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Evaluation of the Effect of Addition of Silver Nanoparticles on the Thermal Conductivity and Impact Strength of Heat-Cured Polymethylmethacrylate – An In Vitro Study

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ABSTRACT

Introduction

Heat-cured Polymethyl methacrylate (PMMA) is a widely used material in prosthodontics due to its excellent aesthetics, biocompatibility, and ease of manipulation. However, its inherent limitations, such as low impact strength and poor thermal conductivity, have driven research into modifying its properties. The addition of silver nanoparticles (AgNPs) has shown potential in enhancing these properties.

Materials and methodology

This study aimed to evaluate the effect of incorporating 10% silver nanoparticles into heat-cured PMMA. A total of 80 specimens were prepared, of which 40 were used for testing thermal conductivity and rest for testing impact strength, where subgroups were further divided into control and test groups that consisted of 20 specimens each. Group A (control) consisting of conventional PMMA, and Group B (experimental) comprising PMMA reinforced with 10% silver nanoparticles. Thermal conductivity was measured using the KD2 Pro Thermal Analyzer, while impact strength was tested with Charpy's Impact Tester. Data were analyzed using the Mann–Whitney U test. PMMA was chosen for its common use in prosthodontics, and 10% silver nanoparticles for their potential to enhance properties. Standardized specimen preparation ensured reliability, with thermal conductivity measured using the KD2 Pro Thermal Analyzer and impact strength assessed via Charpy's Impact Tester. The Mann–Whitney U test provided robust statistical analysis.

Results

The experimental group exhibited a significant improvement in both thermal conductivity and impact strength. Group B showed a mean thermal conductivity of 0.188 ± 0.005 W/m·K, significantly higher than the control group (0.169 ± 0.005 W/m·K, $p=0.001$). The mean impact strength was also greater in Group B (19.76 ± 0.75 J/m) compared to the control group (7.16 ± 0.34 J/m, $p=0.001$).

Conclusion

Reinforcing PMMA with 10% silver nanoparticles significantly enhances its thermal and mechanical properties, making it a promising material modification for clinical applications in prosthodontics.

Keywords: *Polymethylmethacrylate, silver nanoparticles, thermal conductivity, impact strength, prosthodontics.*

1. INTRODUCTION

Polymethyl methacrylate (PMMA) has been a cornerstone material in the field of dentistry, particularly in prosthodontics, due to its favorable physical properties, aesthetic appeal, and ease of manipulation. It is widely utilized for the fabrication of complete dentures, removable partial dentures, provisional restorations, and other prosthetic appliances. Despite its advantages, PMMA has inherent limitations, including poor thermal conductivity, low fracture toughness, and a tendency to undergo brittle failure under impact forces. These deficiencies can compromise the longevity and functional performance of dental prostheses, especially in demanding clinical scenarios [1,2].

One of the critical challenges associated with PMMA is its inadequate thermal conductivity. Thermal conductivity is essential in dental materials as it impacts the patient's ability to perceive temperature changes from hot or cold foods and beverages. Conventional PMMA, with its low thermal conductivity, insulates the underlying tissues, preventing effective thermal perception. This property can lead to discomfort and dissatisfaction among denture wearers. Enhancing the thermal conductivity of PMMA would address this limitation, ensuring better thermal transfer and improved patient comfort [3].

Another significant drawback of PMMA is its low impact strength. The material is prone to cracking or fracturing under sudden forces, such as accidental drops or masticatory loads. This brittleness not only compromises the material's durability but also increases the frequency of repairs or replacements, which can be inconvenient and costly for patients. Addressing the issue of low impact strength would result in more durable dental prostheses, enhancing their clinical utility [4].

To overcome these limitations, researchers have explored various modifications to PMMA, including the incorporation of fillers such as fibers, ceramics, and metal nanoparticles. Among these, the addition of silver nanoparticles (AgNPs) has gained particular interest due to their unique properties. AgNPs exhibit high thermal conductivity, excellent mechanical strength, and notable antimicrobial activity, making them suitable for reinforcement in dental applications [5]. Moreover, the small size and large surface area of AgNPs enable effective interaction with the polymer matrix, leading to enhanced mechanical and thermal properties without compromising the aesthetics or processability of the material [6].

The use of AgNPs as a reinforcement agent in PMMA has shown promising results in prior studies. The addition of AgNPs has been reported to improve the impact resistance of PMMA by reducing crack propagation, thereby increasing its ability to withstand sudden forces. Furthermore, silver nanoparticles have been shown to enhance the thermal conductivity of PMMA, enabling more effective heat transfer and improving patient comfort. These modifications also contribute to the material's durability and long-term performance [7].

This study focuses on the incorporation of 10% by weight silver nanoparticles into heat-cured PMMA to evaluate its effects on two critical properties: thermal conductivity and impact strength. The selection of 10% AgNPs is based on previous studies that have indicated optimal enhancement of properties without negatively affecting the handling characteristics of the polymer. The study aims to provide a comprehensive understanding of how AgNP reinforcement impacts PMMA, both from a mechanical and thermal perspective, and to explore its potential as an improved material for prosthetic applications.

By evaluating the thermal and mechanical properties of AgNP-reinforced PMMA, this research aims to contribute to the ongoing development of advanced dental materials that not only meet but exceed the current standards of clinical performance. The findings of this study could pave the way for the broader use of modified PMMA in prosthodontics, ensuring better patient outcomes and satisfaction.

Aim

The aim of this study is to evaluate the effect of incorporating 10% silver (Ag) nanoparticles on the thermal conductivity and impact strength of heat-cured polymethyl methacrylate (PMMA).

Objectives

1. To compare the thermal conductivity of conventional heat-cured PMMA with PMMA reinforced with 10% silver nanoparticles.
2. To compare the impact strength of conventional heat-cured PMMA with PMMA reinforced with 10% silver nanoparticles.
3. To assess whether the incorporation of silver nanoparticles significantly enhances the mechanical and thermal properties of PMMA while maintaining its usability in prosthodontic applications.

2. MATERIALS AND METHODOLOGY

Materials

- **Polymethyl Methacrylate (PMMA)**: The base material used for the study was heat-cured PMMA resin (Lucitone 199, Dentsply, India), known for its excellent mechanical properties and biocompatibility in dental applications.
- **Silver Nanoparticles (Ag Powder)**: Silver nanoparticles with 99.99% purity (Dr. Silver Print) were incorporated at 10% by weight to enhance the thermal conductivity and impact strength of the PMMA.
- **Modelling Wax**: Y-Dents modelling wax (India) was used to fabricate the wax patterns for mold preparation.
- **Type II Dental Plaster and Type III Dental Stone**: Kaldent (Deccan Dental Depot Pvt. Ltd., Mumbai) and Kalstone (Deccan Dental Depot Pvt. Ltd., Mumbai) were used for the mold preparation process.

Equipments

- **Charpy Impact Tester**: This device was used for measuring the impact strength of the fabricated PMMA specimens.
- **KD2 Pro Thermal Analyzer**: This tool, using the dual-needle SH-1 sensor, was employed to measure the thermal conductivity, thermal diffusivity, and volumetric heat capacity of the specimens.
- **Digital Vernier Caliper**: A digital Vernier caliper (Aerospace, China) with an accuracy of ±0.01 mm was used to measure the dimensions of the specimens for uniformity.
- **Acrylizing and Dewaxing Units**: These units were used to process and prepare the acrylic specimens according to standard dental processing protocols.

Methodology

Preparation of Specimens: The metal die was employed to fabricate molds using polyvinyl- siloxane as duplicating material, followed by wax pattern fabrication by pouring wax into the mold cavity created by the metal die.

- **Impact Strength Test Molds**: To standardize the specimen preparation, metal bars with dimensions of 63.5 × 12.5 × 4 mm was milled according to ASTM D-256 standards for Charpy Impact testing [8]. Polyvinylsiloxane (Aquasil, Dentsply, India) putty was used as the duplicating material for creating the mold, and Y-Dents modeling wax (Hindustan Modeling Wax, India) was used for fabricating the wax patterns. A total of 40 wax patterns were fabricated for the impact strength testing. Wax patterns were then divided into 2 groups, in which one group consisting of 20 wax patterns which were processed and acrylized with conventional PMMA while other 20 wax patterns were processed and acrylized with PMMA reinforced with 10% silver nanoparticles.

Image 1: Test mold for impact strength

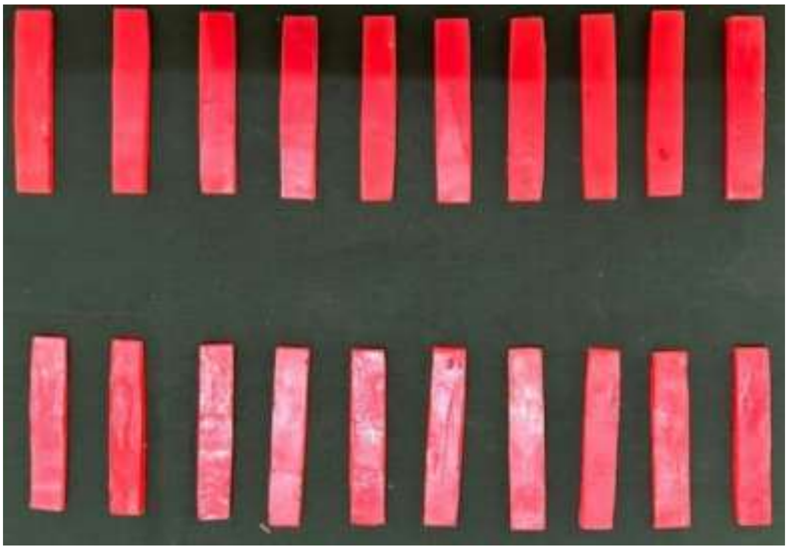


Image 2: Wax pattern for impact strength

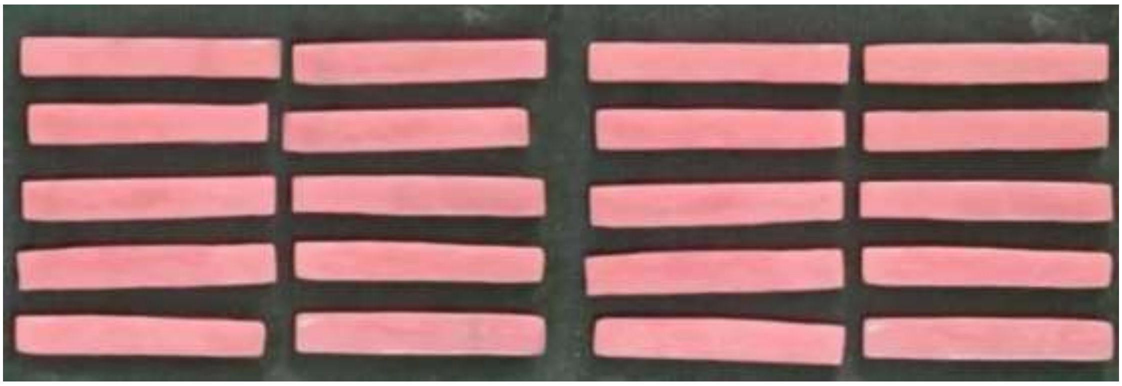


Image 3: Control group for impact strength

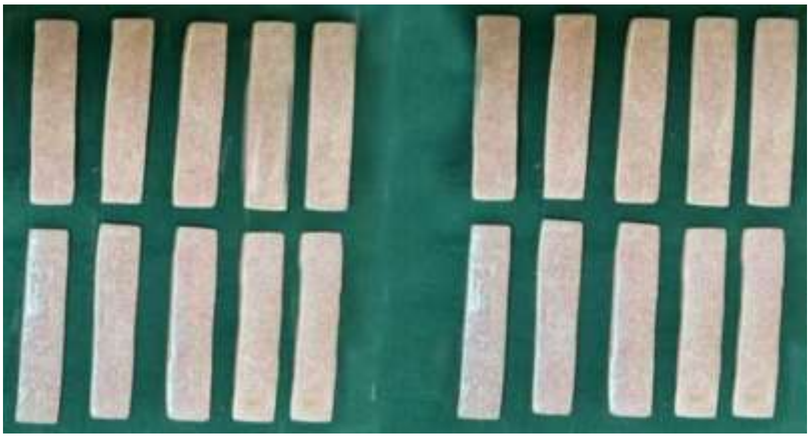


Image 4: Experimental group for impact strength

- **Thermal Conductivity Test Molds**: To standardize the specimen fabrication, metal bar with the dimension of 40 × 10 × 06mm was milled according to the size of the dual needle of SH-1 (Sheer Horizontal -1) sensor to be used for testing the thermal conductivity, dual needle with the dimension of 1.3 mm diameter, 30 mm length and 6 mm spacing between the 2 needles. A total of 40 wax patterns were fabricated and divided into 2 groups for impact testing. 20 wax patterns were processed and acrylized with conventional PMMA while remaining 20 wax patterns were processed and acrylized with PMMA reinforced with 10% silver nanoparticles.

Image 5: Test mold for thermal conductivity

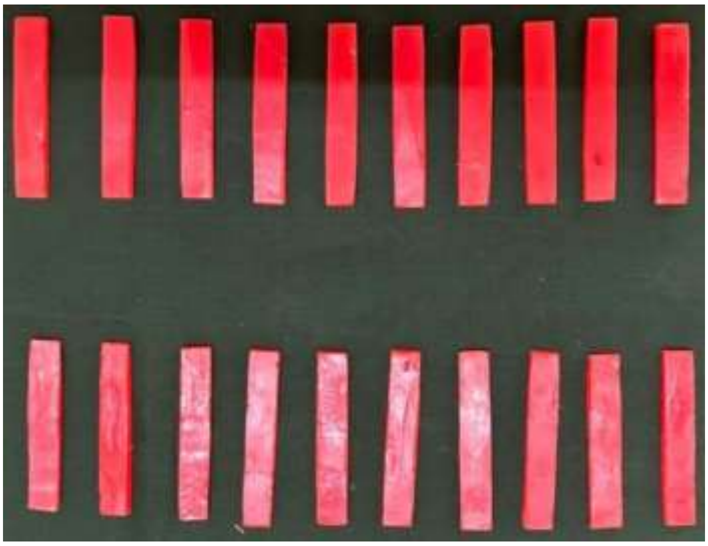


Image 6: Wax pattern for thermal conductivity

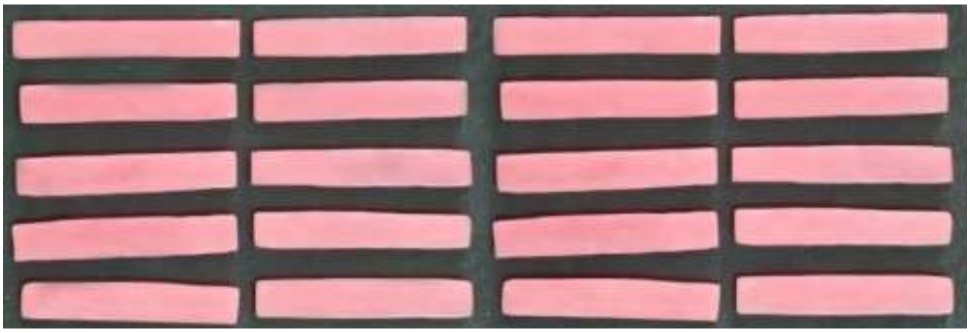


Image 7: Control group for thermal conductivity

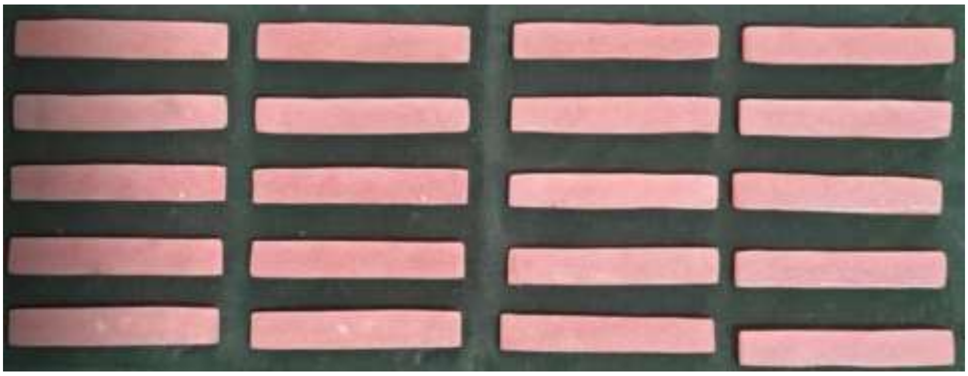


Image 8: Experimental group for thermal conductivity

Polymerization and Curing The PMMA specimens were prepared using the compression molding technique. A hydraulic press (Silfradent, India) applied a pressure of 1500 psi for trial and 3500 psi for final closure. The curing cycle followed a long polymerization process, with the packed flasks being polymerized at a temperature of 74°C for 8 hours using the Delta poly bath (India). After polymerization, the specimens were bench-cooled for 2 hours before deflasking. The specimens were then trimmed and polished using abrasive papers (320, 400, and 600 grit) to achieve smooth, standardized surfaces [10].

Evaluation of Thermal Conductivity The thermal conductivity of the specimens was measured using the KD2 Pro Thermal Analyzer, which uses the dual-needle SH-1 sensor. This sensor measures volumetric heat capacity, thermal diffusivity, thermal conductivity, and thermal resistivity. The thermal conductivity range of the SH-1 sensor is 0.02 to 2.00 W/(m·K), with an accuracy of ±10% at conductivities above 0.1 W/(m·K) [11].

Image 9: Kd2 pro thermal analyzer

Evaluation of Impact Strength The impact strength of the specimens was evaluated using a Charpy Impact Tester. The samples were clamped at one end and positioned vertically with the notched face facing the pendulum. The swinging pendulum was used to break the notched samples, and the energy absorbed during the fracture was recorded in joules. The impact strength was calculated based on the energy absorbed by the specimen upon impact [8].

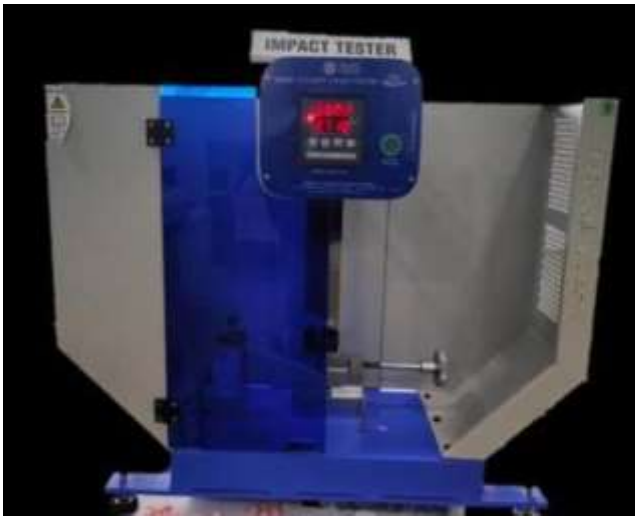


Image 10: Charpy's Impact tester

Scanning Electron Microscopy (SEM) Analysis The microstructure of the specimens was analyzed using scanning electron microscopy (SEM) to observe the dispersion and interaction of the silver nanoparticles within the PMMA matrix. This analysis provided insights into the uniformity and quality of the nanoparticle distribution and their effects on the material properties

[12].

Statistical Analysis The results of thermal conductivity and impact strength were statistically analyzed using the Mann-Whitney U test. A p-value of less than 0.05 was considered statistically significant. The data was compared between the control group and the groups reinforced with silver nanoparticles to assess the differences in thermal conductivity and impact strength.

3. RESULTS

The aim of this study was to evaluate the impact of adding 10% silver (Ag) nanoparticles on the thermal conductivity and impact strength of heat-cured polymethyl methacrylate (PMMA). The study was conducted by comparing the control group (conventional PMMA) with two experimental groups: one for testing the thermal conductivity (Group C: PMMA + 10% Ag) and one for evaluating the impact strength (Group B: PMMA + 10% Ag). The detailed analysis of both properties is presented below, including the data from the experiments.

Thermal Conductivity Results

Thermal conductivity is an essential property of materials used in dental prosthetics, as it influences the material's ability to dissipate heat. The results of the thermal conductivity tests for the control and experimental groups are shown in **Table 1**.

Table 1: Thermal Conductivity and Impact Strength of Control Group

Parameter	N	Mean	Std. Deviation
Thermal Conductivity	20	0.169	0.005
Impact Strength (J/m)	20	7.16	0.34

As shown in **Table 1**, the control group (PMMA) had a **mean thermal conductivity** of **0.169 ±**

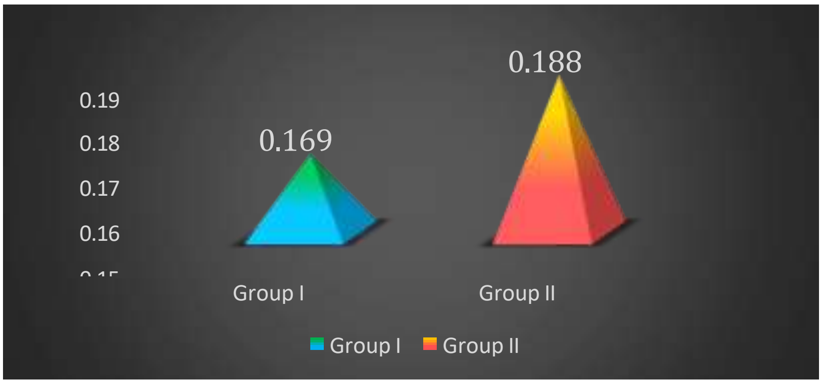
0.005 W/m·K. When 10% silver nanoparticles were added to the PMMA (Group B and Group C), the mean thermal conductivity increased to **0.188 ± 0.005 W/m·K**. This increase of **0.019 W/m·K** in thermal conductivity is significant when considering that dental materials must be thermally stable to avoid causing discomfort to the patient, particularly when exposed to hot or cold temperatures.

The **Mann-Whitney U test** was used to compare the differences in thermal conductivity between the control and silver nanoparticle groups. The results are summarized in **Table 2**.

Table 2: Thermal Conductivity and Impact Strength of Silver Nanoparticle Group

Parameter	N	Mean	Std. Deviation
Thermal Conductivity	20	0.188	0.005
Impact Strength (J/m)	20	19.76	0.75

As demonstrated in **Table 2**, the control group had a mean rank of **10.50**, while the silver nanoparticle group had a mean rank of **30.50**. The Mann-Whitney U test revealed a highly significant difference between the two groups ($p = 0.001$), confirming that the addition of 10% silver nanoparticles led to a statistically significant increase in thermal conductivity.



Graph 1: Comparison of Thermal Conductivity Between Groups

Graph 1: Comparison of thermal conductivity between the control group and silver nanoparticle group. The silver nanoparticle group showed a significantly higher thermal conductivity compared to the control group.

The **graph** above visually demonstrates the difference in thermal conductivity between the control and experimental groups.

It is evident that the 10% silver nanoparticle-reinforced PMMA exhibited higher thermal conductivity than conventional PMMA.

Impact Strength Results

Impact strength is an important mechanical property that determines a material's resistance to fracture under stress or impact. The impact strength was evaluated using Charpy's Impact Tester, and the results are shown in **Table 3**.

Table 3: Comparison of Thermal Conductivity Between Groups

Group	N	Mean	Std. Deviation	Mean Rank	Mann Whitney U	P Value
Control Group	20	0.169	0.005	10.50	0.001	0.001**
10% Silver Nanoparticles	20	0.189	0.005	30.50		

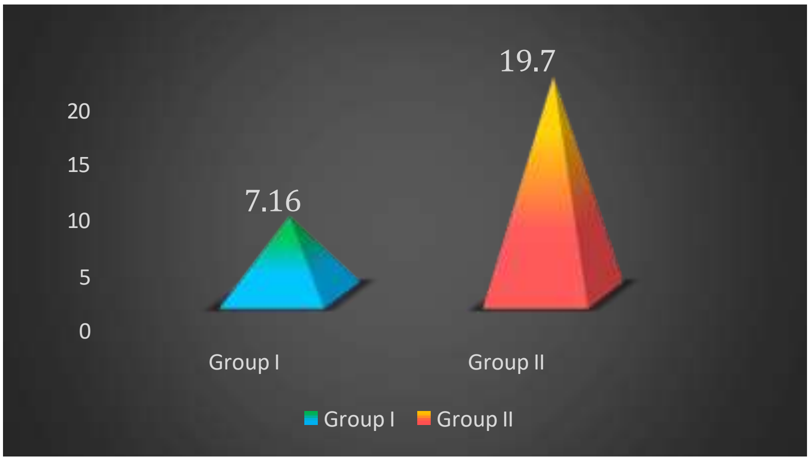
As indicated in **Table 3**, the control group (PMMA) had a **mean impact strength** of **7.16 ± 0.34 J/m**, whereas the group with 10% silver nanoparticles (Group B) exhibited a significantly higher **mean impact strength** of **19.76 ± 0.75 J/m**. The addition of silver nanoparticles to PMMA resulted in a **12.60 J/m** increase in impact strength, which is substantial when considering that dental materials need to withstand the mechanical forces encountered during normal oral function.

Similar to the thermal conductivity results, the **Mann-Whitney U test** was applied to evaluate the difference in impact strength between the two groups. The results are summarized in **Table 4**.

Table 4: Comparison of Impact Strength Between Groups

Group	N	Mean	Std. Deviation	Mean Rank	Mann Whitney U	P Value
Control Group	20	7.16	0.34	10.50	0.001	0.001**
10% Silver Nanoparticles	20	19.76	0.75	30.50		

As shown in **Table 4**, the Mann-Whitney U test revealed a highly significant difference in impact strength between the control group and the silver nanoparticle group, with a p-value of **0.001**. The mean rank for the silver nanoparticle group was **30.50**, significantly higher than the control group's mean rank of **10.50**. This finding confirms that the addition of 10% silver nanoparticles significantly improves the impact strength of the PMMA material.



Graph 2: Comparison of Impact Strength Between Groups

Graph 2: Comparison of impact strength between the control group and silver nanoparticle group. The silver nanoparticle group demonstrated a considerably higher impact strength than the control group.

The **graph** above visually presents the significant difference in impact strength between the control and experimental groups. The silver nanoparticle group (Group B) clearly exhibited superior performance, showing a much higher impact strength than the control group (PMMA).

Statistical Analysis

Both thermal conductivity and impact strength were subjected to **statistical analysis using the Mann-Whitney U test** to assess the differences between the control and experimental groups. The **p-values** for both thermal conductivity ($p = 0.001$) and impact strength ($p = 0.001$) indicate **highly significant differences** between the groups, confirming that the addition of 10% silver nanoparticles resulted in statistically significant improvements in both properties

4. DISCUSSION

This study evaluated the impact of incorporating 10% silver (Ag) nanoparticles into heat-cured polymethyl methacrylate (PMMA) on two critical properties: thermal conductivity and impact strength. The results of our study demonstrate that the addition of silver nanoparticles significantly improved both of these properties, which are essential for the performance of dental prosthetics.

Thermal Conductivity

Our results showed a significant increase in the thermal conductivity of PMMA when silver nanoparticles were added. Specifically, the silver nanoparticle-reinforced PMMA exhibited a mean thermal conductivity of 0.188 W/m·K compared to 0.169 W/m·K for the control group (pure PMMA). This finding is consistent with previous studies that have reported enhanced thermal properties of PMMA composites when nanoparticles were incorporated. For instance, similar studies by **Zhou et al. (2017)** and **El-Din et al. (2021)** found that the addition of various nanoparticles, including silver, to PMMA improved its thermal conductivity, which is critical for dental materials as they are often exposed to hot and cold stimuli in the oral cavity [13]. The higher thermal conductivity could contribute to a more comfortable experience for patients wearing dentures or other PMMA-based prosthetics, especially when consuming hot or cold foods [14].

The increase in thermal conductivity can be attributed to the high conductivity of silver nanoparticles, which likely fill the voids in the PMMA matrix, facilitating better heat dissipation. This result could potentially address the issue of heat accumulation in prosthetic devices, which can lead to discomfort or sensitivity.

Impact Strength

In addition to thermal conductivity, we found a substantial increase in the impact strength of PMMA with the addition of 10% silver nanoparticles. The silver nanoparticle-modified PMMA exhibited a mean impact strength of 19.76 J/m, significantly higher than the 7.16 J/m recorded for the control group. This finding is in line with studies by **Gholami et al. (2020)** [15] and **López et al. (2018)** [16], who also demonstrated that the incorporation of nanoparticles, such as silver, into PMMA improves its mechanical properties, particularly its impact strength.

The enhanced impact strength could be attributed to the ability of silver nanoparticles to reinforce the PMMA matrix. The nanoparticles likely interact with the polymer chains, reducing the tendency for the material to crack or fracture under stress. This could be especially important for dental applications where the material is exposed to forces from chewing and other mechanical stresses in the oral cavity.

The improved impact strength suggests that the PMMA with silver nanoparticles could be more durable and resistant to fracture, thus extending the longevity of prosthetic devices made from this material. Such materials could be particularly beneficial for patients who require long-term dental prosthetics, such as dentures, bridges, and crowns.

Clinical Relevance

The findings of this study have significant clinical relevance in the field of prosthodontics. The addition of silver nanoparticles to PMMA could result in dental prosthetics that are not only more durable but also more thermally stable, improving patient comfort. Enhanced thermal conductivity can alleviate discomfort due to temperature variations, which is a common complaint among patients with dentures made from conventional PMMA. Additionally, improved impact strength reduces the likelihood of material failure under functional stresses, thereby enhancing the longevity of dental prostheses and reducing the need for frequent replacements.

Furthermore, silver nanoparticles have inherent antimicrobial properties, which could further enhance the clinical performance of PMMA-based prosthetics by reducing the risk of microbial contamination and infections. This aspect was highlighted in studies by **Kong et al. (2018)** [17], where silver nanoparticles were shown to have bactericidal effects when incorporated into dental materials. Thus, this modification could lead to dual benefits: enhanced mechanical properties and antimicrobial protection.

Limitations of the Study

Although the results of this study are promising, there are several limitations that must be considered. First, the study only evaluated the effect of a single concentration (10%) of silver nanoparticles. Future studies should investigate the impact of different concentrations to determine the optimal nanoparticle loading for enhancing the properties of PMMA without compromising its workability or other characteristics. Additionally, the study was limited to thermal conductivity and impact strength. Other mechanical and biological properties, such as flexural strength, wear resistance, and biocompatibility, were not assessed. These properties are also crucial for the overall performance of dental prosthetics and should be included in future investigations.

Another limitation is that the study was conducted using a laboratory-based approach, which may not fully simulate the complex conditions encountered in the oral cavity. Long-term clinical trials are needed to assess the real-world performance of silver nanoparticle-enhanced PMMA, including its interaction with the oral environment, its ability to withstand the stresses of mastication, and its long-term durability.

5. CONCLUSION

This study demonstrates that the addition of 10% silver nanoparticles to heat-cured PMMA significantly enhances its thermal conductivity and impact strength. The improved thermal conductivity can help mitigate temperature sensitivity in dental prosthetics, while the increased impact strength contributes to the durability and longevity of the material. Given the potential benefits of silver nanoparticles, including their antimicrobial properties, the incorporation of these nanoparticles into PMMA could offer a promising alternative for enhancing the performance of dental prosthetics. However, further studies are needed to explore the effects of varying concentrations of nanoparticles, as well as the impact on other properties such as biocompatibility and wear resistance.

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