Wadi Alshatti University Journal of
Pure and Applied Sciences

مجلة جامعة وادي الشاطئ
للعلوم البحتة والتطبيقية

Volume 4, No. 1, January-June 2026 Online ISSN: 3006-0877 المجلد 4، الاصدار 1، يناير- يونيو 2026

TYPE OF ARTICLE **BIOMATERIALS**

Assessment of Flexural and Impact Strengths in Polymethyl Methacrylate Denture Base Resin Reinforced with Short E-glass Fiber

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ARTICLE HISTORY
Received 01 December 2025
Revised 25 December 2025
Accepted 28 December 2025
Online 30 December 2025

KEYWORDS
Polymethyl methacrylate;
Denture base resin;
Short E-glass fiber;
Flexural strength;
Impact strength;
Silane treatment.

ABSTRACT

Polymethyl methacrylate (PMMA) is the predominant material for denture base construction, however its low flexural and impact strengths contribute a high rate of clinical failure. This study aimed to evaluate the reinforcing effect of silane-treated short E-glass fiber (SEGF) incorporated into heat-polymerized PMMA at different concentrations (0%, 2%, 4%, 5%, 7%, and 9 wt.%). A total of 180 specimens, fabricated according to ISO 1567, were subjected to three-point bending and Charpy impact tests to determine flexural and impact strengths. Statistical analysis using one-way ANOVA followed by Tukey's post-hoc test ($\alpha = 0.05$) revealed a highly significant improvement in both properties with SEGF incorporation. Flexural strength increased progressively, reaching its maximum at 7 wt.% (106.47 ± 5.78 MPa), followed by a slight decline at 9 wt.% was recorded, likely due to fiber agglomeration and increased void formation. In contrast, impact strength showed a consistent and significant increase across all concentrations, with the highest value at 9 wt.% (12.80 ± 0.33 kJ/m²). These enhancements are attributed to improve interfacial bonding provided by silane treatment, which promotes effective stress transfer and crack-bridging. Within the limitations of this study, SEGF incorporation particularly in the 5-7 wt.% range offers optimal mechanical reinforcement. In conclusion, silane-treated SEGF represent a practical and effective strategy for improving the durability and fracture resistance of PMMA-based prostheses.

تقييم قوة الانثناء والصدمة لراتنج (البولي ميثيل ميثاكريلات) المستخدم في تصنيع قواعد أطقم الأسنان المُعزّزالألياف الزجاجية القصيرة

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قاعدة طقم الأسنان
الألياف الزجاجية القصيرة
قوة الانثناء
قوة الصدمة
المعالجة بالسايلان

الملخص

تُعد مادة الراتنج (بولي ميثيل ميثاكريلات) الأكثر استخداماً في تصنيع قواعد أطقم الأسنان. ومع ذلك، فإن محدودية قوة الانثناء وقوة الكسر فيها لا تزال تُسهم في ارتفاع معدلات الكسر عند استخدامها سريرياً. لذلك هدفت هذه الدراسة إلى تقييم تأثير إضافة الألياف الزجاجية القصيرة المعالجة بالسايلان إلى مادة البولي ميثيل ميثاكريلات المتبلمر حرارياً بتركيزات مختلفة: 0٪، 2٪، 4٪، 5٪، 7٪، و9٪ بالوزن. تم تصنيع 180عينة وفقاً للمواصفات القياسية حسب (ISO 1567)، ثم اختُبرت لتحديد قوة الانثناء وقوة الكسر بالصدمة باستخدام اختبار الانثناء ثلاثي النقاط واختبار الصدمة من نوع (Charpy). أُجري التحليل الإحصائي باستخدام تحليل التباين الأحادي (ANOVA) متبوعاً باختبار ت (Tukey) عند مستوى دلالة إحصائية ($p = 0.05$). حيث أظهرت النتائج المتحصل عليها بإضافة الألياف الزجاجية القصيرة المعالجة بالسايلان لراتنج تحسناً ملحوظاً في كلتا الخاصيتين الميكانيكيتين، زيادة لقوة الانثناء تدريجياً من 2٪ وحتى 7٪ بالوزن، مسجلة أعلى قيمة لها عند هذا التركيز بمتوسط حسابي وانحراف معياري (106.47±5.78 MPa)، قبل أن يظهر انخفاض طفيف عند تركيز 9٪ بالوزن. في المقابل، ارتفعت قوة مقاومة الكسر بشكل مستمر عبر جميع التركيزات، وبلغت أعلى قيمة لها عند 9٪ بالوزن، بمتوسط حسابي وانحراف معياري (12.80 ± 0.33 kJ/m²). يُعزى هذا التحسن إلى زيادة قوة الترابط البيني الكيميائي بين المادتين بفعل المعالجة بالسايلان، وتحسين توزيع الإجهاد، وتقليل انتشار تشققات الكسر المحتملة في قاعدة الطقم. بينما يُعزى الانخفاض الطفيف في قوة الانثناء عند التركيزات الأعلى من 7٪ إلى تكتل الألياف عند إضافتها، وما ينتج عنه تكوين فراغات تحد من الأداء الميكانيكي. وفي حدود هذه الدراسة، فإن دمج الألياف الزجاجية القصيرة خصوصاً عند تركيزات 5-7٪ بالوزن، يحسن بشكل ملحوظ الخواص الميكانيكية للبولي ميثيل ميثاكريلات المستخدم في تصنيع قواعد أطقم الأسنان. وتُبرز هذه النتائج فعالية استخدام الألياف الزجاجية القصيرة المعالجة بالسايلان كوسيلة تدعيم تسهم في زيادة المتانة ومقاومة الكسر. وبشكل عام، تُعتبر الألياف الزجاجية القصيرة المعالجة بالسايلان إضافةً فعالة لتحسين الأداء الميكانيكي لمادة البولي ميثيل ميثاكريلات المستخدمة في تصنيع قواعد أطقم الأسنان.

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https://doi.org/10.63318/waujpasv4i1_04

Introduction

Polymethyl methacrylate (PMMA) has remained the principal material for denture base fabrication since the 1940s because of its low cost, ease of handling, esthetic qualities, lightweight, and biocompatibility [1-4]. On the other hand, PMMA exhibits several mechanical limitations, including low flexural, poor impact strengths, a low elastic modulus, brittleness, susceptibility to water sorption and polymerization shrinkage. These drawbacks compromise dimensional stability and increase the likelihood of fractures during mastication or accidental dropping [5]. The mechanical performance of PMMA is influenced by polymerization technique, material composition, and filler characteristics such as size, concentration, and distribution [4, 5]. Inorganic fillers are surface-treated with silane coupling agents to improve interfacial adhesion with the polymer matrix, improving stress transfer, reducing water sorption, and increasing structural durability [6-9].

Recent developments have focused on reinforcing PMMA with nanoparticles fillers and fibers to improve its mechanical reliability under functional loading. Additives such as Silicon dioxide (SiO_2) [4], Titanium dioxide (TiO_2) [10], Zirconium dioxide (ZrO_2), and hydroxyapatite [7,11] have demonstrated improvements in flexural strength (FS) [4,6,10], wear resistance, and structural stability [6,7].

short E-glass fibers (SEGFs) are among the most promising reinforcements. They combine a high strength-to-weight ratio with effective stress-distribution capabilities [12]. Their reinforcing efficiency depends on fiber length, diameter, concentration, orientation, and dispersion quality [6,13-15]. Compared with continuous fibers, SEGF are easier to incorporate and less technique-sensitive, making them suitable for conventional processing methods [16-18]. Numerous studies have consistently shown that SEGFs enhance flexural and impact strengths by bridging cracks and reducing their propagation [17,18].

However, improvements are most pronounced at low concentrations (around 1%), whereas higher levels (> 5 wt.%) may lead to fiber agglomeration and increased porosity [19]. In contrast, other investigations have reported significant improvements at 5 wt.% when optimized polymerization cycles are employed. Nonetheless, achieving uniform fiber distribution remains challenging due to the size mismatch between PMMA powder particles (> 25 μm) and glass fiber diameters (8-20 μm), which may promote clumping and void formation [20]. Moreover, several studies have shown that SEGF concentrations of 5-7 wt.% significantly enhance both flexural and impact strengths [21,22], while other research has demonstrated optimal (FS) at 2.5 wt.% using 6-mm fibers, underscoring the combined effects of fiber length, concentration, and interfacial bonding quality [23].

Based on the existing evidence, the present study aims to assess the flexural and impact strengths of heat-polymerized PMMA denture base resin incorporating different concentrations of silane-treated SEGF.

Materials and Methods

Conventional heat-polymerized polymethyl methacrylate (PMMA) denture base resin and its corresponding monomer, methyl methacrylate (MMA), by Pyrex Company (India) were used in this study. The reinforcing material consisted of surface-treated SEGF, which were approximately 3 mm in length and 15 μm in diameter, obtained from Interglass AG (Switzerland). To improve the adhesion between the fibers and the PMMA matrix, a silane coupling agent, 3-Trimethoxysilyl propyl methacrylate, was used for the surface treatment of the SEGF. Ethanol (≥ 99.7%) was used as the solvent for the silane solution. Both the silane and the ethanol were obtained from Sigma-Aldrich Chemie GmbH (Germany) [24,25]. Acetic acid (≥ 99.7%) Sigma-Aldrich Chemie GmbH, Germany was employed for pH adjustment of the silane solution to a range of (4.0 - 4.5). This was done to promote the controlled hydrolysis of the silane coupling agent [26]. Table 1 summarizes the materials used in this study.

Table 1: Materials used in the study [10,24-26].

Material	Composition / Specification	Manufacturer
PMMA Denture Base Resin	High Quality Heat Cure Denture Base Acrylic Resin Powder (400 g)	Pyrex Company, India
MMA Monomer	Liquid methyl methacrylate with cross linking additive, mixing ratio 2.5 g powder / 1 mL liquid	Pyrex Company, India
SEGF	Chopped fibers, approx. length 3mm, diameter 15 μm	Interglass AG, Switzerland
Silane Coupling Agent	3-Trimethoxysilyl propyl methacrylate (MPS), purity ≥ 98%	Sigma-Aldrich Chemie GmbH, Germany
Ethanol	Laboratory grade ethanol ≥ 99.7% (solvent for silane treatment)	Sigma-Aldrich Chemie GmbH, Germany
Acetic Acid	Acetic acid, ≥ 99.7% purity, pH adjustment of silane solution to 4.0–4.5 to promote controlled hydrolysis	Sigma-Aldrich Chemie GmbH, Germany

The fiber-reinforced formulations were prepared by partially replacing a proportional weight of PMMA powder with SEGF to achieve fiber weight fractions of (0%, 2%, 4%, 5%, 7%, and 9%).

Surface treatment of SEGF

The surfaces of the SEGF were silanized to enhance chemical bonding with the PMMA matrix, as silane coupling agents promote covalent linkage between inorganic SEGF and organic resin phases [25,26]. First, 15 g of SEGF were dispersed in 70 mL of ethanol and mixed using a speed mixer (DAC 150 FVZ-K, Hauschild, Germany) at 1500 rpm for 10 minutes to ensure uniform wetting and surface cleaning. A silane solution was prepared by adding 0.45 g of 3-methacryloxypropyltrimethoxysilane (MPS) to a mixture of ethanol and deionized water (95:5 v/v), the pH was adjusted to (4.0 - 4.5) with Acetic acid to facilitate controlled hydrolysis of the silane. The silane solution was stirred magnetically for 45 minutes at room temperature to allow hydrolysis. This solution was then combined with the fiber suspension and stirred for 2 hours, followed by gentle heating at 50 C° for 1 hour to promote initial silane condensation. The mixture was centrifuged (Eppendorf 5804, Hamburg, Germany) at 4500 rpm for 20 minutes, and the supernatant was decanted. The silanized fibers were rinsed with Ethanol to remove unreacted silane and dried in a vacuum oven (FALC Instruments, Treviglio, Italy) at 100 C° for 1 hour to complete siloxane bond formation. Finally, the treated fibers were stored in airtight containers in a desiccator until use. [22,26,27].

Specimen preparation

Specimens were prepared according to ISO 1567:1999 [28], standards and divided into two sets of different dimensions: (65 × 10 × 2.5 mm) length × width × thickness for (FS)testing and (55 × 10 × 10 mm) for (IS) testing, with 90 specimens in each set (180 in total). All materials used in this study are summarized in Table 2.

Materials and mixing ratio specification

SEGF and PMMA powder were accurately weighed using a digital balance (Wedo Picco1000, China). SEGFs were incorporated into the PMMA matrix at concentrations of (0%, 2%, 4%, 5%, 7%, and 9%) wt.% (Table 2). The powder-to-liquid ratio was strictly maintained at 2.5 g of powder per 1 mL of MMA monomer, following the manufacturer's instructions. For each specimen, 12 g of PMMA powder and 5 mL of monomer were prepared in the standard 1:2.5 (v/w) mixing ratio. To minimize fiber agglomeration, the required amount of SEGF was first pre-wetted with 4.6 mL of MMA monomer and manually separated. PMMA powder was then gradually incorporated into the wetted fibers in six increments (0.43 g each), with 10 seconds of manual mixing after each addition to gradually increase viscosity and promote uniform fiber dispersion. The blend was then stirred for an additional 2 minutes to ensure complete fiber embedding within the monomer. The remaining PMMA powder (10.4 g) and MMA monomer (1.6 mL) were subsequently incorporated to achieve the final powder-to-liquid ratio of 2.5 g/mL [22,27].

Homogenization and wet mixing

To further enhance fiber dispersion and reduce agglomeration , the dry PMMA-SEGF powder blends were homogenized using a planetary centrifugal mixer (Thinky ARE-250, Thinky Corp., Japan), operating at 3500 rpm for 5 minutes. The homogenized powder was then mixed with the calculated MMA monomer volume, maintaining the 2.5 g/mL ratio, and manually stirred until the mixture reached a uniform, dough-like consistency suitable for packing into molds.

Polymerization

Standard flasking, packing, and heat-polymerization procedures for denture base resin were followed. Polymerization was carried out by immersing the flasks in a thermostatically controlled water bath maintained at 75 ± 1 C° for 8 hours. After curing, the specimens were carefully deflasked then finished and polished using fine abrasive papers to obtain smooth, uniform surfaces.

Storage of Specimens

All specimens were subsequently conditioned by storage in distilled water at 37 C° for one week before mechanical testing [15,22,27].

Grouping of specimens

The total 180 specimens were divided into two main groups: the (FS)group and the (IS) group. Each of these two main groups consisted of 90 specimens, which were further divided into six subgroups of the SEGF concentrations 0%, 2%, 4%, 5%, 7%, and 9%. Each of these subgroups contained 15 specimens. An additional control 0% group consisting of unreinforced PMMA specimens was also prepared.

Table 2: Specimen groups and quantities of acrylic resin powder, monomer, and fiber used per group.

Group	N	SEGF (wt.%)	SEGF (g)	PMMA (g)	MMA (mL)
Control (1)	15	0%	0.00	12.00	5.10
SEGF (2)	15	2%	0.24	11.76	5.10
SEGF (3)	15	4%	0.48	11.52	5.10
SEGF (4)	15	5%	0.60	11.40	5.10
SEGF (5)	15	7%	0.84	11.16	5.10
SEGF (6)	15	9%	1.08	10.92	5.10

Flexural strength testing

Strength is a mechanical property that reflects a material's resistance to deformation under an applied load. It represents the maximum stress a material can withstand at the point of failure during bending [29]. In this study, (FS)was measured using a three-point bending test in accordance with ISO 1567 [28]. All specimens had dimensions of 65 × 10 × 2.5 mm, each specimen was positioned on two parallel supports with a span length of 50 mm, and load was applied at the midpoint using a universal testing machine (Tokyo Testing Machine, Japan), at a crosshead speed of 5 mm/min until fracture occurred. The maximum load (F, N) at fracture was recorded, and the (FS)(σ, MPa) was calculated using the following equation: [15,27].

$$\boldsymbol{\sigma = \frac{3FL}{2bd^2}} \quad (1)$$

Where:

σ = the (FS)(MPa)

F = maximum load at fracture (N)

L = support span (50 mm)

b = specimen width (10 mm)

d = specimen thickness (2.5 mm)

Impact strength testing

Impact strength was determined according to [22,28,30,31] using a Charpy-type pendulum impact testing machine (Model IT 504, Ceast/Instron, Italy). The specimens measured: (55×10×10 mm) were notched at the midpoint to a depth of 2.5 mm, leaving an effective depth of 7.5 mm below the notch. Each specimen was positioned horizontally on two supports spaced 40 mm apart, and the pendulum was released to strike the specimen opposite the notch, causing fracture. The absorbed impact energy was recorded automatically, and the (IS, kJ/m²) was calculated using the following equation: [27].

$$\boldsymbol{a_{iN} = \frac{E_c}{h * b_N} \times 10^3} \quad (2)$$

All specimens were tested at room temperature, and the measured values were recorded for statistical analysis

Statistical Analysis

All collected data were statistically analyzed using IBM SPSS Statistics software, version 26.0 (IBM Corporation, Armonk, NY, USA). One-way analysis of variance (ANOVA) was performed, followed by Tukey's post-hoc test, to identify statistically significant differences between groups.

Result

The present study hypothesized that adding different concentrations of SEGF to heat-cured PMMA would improve its mechanical properties. In particular, both flexural and impact strengths were expected to increase. The Shapiro-Wilk test results (Table 3) confirm that the data for both (FS) and (IS) were normally distributed across all tested groups, as evidenced by all p-values greater than 0.05.

Table 3: Means, standard deviations, & test of normality of (FS) & (IS) values for the tested groups.

Group		**Flexural strength**			**Impact strength**		
wt.%	**N**	**M±S.D**	**S.W.V**	**p-V**	**M±S.D**	**S.W.V**	**p-V**
0%	15	71.53 ±11.14	0.957	0.657	7.18 ± 0.43	0.959	0.682
2%	15	89.67 ± 3.31	0.963	0.744	8.31 ± 0.50	0.951	0.548
4%	15	96.87 ± 2.88	0.948	0.486	10.32 ± 0.42	0.943	0.418
5%	15	104.07 ± 6.32	0.927	0.221	11.01 ± 0.42	0.963	0.742

7%	15	106.47 ± 5.78	0.942	0.404	12.40 ± 0.34	0.947	0.477
9%	15	100.87 ± 5.59	0.953	0.589	12.80 ± 0.33	0.955	0.619

Means, Standard Deviations (M±S.D), Shapiro-Wilk Value (S.W.V), p-Value (p-V).

Table 3 showed that the mean (FS) values for the experimental groups increased progressively with higher SEGF concentrations up to (5-7 wt.%), followed by a slight reduction at (9 wt.%). The highest mean and standard deviation of (FS) were observed in the (7 wt.%) SEGF group (106.47 ± 5.78 MPa), whereas the control group (0 wt.%) exhibited the lowest value with mean and standard deviation (71.53 ± 11.14 MPa). In contrast, the (IS) values showed a different behavior, increasing steadily from the control group to the (9 wt.%) group. The highest mean and standard deviation of (IS) were recorded in the (9 wt.%) SEGF group (12.80 ± 0.33 kJ/m²), slightly lower than the (7 wt.%) SEGF group (12.40 ± 0.34 kJ/m²).

Table 4: One-way ANOVA results for (FS, MPa) & (IS, kJ/m^2).

V	Source of variance	Sum of Squares	df	Mean Square	F	Sig
FS	Between Groups	12460.08	5	2492.01	60.30	<0.001
	Within Groups	3471.20	84	41.324	—	—
	Total	15931.28	89	—	—	—
IS	Between Groups	373.35	5	74.670	443.34	<0.001
	Within Groups	14.148	84	0.168	—	—
	Total	387.498	89	—	—	—

(Flexural strength) (FS), (Impact strength) (IS), Variables (V)

A one-way ANOVA analysis (table 4) confirmed that the fiber concentrations had a statistically significant effect on (FS), F (5, 84) = (60.30), ($p < 0.001$). This finding indicates that the SEGFs reinforcement greatly improved the material's resistance to bending. A significant enhancement was also observed for (IS). The ANOVA showed a highly significant effect based on fiber groups, F (5, 84) = (443.34), ($p < 0.001$). The flexural analysis indicated a violation of the assumption of homogeneity of variance. Consequently, the Tukey-post-hoc test was utilized. This test is appropriate for data exhibiting unequal variances when the group sizes are balanced. The result ($p = 0.541$, > 0.05), confirmed stable variability across the experimental groups.

Therefore, all fiber-reinforced samples achieved substantial enhancements in impact resistance relative to the control group. This finding highlights the critical role of the reinforcing fibers in improving the material's toughness and its capacity for effective energy dissipation during sudden load application. However, a detailed post-hoc comparison of the impact data summarized in Table 5, revealed that several of these numerical differences were not statistically significant.

Table 5 showed the comparison between the SEGF (4%) and SEGF (5%) groups yielded a mean difference of (- 4.00) MPa ($p = 0.909$), indicating no statistically significant difference. Similarly, the comparison of SEGF (4%) versus SEGF (9%) resulted in a difference among groups of (- 5.60) and a p-value of (0.533), which also not reach the threshold for statistical significance. In addition, comparison, SEGF 5% versus SEGF (7%), demonstrated a difference among groups of (3.20) with a p-value of (0.173), non-significant finding. Finally, when comparing the SEGF (7%) and SEGF (9%) groups yielded a difference among groups of (- 2.80) with p-value of (0.092), indicating no significant difference.

Table 5: Summary of Tukey HSD for pairwise comparisons of (FS, MPa) & (IS, kJ/m²).

Comparison	Mean differences	p-value	Sig
Control with all SEGF groups (FS & IS)	- 2.40	<0.001	Yes
4% with 5% (FS)	- 4.00	0.909	No
4% with 9% (FS)	- 5.60	0.533	No
5% with 7% (FS)	3.20	0.173	No
7% with 9% (IS)	- 2.80	0.092	No

Flexural strength (FS), Impact strength (IS).

These data confirm that while all levels of SEGFs reinforcement significantly improved (FS) compared to the control, the strengthening effect reaches a plateau between 5% and 9% concentration, with no statistically significant differences found among these top-performing groups.

Both (FS) and (IS) tests indicate that SEGF provides a consistent reinforcing effect, although the optimal fiber concentrations and the corresponding mechanical response different between the two tests. Flexural performance showed no further statistical increase across the 5 wt.%, 7 wt.%, and 9 wt.% groups. Conversely, impact strength (IS) demonstrated a highly significant and uniform increase across all reinforced levels, with the 7 wt.% and 9 wt.% groups not exhibiting a statistically significant difference.

These findings confirm that SEGF reinforcement enhances both the stiffness (resistance to bending) and toughness (resistance to impact) of PMMA. The combination of improved stiffness and toughness creates a more resilient microstructure capable of withstanding both static deformation and dynamic fracture.

Discussion

The findings of the present study clearly demonstrate that incorporating silane-treated SEGF enhances the mechanical performance of heat-polymerized PMMA denture base resin. These results are consistent with more extensive efforts in prosthodontics purposeful in overcoming the mechanical limitations of conventional PMMA [5,15]. Both flexural and impact strengths increased significantly with the incorporation of short fibers, with optimal reinforcement observed at 5-9 wt.% SEGF. Although (FS) slightly decreased at 9 wt.%, the improvement observed in the 5-7 wt.% range aligns with recent findings by Yerliyurt, et al. [32] and Apimanchindakul. et al. [10], who reported similar trends in fiber-reinforced acrylics. However, impact resistance continued to increase at higher concentrations. This difference in response of the two mechanical properties to increasing fiber content is consistent with previous studies by Alhotan, et al. [33], Hadoush [34], Mathew, et al. [22], and Dagar, et al. [35].

The observed reinforcement mechanisms in this study, including fiber-matrix bonding and crack-bridging, align with

well-established composite theories. Vallittu [24] emphasized that two conditions are essential for fibers to function as effective load-bearing components in PMMA. First, a strong chemical bond at the fiber-matrix interface is necessary. Schauperl, et al. [36] recently highlighted the critical role of surface treatments in optimizing the fiber-matrix interface. The silane treatment applied in the present study ensured a chemically stable bond. Second, the fiber length must exceed the critical length required for adequate stress transfer. The 3 mm fiber length used here exceeded the threshold required for effective reinforcement as described by Vallittu [24].

Garoushi and colleagues [13] demonstrated that properly bonded E-glass fibers act as crack-bridging and crack-deflecting agents, delaying fracture, dissipating energy, and increasing the material's toughness. This is further supported by a systematic review by Albergaria., et al 2023 [9], which confirmed that fiber inclusion significantly improves energy absorption capabilities. These mechanisms explain the progressive increase in (IS) observed across all reinforced groups in the current study. The ability of the fibers to arrest and deflect cracks also contributes to improved flexural behavior up to the optimal reinforcement range. In contrast, previous studies have shown that reinforcement efficiency is highly dependent on fiber concentration, and excessive fiber loading may increase void formation and heterogeneity within the PMMA matrix [13,15,20].

This observation is consistent with the slight decrease in (FS) recorded at 9 wt.% in the present study. This phenomenon is corroborated by Özdemir and Polat [37], who found that poor fiber distribution leads to structural heterogeneity, also Tomar and Gope [12], reported similar limitations in composite matrices. This explanation closely corresponds with the slight reduction in (FS) observed at 9 wt.% SEGF in the current results, suggesting that the threshold for optimal reinforcement had been exceeded. The divergent behavior between flexural and impact properties may also be attributed to the fundamental differences in test mechanics. (FS) is particularly sensitive to internal defects such as voids, incomplete wetting, and fiber agglomeration. These micro-structural inconsistencies initiate premature crack propagation during bending, which explains the decline observed at higher fiber concentrations. [3,7,20,33,38].

This helps explain why (IS) continued to increase at 9 wt.% despite the slight decline in flexural performance. Several additional factors may influence reinforcement effectiveness. Prior studies by Zidan, et al. [27] and Abdulazeez., et al 2023 [15] reported that mismatches between PMMA particle size and glass fiber diameter can generate voids that reduce strength. Zafar, [4], Alhotan, et al. [26] and Prajwala, et al. [39], indicated that fiber orientation, mixing technique, and resin viscosity during processing also affect final mechanical properties. From a clinical perspective, the improvement observed within the 5-7 wt.% range is highly relevant and meets the requirements for denture base polymers. Previous investigations have demonstrated that moderate fiber reinforcement enhances denture fracture resistance under functional loading [26,40,41]. Because SEGF can be incorporated without modifying standard laboratory procedures [42], this method offers a practical approach for strengthening PMMA dentures in routine prosthodontic practice. Overall, this study confirms that silane-treated SEGF significantly enhance both the flexural and impact strengths of PMMA denture base resin.

Limitations and Future Research

The limitation of this study is the absence of microscopic (SEM) analysis of the samples, including evaluation of interfacial bonding quality and void distribution, which are essential for understanding composite failure mechanisms. Future research will focus on investigating different fiber lengths and architectures, alternative surface treatments, hybrid nanoparticle–fiber systems, and advanced polymerization cycles to optimize reinforcement efficiency and improve the long-term performance of PMMA-based denture materials. In addition, advanced fabrication approaches, such as topology optimization [6] and three-dimensional (3D) printing techniques [44], as well as variations in fiber length and architecture reported in recent nanocomposite studies [7, 11, 17, 43], should be explored to further enhance the durability and clinical performance of fiber-reinforced PMMA.

Conclusion

This study demonstrated that incorporating silane-treated SEGF substantially enhances the mechanical performance of heat-polymerized PMMA denture base resin. The greatest improvements in flexural and impact strengths occurred at concentrations between 5-7 wt.%, confirming this range as the optimal reinforcement level. The mechanical enhancements are attributed to efficient interfacial bonding achieved through silane treatment, combined with effective stress transfer and crack-bridging mechanisms provided by the 3 mm fiber length. Although (IS) continued to improve at 9 wt.%, the slight reduction in (FS) at this concentration indicates that exceeding the optimal reinforcement threshold leads to fiber agglomeration and void formation, which diminish the composite's performance. Clinically, the 5-7 wt.% SEGF range offers a promising approach for increasing denture durability and reducing fracture risk without altering conventional processing techniques. Therefore, fiber reinforcement represents a clinically feasible and low-cost strategy to enhance denture longevity.

Author Contributions: "Abdulazeez: Conceptualization and methodology, writing original draft preparation, review editing and data collection. Abdulazeez and Alsateel: results' analysis and discussion. Both authors have read and agreed to the published version of the manuscript."

Funding: "This research received no external funding."

Data Availability Statement: "No data were used to support this study."

Acknowledgments: "The authors would like to express their sincere gratitude to the Faculty of Engineering, Mechanical Engineering Department at the (UOT) for the continuous support and facilities provided to complete this research, and especially to the technical staff in the department's laboratories for their invaluable assistance and efforts in conducting the necessary experiments and tests."

Conflicts of Interest: "The authors declare that they have no conflict of interest."

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