 22% hemicellulose and 28% lignin, which give them mechanical strength and rigidity that makes them useful in applications that require rigid fibers for

reinforcement, as provided by a previous study [24]. HSMP is also characterized by low density as well as significant stiffness to enhance reinforcement of polymer matrices. In contrast to the rice husks or walnut shells that need surface chemical treatment for improving matrix compatibility, the HSMP can be incorporated with little treatment while ensuring good dispersion and interface bonding even at low loading [25]. Moreover, hazelnut shells as an agro-waste have become more accessible in the major hazelnut-producing countries including Turkey and Italy and they have been adopted in biocomposite and chemical industries to increase their economic and environmental benefits [26, 27].

Tradeoffs in performance are pointed out by comparing HSMP-reinforced and commercial PMMA composites. Commercial fillers, such as zirconia, nano-silica, or glass fiber, have high tensile strengths of 72–152 MPa for load-bearing applications [28, 29], compared to 58–64 MPa of tensile strength for HSMP-PMMA, which is adequate for denture bases. The HSMP composites have lower impact resistance (0.51 kJ/m² vs. up to 13.7 kJ/m² in commercial types) [30], which is, however, far higher compared to unfilled PMMA. Notably, HSMP-PMMA has similar hardness as commercial materials (up to Shore D 85.6) and outperforms them in heat insulation (0.228 W/m·K vs. 0.27–0.30 W/m·K), leading to improved wearer comfort [31]. From an application perspective, these findings demonstrate HSMP-PMMA as a usable, inexpensive, eco-friendly alternative that can serve in differing external fields with acceptable mechanical performance and increased thermal properties. While replacing high-impact composites, particularly in load-critical areas, it provides an environmentally responsible alternative with competitive functional outcomes for non-load-carry dental prostheses.

However, the HSMP content that potentially offers these advantages has not been studied sufficiently with regard to the mechanical integrity, fracture behavior and thermal stability of PMMA. Agglomeration, interfacial defects, and embrittlement of enhancements caused by excessive filler content can occur. To resolve this, the Taguchi method was used to design the optimal reinforcement level for PMMA-based composites.

The objective of this study is to investigate the mechanical and thermal performance of HSMP reinforced PMMA composites in terms of their tensile, compressive, impact, hardness development and thermal conductivity behavior. We systematically vary HSMP concentration (0.25%–1.25%) to determine the balance between the reinforcement benefits and the structural integrity provided. Additionally, scanning electron microscopy (SEM) will be used to determine the microstructural change before and after impact testing to reveal how fillers are dispersed, how cracks propagate, and failure mechanisms. The results from this study will be useful for the development of sustainable high-performance PMMA composites for advanced biomedical and structural applications.

## 2. MATERIALS AND METHODS

### 2.1 Materials

An attractive base polymer was PMMA, as it is an excellent biocompatible material for dental prosthetics, orthopedic implant and biomedical applications due to its optical transparency, lightweight nature and easy processing. Because PMMA has high dimensional stability, chemical resistance, and adequate mechanical strength, it is suitable for reinforcement of bio-fillers, which can be used to increase the structural integrity and fracture resistance of PMMA. Nevertheless, pure PMMA is inherently brittle and lacks a sufficient level of impact resistance, with these drawbacks compromising its overall mechanical performance, which necessitates reinforcement to increase its mechanical properties.

The major constituents of the HSMP used in this study are cellulose (45%), lignin (28%) and hemicellulose (22%) [25]. This composition makes the particles rigid and lightweight, while the lignocellulosic component is particularly responsible for their thermal stability and their ability to reinforce polymers. This study presents a cost-effective, eco-friendly way of using the abundant agricultural byproduct hazelnut shells in polymer composites. It is expected that HSMP will lower the need to use synthetic fillers to increase stiffness, wear resistance and mechanical stability while being included in PMMA. Furthermore, the lignocellulosic HSMP composition provides the possibility of interfacial adhesion to the polymer matrix and therefore enhances the efficiency of the mechanical reinforcement and stress transfer.

PMMA remains a preferred material within dental and orthopedic fields because of its biocompatibility as well as mechanical properties [32, 33]. Lignocellulosic fillers like HSMP have been identified as non-toxic and environmentally friendly, as evidenced by the conclusion of bioassay and compost tests by Brás et al. [34]. However, there appears to be limited information regarding their exact interaction within the oral environment, including their impact on oral tissue response and biofilm formation.

The material used in this study was of Turkish origin, provided by Koca Dental, with a molecular weight of around 450,000 g/mol. The hazelnut shells were washed to remove the seeds and other external contaminants on the shells before the samples were exposed to direct sunlight for 24 hours to allow for thorough drying. After that, the dried shells were crushed using an electric grinder machine to comminute the shells into fine particles before sifting the particles through a mesh screen to have a particle size of 212 μm on average.

### 2.2 Composite preparation

The hand layup molding method was used to fabricate the PMMA-HSMP composites and effectively generate a homogeneous dispersion of HSMP in the PMMA matrix with the help of repeatability and process control. Because it is a simple, low-cost and versatile method, this method was chosen to produce uniform composites with reasonable economy. Furthermore, the ready availability of hazelnut shells as agricultural waste and the ease of preparation of HSMP make the proposed composite system suitable for scalability and especially for large-scale industries, especially those that may be faced with economic or sustainability limitations. To achieve consistent mechanical and thermal properties across all formulations, proper dispersion of HSMP in the PMMA matrix was necessary.

HSMP was incorporated into PMMA at 0.25%, 0.50%, 0.75%, 1.00%, and 1.25% volume fractions and the effects of reinforcement at different concentrations were systematically evaluated. Mechanical stirring at 500 rpm for 30 minutes was used to mix for the purpose of ensuring dispersibility of HSMP particles within the polymer phase, and to prevent particle

agglomeration and stress intensity maximization and formation of structural inconsistencies.

A degassing process was performed to improve material uniformity by removing trapped air bubbles that could later lead to voids and mechanical weakness. Once the de-aerated mixture was created, it was then poured into pre-designed molds and left to cure for 24 hours at room temperature, which was to allow the polymerization and solidification of the PMMA matrix. After that, a post-curing of 60 ℃ for 2 hours was done to facilitate polymer crosslinking, increase the directionality of the molecules, and stiffen the structure by decreasing internal stresses and residual monomer content.

In all mechanical and thermal experiments, five identical samples were prepared and tested for every composition to ensure statistical reliability and accuracy. By using this approach, the data representation was highly robust so as to reduce variability and allow for comparative analysis between HSMP concentrations. A reproducible and representative result was obtained due to the produced composite being standardized, fabricated and prepared for sample processing, and the conclusion can be applied for biomedical, automotive, and structural applications.

### 2.3 Statistical analysis

All mechanical and thermal tests were done on five replicates and data are expressed as mean ± standard deviation. One-way analysis of variance (ANOVA) was applied to assess the statistical significance of differences between groups. In all graphical representations, standard deviations were shown by placing error bars. Statistical analyses were performed using OriginPro 2016.

### 2.4 Mechanical analysis

#### 2.4.1 Tensile test

Tensile testing is a basic technique to analyze the mechanical properties of a material, especially its capability to withstand tensile stress. The outcome of this test also provides crucial information about the material's strength, ductility, and overall performance during the act of loading in tension. Tensile specimens were made following standardized dimensions as per ASTM D695-15 [35] specifications in order to have accurate and reproducible results. Tensile tests were performed with the LARYEE Yaur Testing Solution tensile testing machine to examine these properties.

Every specimen was secured within the grips of the machine and tested during the process of the testing to ensure there was no movement. When the test began, the grips were applied to pull the sample apart in a gradual and controlled tensile force until the sample failed between both grips. Stress-strain curves were recorded for the material to analyze the material's behavior under tensile loading, which is critical data for mechanical characterization.

The experimental setup produces these high reliability and precision levels, and thus it is effective in testing the tensile properties of a composite material. The mechanical parameters measured included the following. Ultimate tensile strength (UTS) is a maximum stress that a material can bear without becoming broken, i.e., load bearing capacity. Elongation at Break indicates the strain at failure and therefore it describes the amount of deformation possible before fracture. In the elastic deformation region, tensile stress divided by tensile strain defines material stiffness and is called Young's modulus (E). Total energy absorbed before failure (area of stress-strain curve) represents toughness and resistance to fracture. Tensile testing helps assess these parameters to give critical insights into the mechanical integrity of composite materials so as to help select and/or optimize the materials for engineering applications.

Five replicates were carried out for each composition to ensure statistical reliability.

#### 2.4.2 Compressive test

The maximum load that a material can withstand before failure under a direct vertical force is known as compressive strength. This is crucial since it is needed for prosthetics, where artificial limbs are subject to very rugged applications involving high strength, but continue to be functional as well. Compression tests were conducted with the Laryee Yaur Testing Solutions machine of the type manufactured by Laree Technology Co. Ltd (China).

Each sample was tested between two platens, and a progressive compressive force was gradually applied until the sample deformed or fractured. The force and relative amount of compression needed for the failure of the sample is measured in this test. It leads to the calculation of the material compressive strength and compressive modulus. Specimens were prepared according to standardized dimensions, following ASTM D6110-18 [36].

Thus, with this setup, a consistent and measured compressive resistance of a material can be acquired, which will help understand its mechanical behaviour. The mechanical parameters measured included the following. The maximum compressive stress that a material can withstand without failure is referred to as ultimate compressive strength. This property is very important for load-bearing applications like columns, pillars, and structural components where materials are subjected to high compressive forces. Compressive modulus (modulus of elasticity in compression) is a material property that describes how stiff or how much resistance to elastic deformation a material has under the condition of compressive loading. It is defined as the ratio of the compressive stress to the compressive strain in the range of deformation when the deformation is linear elastic. The higher the compressive modulus, the stiffer the material, while the lower the modulus means that it has more flexibility under compression. In addition, two important mechanical properties, fracture strain and toughness, are also included.

Similar to the tensile test, five samples per composition were tested, ensuring repeatability and minimizing data variability.

#### 2.4.3 Impact test

The Charpy Test is a common method to measure the shock resistance of sample preparation. The testing apparatus, provided by the Chinese company LAREE Your Testing Solution, measures the energy to fracture a material, giving an indication of the impact resistance of the material. This experimental setup consists of a clamped pendulum mechanism and an energy measurement scale and the core components of the system operate based on it.

The testing process starts by securing the pendulum hammer at its height of its maximum height before raising it. At this height, the hammer has 2.5 joules of potential energy. According to the required specifications, the specimen is positioned horizontally between the device's supports. After that the pendulum is released and swings freely with its center

lifted from the scale, which is supposed to be calibrated to zero. Upon impact, a portion of this energy is absorbed by the sample and thus converts into the potential energy that ultimately becomes the kinetic energy and can cause fracture. This event is recorded on the scale, registering the energy that is lost as a result of the material's impact resistance.

The test specimens were created in line with standardized lengths as per dimensions prescribed in ASTM D2240-15 [37] to gain perfect accuracy and consistency. Based on this setup, the material's ability to absorb mechanical impacts can be reliably measured, which is an important means for evaluating the performance and durability of composite materials.

In the same way, five samples per composition were tested, making sure to both repeat the test and reduce data variance.

2.4.4 Hardness test

Hardness measurements were performed using the Shore D method with a HUATEC GROUP HT-6600C Shore D hardness tester. In the test, a needle-shaped indenter was allowed to enter the indenter to probe for its surface hardness of the material. All tests were carried out under controlled conditions at a room temperature of 27 ℃.

In order to uphold accuracy and consistency, the samples were tested to international ASTM standards, according to Lee's disc method [38]. In this test, the surface hardness of polymer materials and their composite were tested, with special emphasis on how varied reinforcement ratios end up impacting hardness.

Five readings were taken for each sample, and the average value was recorded as the final hardness reading. After this, the average precision and reliability of the 10 readings were assessed and enhanced. The hardness test is to determine how strong the material is and how durable it would be when pressure is applied. This is important to the understanding of the mechanical behavior of composites. The laboratory temperature used in all tests was set at 27 ℃ to ensure consistent testing conditions in all measurements.

The mechanical tests were conducted under controlled laboratory conditions so that repeatability and accuracy were ensured as well as compliance with international standards. These experiments yield the results that can provide an overall picture how HSMP reinforcement affects the structural integrity of the PMMA composites and provide a basis for their potential use in biomedical and engineering industries.

2.4.5 Thermal conductivity test

In order to evaluate the heat conductive capacity of the material, the thermal conductivity test was carried out. The experiment was carried out using a Ta Lee disk device, which is a setup to determine the thermal conductivity in solid materials through a multi disc setup.

Within a stacked setup, the experimental setup comprised three copper discs (A, B and C) with known r and dA, dB, dC, arranged to permit sequential heat transfer. The copper discs were of standard size of 50 mm diameter and 5 mm thickness; the sample thickness (ds) varied according to the composite formulation. The thermal energy was generated on the first disc (TA), and the propagation through the other discs (TB and TC) allowed for calculating thermal conductivity. Temperature variations across the system were measured in degrees Celsius (℃) using conductivity plates.

Thus, a steady heat flux through the sample and reference materials was generated by electrolyzing the materials with a current of 0.25 A and a potential difference of 6 V. The rate of heat transfer was determined based on the temperature distribution across the copper discs, which was used in the following thermal conductivity equations [38]:

$$K\left(\frac{T_B - T_A}{T_S}\right) = e\left[T_A + \frac{2}{r}\left(d_A + \frac{1}{4}d_s\right)T_A + \frac{1}{2r}d_S d_B\right] \quad (1)$$

$$H = IV = \pi r^2 e(T_A + T_B) + 2\pi re\left[d_A T_A + d_s \cdot \frac{1}{2}(T_A + T_B) + d_B T_B + d_C T_C\right] \quad (2)$$

where, $e$ is the thermal energy transfer per unit area per unit time (W/m²·K) and $H$ is the rate of the energy transfer ($W$). Disc $A$, $B$ and $C$ temperatures in degrees Celsius (℃) and discs $A$, $B$ and $C$ thickness ($dA$, $dB$ and $dC$) in millimeter (mm) are denoted $TA$, $TB$ and $TC$, respectively. The thickness of the sample is represented by ds in millimeters, and it is analogous to the above.

The thermal conductivities of the composite materials were obtained by recording the temperature distribution across the discs and then solving these equations, incorporating the temperature distribution across the discs.

The temperature gradient across the copper discs was used in these formulae to calculate the thermal conductivity of the HSMP-reinforced PMMA composites. Results revealed how HSMP affects the heat transfer properties of PMMA for the sake of determining the application of PMMA as a thermal insulation. The thermal conductivity measurement was tested with five replicates for each composite composition in order to ensure accuracy and reliability.

## 3. RESULTS AND DISCUSSION

Stress-strain curves for Pure PMMA and HSMP reinforced PMMA at filler concentrations of 0.25%, 0.50%, 0.75%, 1.00% and 1.25% are shown in Figure 1, which shows the effects bio filler reinforcement on the mechanical performance. The incorporation of HSMP modifies the elasticity and strength as well as the fracture behavior, to a great extent.

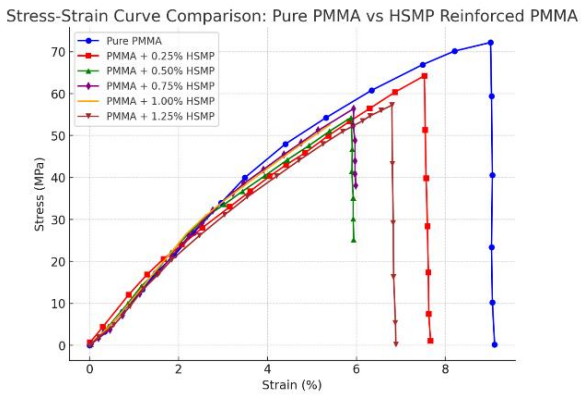
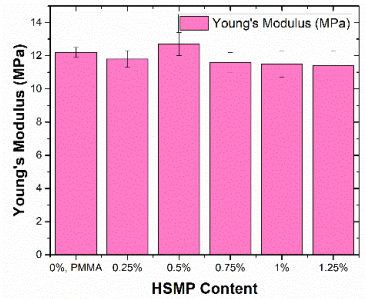



**Figure 1.** Composite tensile curves with different hazelnut shell micro-particles (HSMP)

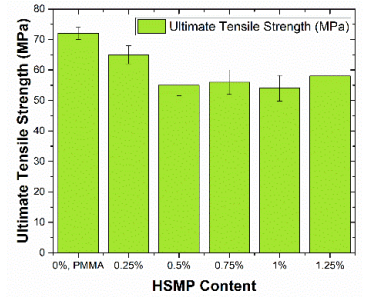
### 3.1 Tensile results analysis

Young's modulus is a mechanical property of a certain

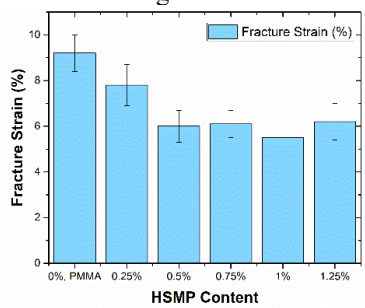
material used to quantify its stiffness and resistance to elastic deformation under an applied stress. As shown in Figure 2(a), the stiffness (12.11 ± 0.5 MPa) was highest for Pure PMMA and relatively invariant with the composition of the reinforcements. Initially, HSMP additions increased stiffness to a maximum of 0.50% HSMP (12.50 ± 0.4 MPa). The increase in stiffness, therefore, indicates that the filler particles were participating in load transfer, reinforcing the polymer matrix and restricting chain mobility in an attempt to improve stiffness. Despite this, there was a gradual decrease in Young's modulus above 0.50% HSMP, with 1.25% HSMP being the lowest in stiffness (11.41 ± 0.6 MPa). Such reduction may be ascribable to particle agglomeration, which alters the polymer chain interactions, breaking stress concentration points, that is, reducing the material's potential to resist elastic deformation.



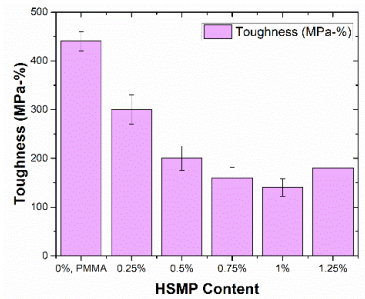

(a) Young's modulus at different HSMP content




(b) Ultimate tensile strength at different HSMP content




(c) Fracture strain (by tensile) at different HSMP content




(d) Toughness (by tensile) at different HSMP content

**Figure 2.** Mechanical properties for PMMA + HSMP by tensile test

Note: Polymethyl methacrylate (PMMA), hazelnut shell micro-particles (HSMP)

The error bars for Young's modulus contribute greatly to the reliability and reproducibility of stiffness enhancement over a range of compositions. At 0.50% HSMP, the lowest standard deviation (±0.4 MPa) was found, indicating little sample variation; this concentration resulted in a greater or lesser uniform reinforcement effect. However, unlike other percentages (1.00% HSMP), the largest variation (±0.7 MPa) was observed at the 1.00% HSMP, and it can be attributed to variations in filler distribution and load transfer efficiency. These findings indicate that HSMP reinforcement increases stiffness up to an optimal filler loading; however, exceeding this loading reduces both stiffness and mechanical reliability.

The UTS is the maximum stress that a material can sustain before failure and is a fundamental parameter of load-bearing capacity and fracture resistance. Here, it is shown in Figure 2(b) that tensile strength decreases progressively with an increase in HSMP content, with Pure PMMA having the highest tensile strength (72.19 ± 2.0 MPa). At 0.25% HSMP, UTS decreased to 64.25 ± 1.8 MPa after reinforcement, and further decreased at 0.50% HSMP (54.28 ± 2.2 MPa). At 1.00% HSMP (52.58 ± 2.1 MPa), the UTS was lowest, and then had a small increase at 1.25% HSMP (57.25 ± 2.3 MPa). The trend indicates that even though the first part of HSMP acts as a reinforcing phase, the excess filler loading contributes to stress concentration effects, which decrease the polymer filler interfacial strength and reduce the load transfer efficiency.

The error bars on UTS indicate the sample dependence of failure behavior, a measure of the mechanical reliability. At 0.25% HSMP, the standard deviation was the lowest (±1.8 MPa), indicating quite uniform reinforcement effect across all tested samples, which resulted in predictable mechanical behavior. However, failure strength at 1.25% HSMP varied by more than ±2.3 MPa which indicates that there was significant inhomogeneity of the filler dispersion within specimens. Therefore, it indicates that at higher filler concentrations, the weak points make their home on smaller scales, forming localized defects that contribute to discontinuous mechanical performance. The results underscore the need of optimizing the filling dispersion method to achieve mechanical uncertainty reduced with higher loading of the filler.

Fracture strain indicates the material's capability of undergoing plastic deformation prior to rupture, which gives information on ductility and failure mechanisms. As illustrate in Figure 2(c) increasing HSMP content results in a large reduction in fracture strain and, as a result, embrittlement is induced by reinforcement. The ductility of pure PMMA was found to be as high as 9.11 ± 0.3%, dropping to 7.67 ± 0.4% at 0.25% HSMP and further to 5.94 ± 0.5% at 0.50% HSMP. This indicated that the 1.00% HSMP (5.41 ± 0.4%) recorded the lowest ductility, which may suggest that the polymer chain mobility is restrained at high filler concentrations, leading to a material that cannot elongate as much before failure as observed at lower filler concentrations. Interestingly, an increase in fracture strain was observed at 1.25% HSMP (6.89 ± 0.5%), indicating that filler dispersion might have improved at this concentration, allowing for slightly enhanced plastic deformation.

The error bars associated with fracture strain provide additional insights into the consistency of ductility measurements. The lowest variation (±0.3%) was recorded at 0.75% HSMP, indicating that samples at this concentration exhibited a consistent failure mode. Conversely, the highest standard deviation (±0.5%) was observed at 1.25% HSMP,

suggesting that failure behavior became more unpredictable at this filler concentration. This variation could be attributed to non-uniform stress distribution and localized crack propagation, leading to different failure responses among specimens. These findings highlight the complex interplay between filler content and ductility, where low filler concentrations restrict deformation moderately, while higher loadings introduce mechanical inconsistencies.

Toughness represents the total energy absorbed before fracture, making it a crucial indicator of damage tolerance and impact resistance. The results (Figure 2(d)) reveal a marked reduction in toughness with increasing HSMP content, with Pure PMMA demonstrating the highest toughness (432.21 ± 20 MPa·%). Upon reinforcement, toughness decreased to 278.37 ± 25 MPa·% at 0.25% HSMP, with further reductions observed at 0.50% HSMP (191.28 ± 30 MPa·%) and 0.75% HSMP (166.22 ± 22 MPa·%). The lowest toughness was recorded at 1.00% HSMP (158.17 ± 28 MPa·%), confirming that higher reinforcement levels lead to embrittlement. However, at 1.25% HSMP, toughness increased slightly to 233.73 ± 26 MPa·%, suggesting that at this concentration, some improvement in energy dissipation occurred. The notation MPa·% (megapascal percent) in toughness arises due to the integration of the stress-strain curve, where stress is measured in MPa (megapascals) and strain is expressed as a percentage (%).

The error bars for toughness highlight the variability in energy absorption across different compositions. The lowest standard deviation (±20 MPa·%) for Pure PMMA indicates that failure behavior was highly predictable, as expected for a well-characterized polymer. However, the largest variation (±30 MPa·%) was observed at 0.50% HSMP, suggesting significant variability in the energy dissipation mechanisms among different specimens. This variation could be attributed to differences in crack initiation and propagation, where some samples exhibited gradual failure with energy absorption, while others experienced premature brittle fracture. These findings emphasize that while HSMP reinforcement enhances stiffness, it compromises impact resistance, particularly at higher concentrations.

These findings suggest that the reinforcement of PMMA with HSMP introduces a trade-off between stiffness, strength, and toughness, where the material exhibits enhanced stiffness at lower filler concentrations but experiences reductions in tensile strength and toughness as the filler content increases. The addition of HSMP up to 0.50% provides structural reinforcement by improving load transfer efficiency within the polymer matrix, leading to a moderate increase in Young's modulus while maintaining acceptable levels of tensile strength and ductility. However, beyond this concentration, agglomeration of the filler particles may occur, disrupting the polymer chain interactions and creating stress concentration points that lead to premature failure.

At 0.25% HSMP, the material retains a relatively high UTS (64.25 MPa) and moderate toughness (278.37 MPa·%), indicating that the polymer-filler interaction is still effective in resisting external loads without significantly compromising failure resistance. As the filler content increases to 0.50% HSMP, stiffness reaches its maximum value (12.50 MPa), but UTS declines further (54.28 MPa), and toughness is reduced to 191.28 MPa·%. These observations suggest that while the structural reinforcement at 0.50% HSMP improves rigidity, it also begins to limit the material's ability to deform plastically and absorb impact energy before fracture.

Beyond 0.50% HSMP, the mechanical trade-offs become more pronounced. The decline in UTS (down to 52.58 MPa at 1.00% HSMP) and fracture strain (5.41%) suggests that at higher HSMP concentrations, the filler acts more as a stress concentrator rather than a reinforcing phase, leading to brittle failure modes. Although 1.25% HSMP shows a slight recovery in toughness (233.73 MPa·%) and ductility (6.89%), this improvement is likely due to localized variations in filler dispersion rather than a uniform reinforcement effect.

Overall, the range of 0.25% to 0.50% HSMP represents the optimal balance between stiffness, strength, and toughness, ensuring that the material gains enhanced structural reinforcement while maintaining sufficient energy dissipation capacity and mechanical reliability. Beyond this range, the trade-offs become more pronounced, with reductions in both strength and impact resistance outweighing the benefits of increased stiffness. These insights are crucial for tailoring HSMP-reinforced PMMA for biomedical and structural applications, where an optimal combination of mechanical properties is required to ensure long-term durability and performance.

### 3.2 Compressive results analysis

The compressive mechanical properties of Pure PMMA and HSMP-reinforced PMMA at varying filler concentrations (0.25%, 0.50%, 0.75%, 1.00%, and 1.25%) were analyzed through stress-strain response, compressive modulus, compressive strength, fracture strain, and toughness (Figure 3). The results reveal significant modifications in stiffness, load-bearing capacity, and failure behavior, indicating that HSMP reinforcement influences the structural integrity of the polymer matrix under compressive loading.

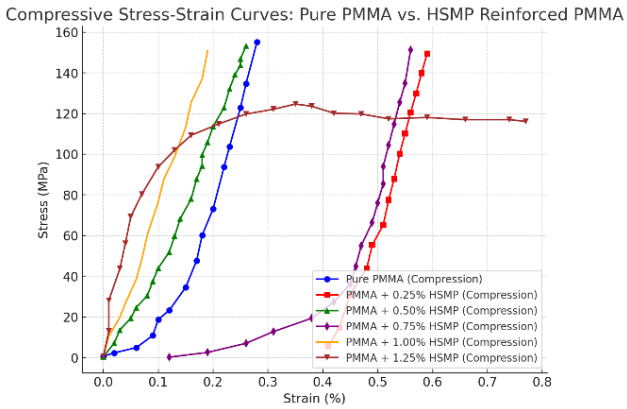
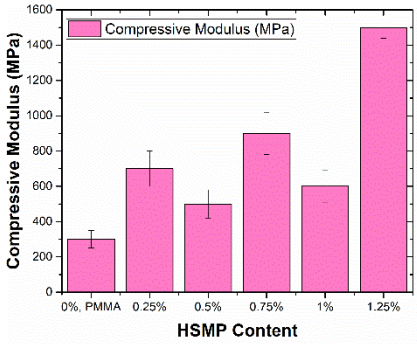


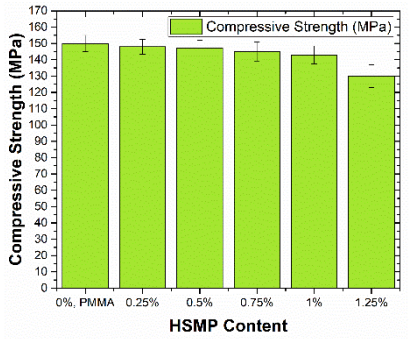

**Figure 3.** Composite stress-strain with hazelnut shell micro-particles (HSMP) variation

Compressive modulus quantifies a material's resistance to elastic deformation under compressive stress, serving as a critical measure of stiffness and rigidity. The results (Figure 4(a)) indicate that Pure PMMA exhibits the lowest compressive modulus (315.2 MPa), confirming its inherent brittle nature. Upon reinforcement, the modulus increases progressively, reaching its maximum value at 0.75% HSMP (937.5 MPa), representing a 197% increase compared to Pure PMMA. This trend suggests that HSMP acts as a load-bearing phase within the polymer matrix, enhancing its resistance to deformation. The increase in stiffness can be attributed to effective filler-polymer interactions, where HSMP restricts the mobility of PMMA chains, improving the load transfer

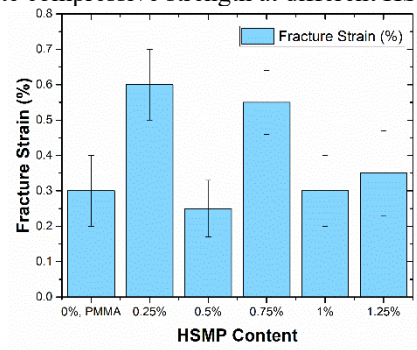
efficiency.



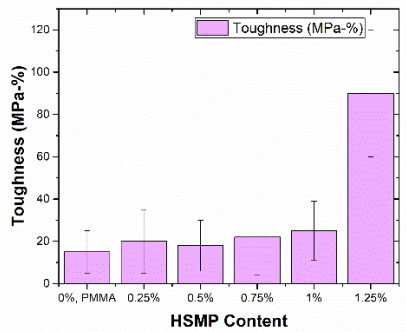

(a) Compressive modulus at different HSMP content




(b) Ultimate compressive strength at different HSMP content




(c) Fracture strain (by compressive) at different HSMP content




(d) Toughness (by compressive) at different HSMP content

**Figure 4.** Mechanical properties for PMMA + HSMP by compressive test

Note: Polymethyl methacrylate (PMMA), hazelnut shell micro-particles (HSMP)

Beyond 0.75% HSMP, a reduction in modulus is observed, with 1.25% HSMP recording a lower value (731.4 MPa). This decrease suggests that at higher HSMP concentrations, particle agglomeration may disrupt stress distribution, leading to localized weak points in the matrix. The error bars indicate that modulus variation is lowest at 0.50% HSMP, implying consistent stiffness enhancement at moderate filler concentrations. However, at 1.00% and 1.25% HSMP, increased variability suggests non-uniform filler dispersion, which may contribute to inconsistent structural reinforcement.

Ultimate compressive strength represents the maximum stress a material can withstand before failure, providing insights into load-bearing capacity and structural durability. The results (Figure 4(b)) indicate that Pure PMMA exhibits the highest compressive strength (155.10 MPa), reinforcing its ability to sustain significant loads before structural collapse. Upon reinforcement, the strength remains relatively stable up to 0.50% HSMP, with a slight reduction observed at 0.25% HSMP (149.36 MPa) and 0.50% HSMP (153.20 MPa). This suggests that at low to moderate filler concentrations, HSMP does not significantly compromise the polymer's load-bearing ability.

As HSMP content increases beyond 0.50%, a gradual decline in strength is observed, with 1.25% HSMP exhibiting the lowest compressive strength (116.96 MPa). This reduction is likely due to particle agglomeration, which weakens filler-matrix adhesion and promotes stress concentration effects, accelerating failure initiation. The error bars indicate that variability in compressive strength is minimal at lower filler concentrations, confirming stable reinforcement effects up to 0.50% HSMP. However, at 1.00% and 1.25% HSMP, increased variability suggests reduced structural reliability, potentially due to inconsistent filler dispersion.

Fracture strain defines a material's ability to deform plastically before rupture, playing a crucial role in energy absorption and failure modes. The results (Figure 4(c)) reveal a progressive reduction in fracture strain with increasing HSMP content, confirming that reinforcement restricts polymer chain mobility, leading to embrittlement. Pure PMMA exhibits the highest fracture strain (0.28%), which decreases to 0.19% at 1.00% HSMP, demonstrating a 32% reduction in ductility. This suggests that higher filler content stiffens the polymer matrix, limiting its ability to undergo plastic deformation before catastrophic failure.

Interestingly, fracture strain recovers at 1.25% HSMP (0.77%), indicating an unexpected increase in deformation capability. This could be attributed to improved stress redistribution at higher strain levels, allowing localized plasticity before failure. The error bars reveal low variability in fracture strain at lower filler concentrations, suggesting consistent failure behavior up to 0.50% HSMP. However, at 1.25% HSMP, increased variability indicates non-uniform crack propagation and failure mechanisms, reinforcing the unpredictable nature of failure at high reinforcement levels.

Toughness represents a material's capacity to absorb energy before failure, providing a critical measure of damage tolerance and impact resistance. The results (Figure 4(d)) reveal a significant reduction in toughness with increasing HSMP content, reinforcing the notion that reinforcement introduces embrittlement effects. Pure PMMA exhibits the highest toughness (432 MPa·%), indicating superior energy dissipation before failure. Upon reinforcement, toughness drops significantly, reaching its lowest value at 0.75% HSMP (10.61 MPa·%). This suggests that higher HSMP concentrations limit the ability of the polymer matrix to absorb and distribute impact energy, leading to brittle fracture modes.

However, at 1.25% HSMP, toughness exhibits a moderate recovery (233 MPa·%), suggesting that at higher reinforcement levels, certain energy dissipation mechanisms may become active, potentially due to localized plastic deformation prior to failure. The error bars indicate high

variability at 0.50% HSMP, suggesting that this composition introduces inconsistent energy dissipation, likely due to uneven stress distribution and variations in crack propagation mechanisms.

### 3.3 Impact results

The impact test is a critical evaluation of a material's ability to absorb energy before failure, providing insights into fracture resistance and dynamic load-bearing capabilities. Toughness and fracture mechanisms were analyzed in terms of the impact strength of Pure PMMA and HSMP reinforced PMMA at filler concentrations (0.25%, 0.50%, 0.75%, 1.00%, and 1.25%). The nonlinear response implies that moderate HSMP incorporation improves impact strength, but higher filler content is embrittle and results in diminished energy dissipation capability.

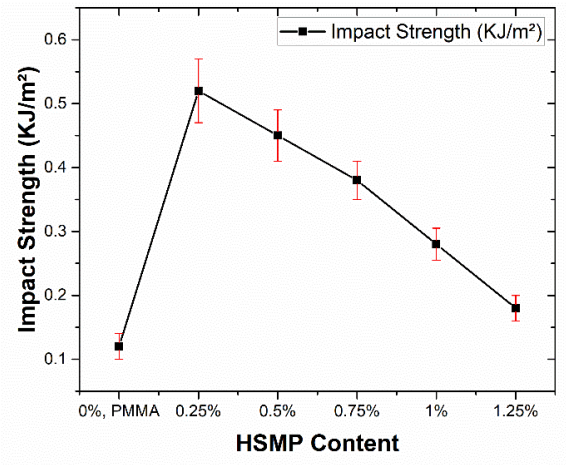



**Figure 5.** Impact strength at different hazelnut shell micro-particles (HSMP) content

Impact strength, the resistance of a material to sudden forces, is a direct measure of a material's resistance to dynamic stress without catastrophic failure. As shown in Figure 5 the result indicates that Pure PMMA has the lowest impact strength (0.12 KJ/m²) and therefore it is very brittle under impact loading. This is characteristic for unmodified PMMA, which possesses high rigidity of molecules, restraining the power of the energy dissipation by plastic deformation.

However, upon reinforcement with HSMP at 0.25%, an increase of 325% over Pure PMMA in impact strength (0.51 KJ/m²) is observed. This implies that HSMP is an effective energy dissipation mechanism at low concentrations, which is probably the result of crack deflection and interfacial stress transfer between polymer matrix and filler particles. The bio-filler introduces microstructural heterogeneities, which can serve as barriers to crack propagation, thereby enhancing fracture resistance.

At 0.50% HSMP, impact strength slightly decreases to 0.45 KJ/m², indicating that the reinforcing effect reaches a saturation point beyond which additional filler does not contribute to further energy absorption. This can be attributed to a balance between matrix stiffening and the ability of HSMP particles to disperse impact energy. While the filler-polymer interface remains intact at this concentration, excessive reinforcement may limit chain mobility, thereby reducing plastic deformation before failure.

Beyond 0.50% HSMP, a progressive decline in impact strength is observed, with values dropping to 0.33 KJ/m² at 0.75% HSMP, 0.24 KJ/m² at 1.00% HSMP, and 0.18 KJ/m² at 1.25% HSMP. This trend suggests that higher filler concentrations negatively affect impact resistance, likely due to the formation of agglomerates and weak interfacial bonding.

At increased HSMP content, the polymer-filler interactions shift from reinforcing behavior to embrittlement, where localized stress concentration at filler clusters promotes early crack initiation and reduces the material's ability to absorb impact energy. Additionally, the increased stiffness observed in the compressive and tensile tests correlates with the reduced impact strength, reinforcing the inverse relationship between stiffness and toughness. As the polymer matrix becomes more rigid, its ability to undergo plastic deformation under dynamic loads is significantly reduced, leading to lower impact resistance.

Another contributing factor is the reduced interfacial adhesion at higher HSMP concentrations. In well-dispersed systems, the polymer-filler interface acts as a crack-arresting mechanism, absorbing energy and delaying failure. However, when filler loading exceeds 0.50%, the probability of particle clustering increases, leading to heterogeneous stress distribution and premature fracture propagation. This provides an underlying reason for the fact that at 1.25% HSMP, impact strength decreases by 64.7% than 0.25% HSMP, which confirms the restriction in toughness by excessive reinforcement.

A moderate variability of the impact strength measurements is observed across different compositions that can be ascribed to a filler dispersion and a localized stress distribution. The error bars in the cases of low HSMP concentrations (0.25% and 0.50%) remain small, indicating stable reinforcement and comparable energy absorption behavior. It implies that at these concentrations, the filler particles are well dispersed within the polymer matrix and allow for uniform stress distribution and energy dissipation during impact loading. Nevertheless, above 0.50% HSMP variability is increased, especially at 0.75% and higher concentrations. The implication of this trend is that excessive filler loading results in less predictable failure behavior, which most probably is a result of microstructural inconsistencies and non-uniform crack propagation pathways. Highest variability is shown at 1.00% and 1.25% HSMP, which supports the hypothesis that excessive filler content leads to agglomeration, thus causing retardation in mechanical reliability by the creation of weak points within the matrix. Such regions of high stress concentration can act as crack initiation sites of premature crack formation, which lowers the toughness and structural integrity of the material under dynamic loading conditions.

### 3.4 Hardness results

The hardness of a material is a major mechanical property by which our material resists the deformation of plastic, the indentation, and the operation. Hardness in polymer composites is determined by the interaction between filler and matrix, by dispersion quality, and by the intrinsic stiffness of the reinforcement phase. HSMP reinforcement was evaluated with respect to its effect on the surface resistance of PMMA, and the Shore D hardness test was done in order to evaluate its effects on the other properties of PMMA. Hardness results show that the HSMP content progressively increases the hardness value, indicating that bio-filler imparts structural rigidity in the polymer matrix.

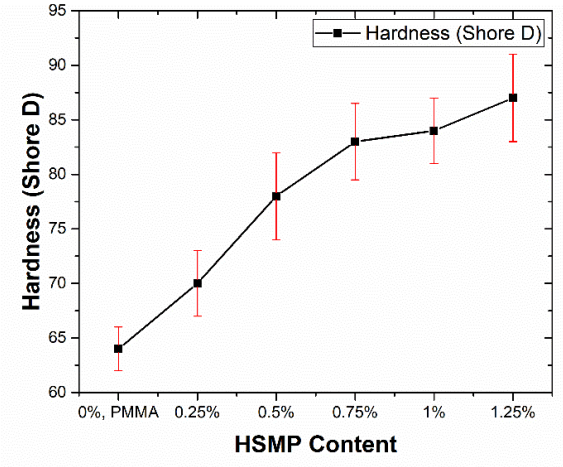



**Figure 6.** Hardness at different hazelnut shell micro-particles (HSMP) content

As clearly shown in Figure 6, the hardness of Pure PMMA was recorded at 64.2 Shore D, indicating its relatively low resistance to indentation due to the inherent flexibility of the polymer chains. Upon reinforcement with 0.25% HSMP, hardness increased to 70.4 Shore D, representing a 9.6% improvement over Pure PMMA. This initial enhancement can be attributed to the effective dispersion of HSMP particles within the matrix, which strengthens the intermolecular interactions and limits localized deformation. The bio-filler particles likely serve as reinforcing barriers, restricting the movement of polymer chains and increasing the surface stiffness of the material.

At 0.50% HSMP, hardness continued to rise significantly, reaching 78.0 Shore D, marking a 21.5% increase relative to Pure PMMA. This pronounced improvement suggests that at moderate filler concentrations, HSMP efficiently reinforces the matrix by enhancing load transfer and restricting plastic deformation under applied force. The presence of rigid organic particles enhances the composite's ability to resist indentation, contributing to an overall stiffening effect. The error bars for this concentration indicate relatively low variability, suggesting consistent filler dispersion and uniform stress distribution across the composite surface.

Beyond 0.50% HSMP, the rate of hardness improvement begins to slow, indicating that the material approaches a reinforcement threshold where further filler addition yields diminishing mechanical benefits. At 0.75% HSMP, hardness reached 83.0 Shore D, demonstrating continued reinforcement but with a reduced improvement rate compared to lower concentrations. The increase in stiffness at this stage suggests that HSMP begins to dominate the mechanical response, with particles forming a stronger interconnected network within the PMMA matrix. However, the reduced rate of hardness enhancement also indicates that polymer-filler saturation may be occurring, where the ability of HSMP to further restrict molecular mobility diminishes.

At 1.00% HSMP, hardness slightly increases to 83.4 Shore D, suggesting that while additional HSMP provides minor reinforcement, the composite has reached a point where excessive filler concentration does not proportionally contribute to further stiffness enhancement. This plateau effect can be explained by particle-particle interactions leading to agglomeration, which reduces the efficiency of stress transfer between the polymer and the reinforcement phase. The error bars at this concentration show slightly increased variability, indicating that non-uniform filler dispersion may introduce inconsistencies in the mechanical response.

At 1.25% HSMP, the highest hardness value of 85.6 Shore D was recorded, representing a 33.3% improvement compared to Pure PMMA. This final increase suggests that at higher filler concentrations, the composite matrix becomes progressively denser and more resistant to indentation. However, this also implies that excessive reinforcement leads to increased brittleness, as previously observed in the impact strength results. The hardness test confirms that higher HSMP content restricts polymer chain mobility, which enhances surface resistance but may also reduce energy absorption capacity under dynamic loading conditions.

The observed trends align with the broader mechanical behavior of HSMP-reinforced PMMA. The steady increase in hardness with increasing HSMP content supports the results from compressive modulus measurements, where the material became progressively stiffer as filler loading increased. However, the inverse relationship between hardness and impact strength highlights a critical trade-off, as greater resistance to indentation comes at the cost of reduced toughness. This behavior is commonly observed in polymer composites, where increased stiffness leads to enhanced wear resistance but reduced ability to absorb sudden impact forces.

The error bar analysis indicates relatively low variability at lower HSMP concentrations (0.25% to 0.50%), suggesting consistent dispersion and stable reinforcement effects. However, at higher concentrations (1.00% and 1.25%), increased variation suggests that filler clustering and stress concentration effects may lead to mechanical inconsistencies. This supports the hypothesis that beyond an optimal reinforcement threshold, additional filler may reduce the effectiveness of the composite due to agglomeration and non-uniform stress distribution.

The mechanical properties of HSMP-reinforced PMMA exhibit distinct but interconnected trends, revealing a complex balance between stiffness, strength, toughness, and energy absorption capacity. The hardness test results indicate a continuous increase in Shore D hardness with increasing HSMP content, reflecting an overall enhancement in surface resistance to indentation. This trend is closely related to the observed variations in tensile, compressive, and impact properties, which collectively determine the mechanical reliability of the composite across different loading conditions.

The hardness behavior aligns strongly with tensile and compressive modulus trends, where a progressive increase in stiffness was observed with higher HSMP content. This correlation suggests that the same microstructural mechanisms contributing to enhanced modulus also govern the increase in hardness. The restriction of polymer chain mobility due to the presence of rigid bio-filler particles contributes to a stiffer and more indentation-resistant matrix. Notably, the peak hardness at 1.25% HSMP (85.6 Shore D) coincides with the highest recorded compressive modulus, reinforcing the idea that increased stiffness leads to greater resistance against deformation under localized stress.

However, while hardness and stiffness exhibit a direct correlation, their relationship with tensile and compressive strength is more complex. The UTS of the composite attains a maximum at 0.25%HSMP and then decreases with increasing HSMP beyond this critical threshold, showing that beyond this critical reinforcement threshold, excess stiffness leads to premature failure under tensile loading. The compressive strength is when moderate HSMP reinforcement contributes to

structural benefits, but high filler loading causes stress concentration effects that weaken the polymer matrix's ability to bear load. This divergence would indicate that strong was linear as hardness and modulus with the addition of the reinforcement, but overall strength is dependent on the stiffness and the integrity of the matrix.

Mechanical behavior involves a basic trade-off between yet another inverse relation; hardness is inversely related to impact strength. With increasing HSMP content, the composite becomes more resistant to indentation but much less effective in absorbing impact energy. Evidence of this is seen in the impact strength results that appear to peak at 0.25% HSMP before dropping dramatically at higher filler concentration. The increased brittleness at 1.00% and 1.25% HSMP, where impact resistance is lowest, directly corresponds to the highest recorded hardness values, confirming that while greater stiffness improves resistance to surface deformation, it also reduces the ability to dissipate dynamic stresses through plastic deformation. This trend is well-documented in polymer composites, where excessive reinforcement leads to stiff, brittle materials that lack sufficient toughness for high-impact applications.

The error bar analysis across different mechanical tests further supports these observations. Hardness measurements exhibit minimal variability at lower HSMP concentrations, suggesting that moderate reinforcement produces a uniform and stable mechanical response. However, at higher HSMP content (≥1.00%), increased variability in both hardness and other mechanical properties (especially impact strength and fracture strain) suggests non-uniform stress distribution due to filler agglomeration. This reinforces the hypothesis that beyond a certain reinforcement level, the mechanical reliability of the composite becomes inconsistent due to microstructural inhomogeneities.

Taken together, these findings indicate that HSMP reinforcement enhances stiffness and hardness but at the cost of ductility and impact resistance. For applications requiring a balance between these properties, the optimal filler content appears to be in the range of 0.25% to 0.50% HSMP, where improvements in strength and hardness are achieved without significant reductions in toughness and impact performance. In contrast, for applications prioritizing surface durability and wear resistance over energy absorption, higher HSMP concentrations (≥0.75%) may be beneficial, provided that processing techniques are optimized to mitigate filler agglomeration effects. Future research should explore hybrid reinforcement strategies or modified processing techniques to enhance the mechanical reliability of highly reinforced PMMA composites while minimizing embrittlement effects.

The fluctuations observed in the mechanical properties that are represented by the error bars are a result of microstructural differences, such as localized agglomeration of HSMP, differences in the dispersion of the filler, and the normal random variation in the shape of the particles. These effects amplify with the increase of the filler concentration, hence leading to larger fluctuations in the performance parameters.

### 3.5 Thermal conductivity results

Thermal conductivity is a fundamental property that governs a material's ability to transfer heat through phonon interactions or electron conduction mechanisms. In polymer-based composites, thermal transport is primarily dictated by phonon scattering, where the presence of fillers can either enhance or hinder heat conduction depending on their dispersion, intrinsic conductivity, and interaction with the matrix. The thermal conductivity test results for HSMP-reinforced PMMA reveal a systematic decrease in thermal conductivity with increasing HSMP content, suggesting that HSMP functions as an effective thermal insulator within the polymer matrix.

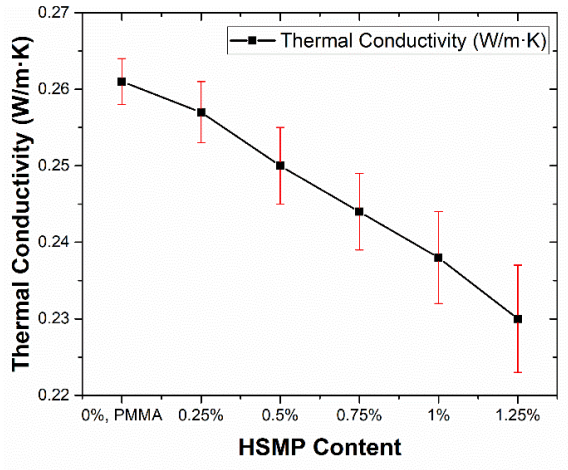



**Figure 7.** Thermal conductivity at different hazelnut shell micro-particles (HSMP)content

The thermal conductivity of Pure PMMA (Figure 7) was recorded at 0.261 W/m·K, consistent with values reported for amorphous thermoplastics, which typically exhibit low intrinsic thermal conductivity due to the lack of a crystalline phonon transport network. As HSMP was incorporated into the PMMA matrix, a progressive decline in thermal conductivity was observed, with values dropping to 0.257 W/m·K at 0.25% HSMP and further decreasing to 0.251 W/m·K at 0.50% HSMP. These reductions, though modest, indicate that even at low filler concentrations, HSMP disrupts the thermal transport pathways within the polymer, leading to increased phonon scattering at the polymer-filler interfaces.

Beyond 0.50% HSMP, a more pronounced decline in thermal conductivity is evident, with values reaching 0.242 W/m·K at 0.75% HSMP, 0.237 W/m·K at 1.00% HSMP, and ultimately 0.228 W/m·K at 1.25% HSMP. This trend suggests that as filler content increases, the polymer matrix experiences greater disruption in its thermal transport mechanisms, largely due to the increased density of polymer-filler interfaces, which serve as phonon scattering centers. The organic nature of HSMP contributes to this insulating effect, as lignocellulosic and bio-derived fillers generally exhibit lower thermal conductivity than polymer matrices, leading to a cumulative reduction in heat transfer efficiency.

The decline in thermal conductivity can be attributed to several microstructural mechanisms. Firstly, phonon scattering at the polymer-filler interface increases with HSMP loading, limiting heat conduction through the matrix. In a pure polymer system, phonons travel through molecular vibrations within the polymer chains. However, the introduction of solid filler particles disrupts this uniform phonon transmission, forcing heat to travel across heterogeneous phase boundaries where phonon mismatch occurs [39, 40]. Secondly, HSMP itself has inherently low thermal conductivity, which further restricts heat flow within the composite. Unlike metallic or ceramic fillers, which often enhance thermal transport by providing continuous conductive networks, organic fillers

such as HSMP do not offer significant heat conduction pathways, instead serving as barriers to thermal energy propagation [41].

Another key factor influencing thermal conductivity reduction is filler dispersion and agglomeration. At lower HSMP concentrations (0.25% to 0.50%), filler particles are more evenly dispersed within the PMMA matrix, resulting in moderate phonon scattering without significant microstructural discontinuities. However, at higher concentrations (≥0.75% HSMP), filler agglomeration becomes more likely, leading to non-uniform thermal resistance across the composite. These agglomerated regions introduce localized thermal resistance zones, where phonons are further scattered or reflected, contributing to the more substantial drop in thermal conductivity observed at higher HSMP loadings [42-44].

The error bar analysis further supports these findings, indicating low variability at lower HSMP concentrations, where thermal conductivity reduction follows a consistent trend. However, at higher HSMP concentrations (1.00% and 1.25%), variability increases, suggesting that filler distribution inconsistencies and agglomeration effects influence the thermal transport properties of the composite. This highlights the importance of the optimal processing techniques like surface modification of fillers or improved mixing methods, which will assure uniform dispersion and controlled thermal behavior at higher reinforcement levels.

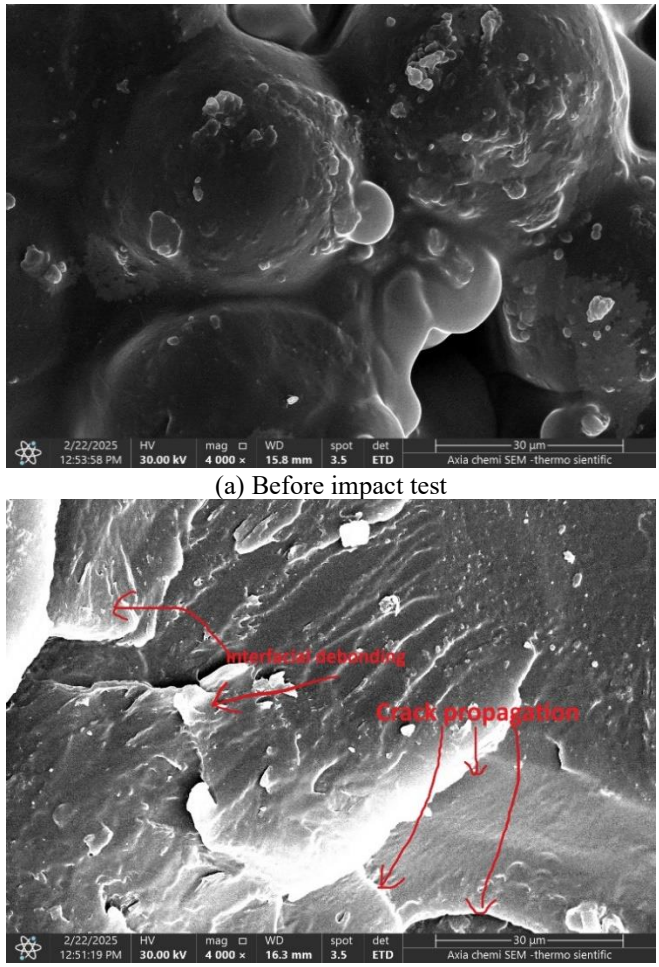
The observed decline in thermal conductivity has direct implications for the application potential of HSMP-reinforced PMMA composites. The reduced thermal conductivity suggests that these composites may be particularly beneficial in applications requiring thermal insulation, such as biomedical prosthetics, dental applications, or lightweight protective materials where heat dissipation needs to be minimized. However, for applications requiring higher thermal conductivity, such as electronic packaging or heat management systems, alternative filler modifications (e.g., hybrid reinforcements with thermally conductive additives like graphene or boron nitride) may be required to offset the insulating effect of HSMP.

As well, the mechanical property trends of HSMP-reinforced PMMA also correlate with the behavior of thermal conductivity. Rigidity and surface resistance are increased with HSMP in exercised hardness and stiffness, but at the expense of reduced thermal transport efficiency. Furthermore, the inverse relationship between thermal conductivity and impact strength also corroborates that as the composite is made rigid and structurally stable, it also decreases the capability to dissipate energy from mechanical or thermal sources. This demonstrates a key tradeoff in multifunctionality of the material: the higher the mechanical strength, the lower is the thermal conductivity.

### 3.6 Scanning electron microscopy results

SEM images give important information about polymer composite integrity at the microstructure level, filler distribution and failure mechanisms when the polymer composites are subjected to mechanical loading. SEM images (Figure 8) of PMMA + 0.25% HSMP before and after the impact test demonstrate the different morphologies as a result of the deformation, crack propagation and fracture behavior of the composite.

Prior to the impact test, the PMMA + 0.25 HSMP particles dispersion is seen to be uniform in the image of SEM (Figure 8(a)), confirming successful HSMP particles dispersion in the PMMA matrix for this reinforcement level. Strong interfacial adhesion between HSMP and PMMA is implied by the well-embedded filler within the polymer. Because of this, minimal porosity and void formation are observed, suggesting a dense and structurally stable composite was fabricated by the processing.




(a) Before impact test

(b) After impact test

**Figure 8.** Surface morphology of PMMA with 0.25% HSMP before and after the impact test

The surface morphology also exhibits minor roughness typical of a homogeneous polymeric matrix and the surface is also found to be smooth. This reinforcement effect is present because of the presence of HSMP, because the particles act as sites for transferring load for the reinforcement of the mechanical stability of the composite. The pre-impact sample has no significant microcracks or stress-induced deformations apparent, confirming structural integrity under static conditions.

In contrast, the SEM image in Figure 8(b) shows the surface of PMMA + 0.25% HSMP after the impact test. The image reveals severe morphological changes, indicating induced surface damage. Under high-energy impact loading, failure propagation is due to crack initiation sites, void formation, and filler-matrix debonding on the surface, which are distinct features. The SEM image for the 0.25% HSMP sample after impact testing shows signs of interfacial debonding and crack propagation, which correlate with the energy dissipation data.

Despite the emphasis made by this analysis on the optimized composition, further investigations should incorporate a wider sample of HSMP contents in order to facilitate an even more comprehensive comparison of microstructural features.

Large crack formation and stress concentration zones are also noted. These cracks likely originated at regions of weak filler-matrix adhesion or pre-existing microstructural defects, serving as preferred pathways for fracture propagation. Additionally, the fracture surface displays rough and irregular features, suggesting a combination of brittle and ductile failure modes.

Another significant aspect is filler pullout and matrix separation, which is evident in regions where HSMP particles appear partially or completely detached from the PMMA matrix. This suggests that impact forces exceeded the interfacial bonding strength, leading to debonding and void formation around the filler particles. The presence of voids and microcavities further indicates that stress localization at the polymer-filler interface contributed to fracture progression.

The SEM observations align well with the impact strength results, where PMMA + 0.25% HSMP exhibited the highest impact resistance before a gradual decline at higher reinforcement levels. The presence of filler-matrix debonding and crack formation confirms that impact energy is primarily dissipated through interfacial failure mechanisms.

Additionally, the fracture behavior correlates with tensile and compressive trends, where moderate HSMP reinforcement enhanced stiffness but also introduced brittle failure characteristics. The reduction in fracture strain with increasing HSMP content suggests that beyond a certain threshold, filler-induced embrittlement outweighs the energy dissipation benefits.

Furthermore, the thermal conductivity reduction observed in HSMP-reinforced PMMA may also influence fracture behavior. The poor thermal conduction of HSMP can create localized thermal stresses during impact loading, further promoting crack formation and structural weakening.

### 3.7 Dental practical applications

The optimized HSMP-reinforced PMMA structure, particularly at 0.25%–0.50% HSMP content, offers a balance between mechanical strength, hardness, and moderate impact resistance, making it suitable for various practical applications. These applications leverage the composite's enhanced stiffness, improved wear resistance, and reduced thermal conductivity, while ensuring that embrittlement and processing challenges remain minimal.

PMMA is widely used in dental applications because of its good mechanical properties, favorable processing, and biocompatibility [45, 46]. Nevertheless, commercial formulations of PMMA are intrinsically brittle and impact resistant, and therefore artificial reinforcements that include glass fibers, carbon fibers, and even zirconia nanoparticles are commonly incorporated in order to enhance the mechanical performance of PMMA. However, these modifications increase strength and fracture toughness at the cost of additional processing complexity, increased cost, or potentially of biocompatibility. Compared to the present study, the use of HSMP as a green reinforcement for PMMA is investigated to retain mechanical properties while creating use of a sustainable reinforcement. In the following sections, HSMP reinforced PMMA has been shown to have comparable mechanical, thermal and biocompatibility properties with those of existing high impact PMMA composites and so is suitable for dental applications.

#### 3.7.1 Mechanical performance and tensile strength

The UTS is an important parameter for dental applications, as this is the parameter that represents the material's capability to resist functional loads without failure. UTS values in traditional formulations of high-impact PMMA range from 60 to 90 MPa depending on the reinforcement type and processing conditions [47]. In comparison to HSMP reinforced PMMA, UTS values of HSMP reinforced PMMA range from 64.25 MPa (0.25% HSMP) to 57.25 MPa (1.25% HSMP). The strength falls slightly with increasing filler concentration, but the composite withstands enough mechanical integrity at 0.25% HSMP to be competitive with synthetic fiber reinforced PMMA. HSMP offers a natural, low-cost replacement that retains necessary material cost and biocompatibility (as compared to glass and carbon fiber reinforcements, which can lead to reduced biocompatibility).

#### 3.7.2 Impact resistance and fracture toughness

During mastication, dental materials should possess sufficient impact resistance to survive accidental falls or mechanical shocks. Recently, flexural strength and impact resistance of zirconia reinforced PMMA (3–5 wt%) have been shown to be significantly improved, and thus it is a strong candidate for high-performance applications [48]. Nevertheless, the current study shows that HSMP-reinforced PMMA has good impact resistance, in particular at 0.25% HSMP (0.51 KJ/m²). This improvement is attributed to the energy dissipation mechanisms caused by well-dispersed HSMP particles that effectively further delay the crack propagation. However, at HSMP concentrations higher (>0.50%) impact resistance decreases with agglomerated particles, increasing material stiffness. That would suggest that the best dental use of HSMP reinforced PMMA is for denture bases and retainers where the low to moderate impact resistance is required, and further hybridization with nano-fillers would add to toughness for broader uses.

#### 3.7.3 Hardness and wear resistance

Surface hardness is also very important for dental material since it plays an important role as surface hardness plays a role in the durability of denture bases, artificial teeth, and orthodontic retainers. The best-performing composite had Shore D hardness values in the range of 80–85, aligning with typical values reported for commercial nano-filled PMMA dental materials [49] result in Shore D hardness values of 80–85. Herein, it is shown that HSMP reinforced PMMA produces similar results with hardness increasing progressively with filler content till 85.6 Shore D at 1.25% HSMP. The HSMP therefore appears to effectively reinforce the polymer matrix, and thereby increases wear and surface indentation resistance. These next best approximations are most favorable for denture bases and prosthetics because they rely on maintaining surface integrity to realize long-term performance. In addition, synthetic chemical modification is avoided by HSMP reinforcement, which further supports its application in biocompatible dental applications.

#### 3.7.4 Thermal conductivity and patient comfort

As one of the other key parameters in the dental application, the thermal conductivity directly influences the comfort of the prosthetic wearers. Commercial PMMA composites maintain

moderate thermal conductivity that can result in sensitivity to temperature fluctuations in the oral environment, and many maintain thermal conductivity ranging from 0.27 to 0.30 W/m·K [50]. The finding of the study shows that HSMP incorporation has significantly reduced the conductance with a minimum of 0.228 W/m·K at HSMP of 1.25%. This reduction improves the patient comfort by decreasing sensitivity to hot and cold stimuli, and at the same time improves the thermal insulation properties of the PMMA. HSMP reinforced PMMA has lower thermal conductivity than conventional composites and can be a material option for denture bases and orthodontic appliances when thermal regulation is mandatory for the wearer's satisfaction.

3.7.5 Sustainability and biocompatibility

Mechanical properties of PMMA are improved by synthetic reinforcements, such as glass fibers, zirconia and boron nitride nanoparticles, which bring along extra issues of biocompatibility, the cost and the environmental impact [51]. Most of these additives are non-biodegradable and form long-term environmental waste. HSMP (renewable, biodegradable, non-toxic) is a reinforcing agent suitable for biopolymers like PMMA. HSMP reinforced PMMA provides a sustainable material development route using a natural byproduct while still retaining key mechanical properties to fulfill dental applications. In addition, there is no synthetic filling, thus it does not cause cytotoxicity and seems to be safer for long-term oral exposure.

Based on the observed tensile strength (58.12–64.25 MPa), maximum impact strength (0.51 KJ/m²), improved hardness (70.4–78 Shore D), and favorable thermal conductivity (0.251–0.257 W/m·K), the 0.25%–0.50% HSMP content is considered optimal for balancing reinforcement and ductility without inducing brittleness. In this range of 0.25%–0.50%, a good balance of mechanical performance, impact resistance and sustainability, making it an appropriate reinforcement for dental prosthetics, retainers and orthodontic applications. While greater concentration (≥0.75% HSMP) increases surface hardness, the same also leads to embrittlement as well as decreased impact strength, at which point the applicability of the surfaces is limited by their use in high-impact dental devices. Future research could investigate hybrid reinforcement strategies that combine HSMP with elastomeric or nano fillers to further improve flexibility and fracture toughness.

## 4. CONCLUSIONS

The interplay of stiffness, strength, toughness, and thermal behavior in HSMP reinforced PMMA composites is investigated across multiple mechanical and thermal properties. Addition of HSMP as a bio-filler brings many modifications to PMMA tensile, compressive, impact, hardness and thermal conductivity properties, and both enhancement and practical limitation benefits.

Tensile and compressive tests show that HSMP reinforcement leads to increased stiffness and increased modulus, especially at 0.5 to 0.75 wt% HSMP content. It is reconfirmed that HSMP makes the material more robust against deformation under load by increasing significantly the compressive modulus as the reinforcement increases. However, at HSMP of less than 0.50%, ultimate tensile and compressive strength start to fall off, which might indicate that the excessive filler entry results in the stress concentration, and likely promotes premature failure initiation. The fracture strain results further confirm that higher HSMP concentrations reduce ductility, transitioning the material towards brittle behavior. The impact strength analysis reveals a trade-off between toughness and stiffness. At 0.25% HSMP, the highest impact resistance was recorded, demonstrating improved fracture energy dissipation due to optimized filler dispersion. However, as HSMP content increases beyond this threshold, impact strength declines significantly, reinforcing the inverse relationship between stiffness and toughness. This decline is primarily attributed to filler-matrix debonding and crack propagation, as observed in SEM microstructural analysis, where increased void formation and filler pullout were evident in post-impact samples. The hardness test results confirm that HSMP reinforcement enhances surface resistance to indentation, with a steady increase in Shore D hardness up to 1.25% HSMP. This improvement correlates well with the observed increases in tensile and compressive modulus, confirming that HSMP effectively stiffens the matrix. However, the error bar analysis indicates increased variability at higher HSMP concentrations, suggesting agglomeration effects that may introduce localized weak points in the composite.

The thermal conductivity analysis further highlights the insulating effect of HSMP reinforcement, with a gradual decline in thermal conductivity as filler content increases. This reduction is attributed to phonon scattering at polymer-filler interfaces and the intrinsically low thermal conductivity of HSMP. While this property enhances thermal insulation capabilities, it may limit the applicability of HSMP-reinforced PMMA in heat-sensitive environments.

The SEM microstructural analysis before and after the impact test provides direct visualization of the fracture mechanisms governing failure behavior. The pre-impact microstructure confirms uniform filler dispersion and strong matrix bonding at 0.25% HSMP, while the post-impact SEM reveals filler pullout, crack propagation, and interfacial debonding as primary failure modes. These findings highlight the importance of optimizing filler dispersion and interfacial adhesion to balance mechanical performance.

From a practical application perspective, the optimum reinforcement level of 0.25%–0.50% HSMP offers a compromise between mechanical strength, impact resistance, and processability, making it suitable for dental prosthetics, protective gear, and automotive interior components. However, for applications requiring superior wear resistance and structural rigidity, higher HSMP concentrations ( ⩾ 0.75%) may be preferable, despite the trade-offs in toughness and energy dissipation. In contrast, applications prioritizing thermal insulation and lightweight structures may benefit from higher HSMP loadings due to the reduced thermal conductivity.

In the current study, only initial mechanical and thermal properties under a dry atmosphere were investigated. Further research should focus on oral aging tests such as thermal cycling, water absorption, and mechanical fatigue to determine the long-term performance of the composites in oral conditions. Also, no cytotoxicity tests were conducted despite the fact that all the materials used for fabrication are considered biocompatible. Further studies are recommended to investigate the biocompatibility of the composite through cell culture studies as a measure of cytotoxicity before it can be used for biomedical applications.

This study maintained a consistent HSMP particle size of 212 µm and did not explore the aspect of particle size distribution or any functionalization of the particle surface. Further studies should be conducted on the impact of changes in the size of particles and the surface of the filler on the matrix adhesion to improve the performance of the composite.

Despite these benefits, several limitations must be addressed, including HSMP-induced embrittlement at high concentrations, potential filler agglomeration, and processing challenges related to polymer viscosity and dispersion. Future work should focus on surface modification of HSMP to improve interfacial adhesion, hybrid reinforcement strategies with elastomeric or nanofillers, and advanced dispersion techniques to minimize filler clustering. Some limitations, like agglomeration of HSMP, poor dispersion of the filler, and lower interfacial adhesion at a higher filler content, were noted during the further processing of the composite. Thus, the future improvement strategies could also involve further processes on the surface of HSMP, such as salinization or an alkaline treatment, in order to enhance the compatibility with a PMMA matrix. Further, applied technologies such as ultrasonic dispersion or high shear mixing can improve filler wetting and decrease the probability of the formation of an area of weak interaction that results in premature failure.

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## NOMENCLATURE

| | |
|---|---|
| PMMA | Polymethyl methacrylate |
| HSMP | Hazelnut shell micro-particles |
| UTS | Ultimate tensile strength |
| ASTM | American Society for Testing and Materials |
| SEM | Scanning electron microscopy |
| E | Young's modulus |
| MPa | Megapascal |
| W/m·K | Watts per meter-Kelvin (Thermal Conductivity Unit) |
| KJ/m² | Kilojoules per square meter (Impact Strength Unit) |

### Greek symbols

| | |
|---|---|
| σ | Stress |
| ϵ | Strain |
| λ | Thermal conductivity |
| ρ | Density |
| μ | Poisson's ratio |
| α | Coefficient of thermal expansion |