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Exploring Flexural Strength Variation in Polymeric Materials for Provisional Fixed Prosthetic Structures: Comparative Analysis with and without Reinforcement through Laboratory Experimentation and Statistical Evaluation

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Abstract: Provisional fixed partial dentures represent a critical phase in dental treatment, necessitating heightened mechanical durability, particularly in comprehensive and extended treatment plans. Strengthening these structures with various reinforcing materials offers a method to enhance their resilience. Utilizing a three-point testing methodology on standardized trial specimens allows for a comparative assessment of various materials and reinforcement techniques for pre-prosthetic applications. This study aims to validate and assess the significance of integrating different reinforcing materials into standardized test bodies. The study focuses on test specimens comprising three types of unreinforced laboratory and clinical polymers for provisional constructions ($n = 6$)—heat-cured PMMA (Superpont C+B, Spofa Dental, Czech Republic), CAD-CAM prefabricated PMMA (DD temp MED, Dental Direkt, Germany), CAD-CAM printing resin (Temporary CB Resin, FormLabs, USA), self-polymerizing PEMA (DENTALON plus, Kulzer, Germany), light-polymerizing composite (Revotek LC, GC, Japan), and dual-polymerizing composite (TempSpan, Pentron, USA). Additionally, laboratory polymers are evaluated in groups with five types of reinforcing filaments (n = 15)—Glass Fiber (Fiber Splint One-Layer, Polydentia, Switzerland), Polyethylene thread (Ribbond Regular 4.0 mm, Ribbond Inc., USA), triple-stranded chrome-cobalt wire for splinting 015″ (Leone S.p.a., Italy), Aesthetic ligature wire 012″ (Leone S.p.a., Italy), and Glass Fiber coated with light-cured composite 8.5 × 0.2 mm (Interlig, Angelus, Brazil). Analysis of the data using Generalized Linear Models (GLMs) reveals that the experimental bodies, produced via the subtractive digital method using PMMA (DD temp MED, Dental Direkt GmbH, Germany) as the polymer and glass filaments as the reinforcement, exhibit superior mechanical properties, particularly when pre-wetted with Interlig liquid composite (Angelus, Brazil).

Keywords: mechanical characteristics; dental polymers; provisional non-removable (fixed) prosthetics; provisional dental materials; reinforced provisional polymers

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1. Introduction

The commencement of provisional fixed prosthetics in cases of partial edentulism represents a crucial phase within the realm of prosthetic treatment. This stage necessitates structures endowed with heightened mechanical integrity, primarily due to the inclusion of one or more bridge abutments. Given the pivotal role it plays in ensuring a predictable and reliable treatment outcome, investing time and resources into the adoption of more sophisticated treatment protocols is fully justified [1]. For cases demanding an extended duration of provisional prosthetics, extending beyond the conventional timeframe of 1 month, certain experts advocate for the adoption of alternative approaches. These may include the utilization of indirect, direct–indirect, or even indirectly reinforced temporary structures. Such recommendations underscore the complexity and significance of achieving optimal outcomes in prosthetic treatment [2–5]. The diverse array of materials and technologies available for fabricating provisional constructions further underscores the need for a thorough investigation into the various methods and protocols employed for long-term provisional prosthodontics. This necessitates a comprehensive examination of both indirect and direct–indirect approaches, considering factors such as material properties, fabrication techniques, and clinical outcomes. By delving deeper into these methodologies, clinicians can optimize treatment strategies and enhance patient outcomes in the realm of prosthodontics [6].

As prototypes of permanent prosthetic structures, provisional restorations must adhere to rigorous standards concerning functionality, aesthetics, and preventive qualities, all while being efficiently fabricated to minimize time, labor, and costs. Despite the importance of these criteria, there remains a lack of consensus regarding the optimal methods and materials for their fabrication. Consequently, numerous studies have been conducted to compare various preprosthetic protocols against these criteria [7–11].

One of the predominant challenges encountered in the use of provisional restorations is the occurrence of fractures around the bridge bodies due to the functional loads they endure within the oral cavity. To address this issue, some researchers have proposed the method of reinforcing polymer structures with various filamentous materials to enhance their mechanical properties and resistance to fracture [12–14]. In the assessment of the mechanical properties of polymeric materials for pre-prosthetic applications, the three-point test method has emerged as a preferred technique in the literature. This method enables the determination of crucial parameters such as bending strength (FS), modulus of elasticity (E), and maximum loading force (Fmax), providing valuable insights into the material's mechanical behavior [14–16].

The testing of standardized test specimens for flexural strength serves as a reliable approach for comparing the mechanical resistance of different polymeric materials intended for preprosthetic use. By subjecting these specimens to standardized loading conditions, researchers can assess and evaluate the performance and durability of various materials, aiding in the selection of optimal materials for provisional restorations [17–31].

Testing standardized test specimens for flexural strength represents a crucial method for evaluating the mechanical resilience of various polymeric materials intended for pre-prosthetic applications. By subjecting these materials to standardized loading conditions, researchers can effectively compare their performance and durability [18,20–28,30–33].

Moreover, the comparison of different reinforcement strands for pre-constructions can be facilitated by positioning them uniformly within the cross-section of standardized test bodies. This exploratory approach is made possible through the utilization of a specialized device, registered as an industrial property (utility model), designed for fabricating test bodies from polymeric materials for crowns and veneers, with the capability of incorporating reinforcements [34].

The primary objective of this study was to conduct a comparative analysis of the physico-mechanical characteristics of modern materials utilized in the fabrication of provisional fixed prosthetic structures (PNPCs), both with and without reinforcing threads. The hypothesis posits that reinforcing these structures with metal threads, glass, or polypropylene fibers during manufacturing or repair processes for medium- and long-term provisional structures represents a cost-effective and efficient means to meet the elevated mechanical requirements essential for fulfilling their clinical functions.

2. Materials and Methods

The researchers conducted a comprehensive investigation wherein they examined and compared the strength properties of 1260 test specimens (OTs) comprising three distinct types of clinical dental polymers (light-cured, self-cured, and dual-cured) and laboratory dental polymers for PNPCs (heat-cured, factory-cured for subtractive manufacturing via CAD/CAM, light-cured for additive manufacturing via CAD/CAM) (Table 1).

Table 1. Distribution of the examined test specimens by material.

Group	N	Subgroup	N	Storage	N
Laboratory dense test specimens	180	Heat-cured PMMA Superpont C+B (Spofa Dental, Czech Republic)	60	Dry	30
				Aqua dest.	30
		CAD-CAM prefabricated PMMA (DD temp MED, Dental Direkt GmbH, Germany)	60	Dry	30
				Aqua dest.	30
		CAD-CAM printing resin (Temporary CB Resin, FormLabs, USA)	60	Dry	30
				Aqua dest.	30
Clinical dense test specimens	180	Self-polymerizing PEMA DENTALON plus (Kulzer, Germany)	60	Dry	30
				Aqua dest.	30
		Light-polymerizing composite (Revotek LC, GC, Japan)	60	Dry	30
				Aqua dest.	30
		Dual-polymerizing composite TempSpan (Pentron, USA)	60	Dry	30
				Aqua dest.	30

These specimens were reinforced using five different types of dental reinforcing threads (Table 2).

To produce the experimental bodies, each specimen required the placement of a single thread in the center, a process facilitated by a specialized device designed for fabricating experimental bodies from polymer materials for crowns and veneers. This device, registered as utility model No. 4383 U1 in the Patent Office of the Republic of Bulgaria, played a critical role in ensuring uniformity and precision during the fabrication process (Figure 1).

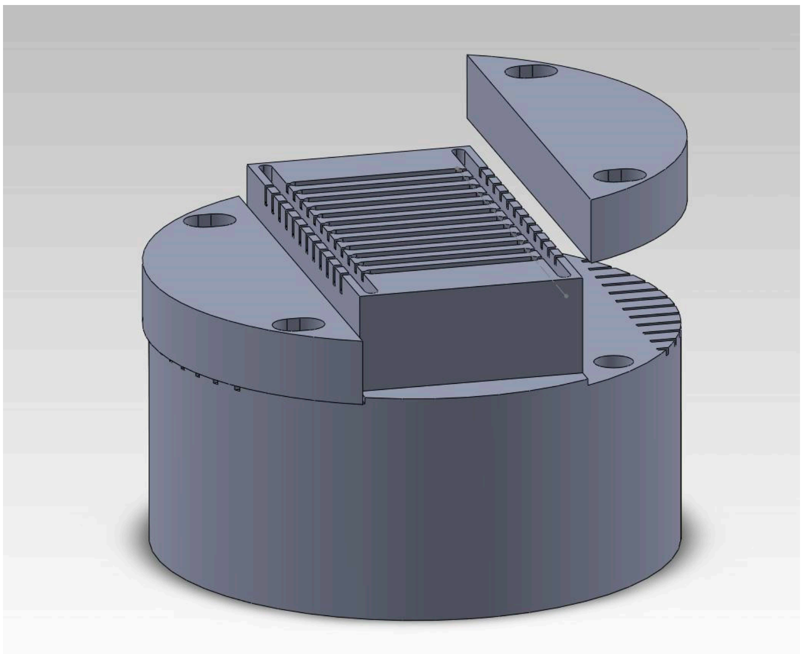


Figure 1. Preview of the appliance, utility model #4383 U1.

Table 2. Distribution of the examined test specimens by reinforcement.

Reinforcement	N	Polymer	N	Storage	N
Glass Fiber (Fiber Splint One Layer) (Polydentia, Switzerland)	180	HC—PMMA	60	Dry	30
				Aqua dest.	30
		CAD-CAM—PMMA	60	Dry	30
				Aqua dest.	30
		CAD-CAM resin	60	Dry	30
				Aqua dest.	30
Polyethylene thread Ribbond Regular 4.0 mm (Ribbond Inc., USA)	180	HC—PMMA	60	Dry	30
				Aqua dest.	30
		CAD-CAM—PMMA	60	Dry	30
				Aqua dest.	30
		CAD-CAM resin	60	Dry	30
				Aqua dest.	30
Triple-stranded chrome–cobalt wire for splinting 015″ (Leone S.p.a., Italy)	180	HC—PMMA	60	Dry	30
				Aqua dest.	30
		CAD-CAM—PMMA	60	Dry	30
				Aqua dest.	30
		CAD-CAM resin	60	Dry	30
				Aqua dest.	30
Aesthetic ligature wire 012″ (Leone S.p.a., Italy)	180	HC—PMMA	60	Dry	30
				Aqua dest.	30
		CAD-CAM—PMMA	60	Dry	30
				Aqua dest.	30
		CAD-CAM resin	60	Dry	30
				Aqua dest.	30
Glass Fiber coated with light-cured composite (Interlig, 8.5 × 0.2 mm) (Angelus, Brazil)	180	HC—PMMA	60	Dry	30
				Aqua dest.	30
		CAD-CAM PMMA	60	Dry	30
				Aqua dest.	30
		CAD-CAM resin	60	Dry	30
				Aqua dest.	30

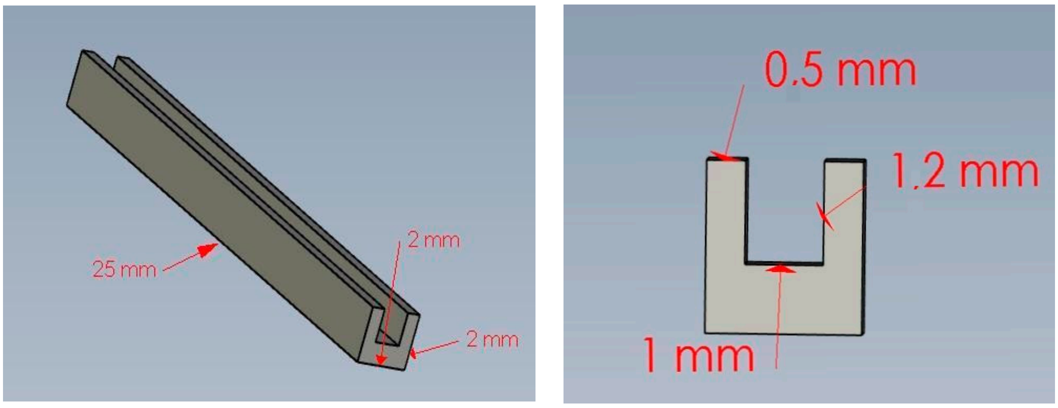
2.1. The Groups Categorized According to the Reinforcements of the Test Bodies Were Delineated as Follows

2.1.1. Control Group

This group comprised solid experimental bodies without any reinforcement, consisting of three clinical and three laboratory specimens.

2.1.2. Fiberglass Fiber Splint

Each thread of this reinforcement material, supplied by Polydentia, Switzerland, measured 200 cm in length, 4 mm in width, and 0.06 mm in thickness. From a single piece with a width of 4 mm, five threads of identical size (0.06 mm) were untwisted, as per the manufacturer's specifications. To utilize this material with the fabrication device, a length of 15 cm was required for each experimental body. To manufacture the experimental bodies, it was imperative to position a single thread in the center of each body using the aforementioned device. In the CAD design, as per ISO 10477:2020 standards [30], a longitudinal groove measuring 1.2 × 1 × 25 mm (depth/width/length) was provided on one side of each test specimen (Figure 2a,b). When incorporating filaments into the test fixtures fabricated via subtractive or additive CAM, the test specimens were oriented with the grooves (1 × 1.2 mm) facing upward. After cleaning, the filaments were inserted, tightened to ensure centered positioning, and then secured using a rebasing self-polymerizing material—Dentalon Plus. This assembly was pressed with a glass plate, subjected to a 1 kg weight, and allowed to polymerize for 10 min at room temperature.



(**a**) (**b**)

Figure 2. (**a**) A test specimen with a channel for manufacturing using CAM technologies; (**b**) cross section if the same object.

2.1.3. Polyethylene Thread—Ribbond Regular, Manufactured by Ribbond Inc., USA

Each thread was 22 cm in length, with a width of 4 mm and a thickness of 0.06 mm. From a single piece with a width of 4 mm, 10 threads of the same size, measuring 0.06 mm according to the manufacturer's specifications, were untwisted. For use with the instrument, a length of 15 cm was required for each experimental body. However, since they were packaged in lengths of 22 cm, this length was utilized.

2.1.4. Metal Multiwire Triple-Twisted Wire for Splinting, 015″, from Leone S.p.a., Italy

Each wire comes in a length of 35 cm with a diameter of 0.38 mm. The diameter was adequate for positioning in the center of the OT. To fit the instrument, a length of 15 cm was needed for each experimental body. However, as they are packaged in lengths of 35 cm, they were halved to 17 cm for use.

2.1.5. Aesthetic ligature Wire, 012″, from Leone S.p.a., Italy

Each wire is 30 cm in length with a diameter of 0.30 mm. The diameter was suitable for positioning in the center of the OT. To fit the instrument, a length of 15 cm was required for each experimental body. However, as they are packaged in lengths of 30 cm, they were cut in half to 15 cm for use.

2.1.6. Glass Filament Fiber Coated with Light-Cured Resin for Dental Use (Interlig from Angelus, Brazil)

Each filament measured 8.5 cm in length with a diameter of 0.2 mm. The package contained one strip of 5 intertwined threads with a diameter of 0.3 mm and a length of 8.5 mm. A diameter of 0.2 mm was sufficient for positioning in the middle of the OT. To use with the instrument, a length of 8.5 cm was required for each test body. These threads were unwound from the tape under minimal daylight illumination to prevent pre-polymerization of the liquid photopolymer resin.

2.2. Each Group of Test Specimens, Relative to the Reinforcement (n = 6), Was Further Subdivided into Three Groups of Laboratory Polymers Based on the Type of Activation of the Polymerization Reaction

2.2.1. Trial Bodies Made from Heat-Polymerizing PMMA (Superpont C+B, Spofa Dental, Czech Republic)

The manufacturing process involves several steps. Firstly, after cleaning the instrument and positioning the threads, the material for PNPCs (powder and liquid) is manually mixed according to the manufacturer's instructions. This mixture is then placed in the polymerization channels of the instrument and firmly pressed by hand with a glass tile, ensuring contact with the support and side boards of the channels. The pressing process is conducted on a powered vibrating table to prevent the inclusion of air pockets in the future Ots. Subsequently, the device, along with the glass tile, is transferred to a laboratory heat polymerizer (GAMA POLI, Bulgaria), where a polymerization cycle is initiated. This cycle involves a gradual heating and pressure increase until the water temperature reaches 100 °C, with a pressure of 2 bar applied for 30 min. Following the completion of the temperature cycle, the water is evacuated from the polymerization chamber of the apparatus, and a waiting period of 30 min ensues for gradual cooling of the apparatus with the OT. After removing the test bodies, the connections to the drainage channels are severed, and any excess polymerized material is carefully removed.

2.2.2. Trial Bodies Made from Factory-Polymerized PMMA for Subtractive Fabrication by CAD/CAM (DD Temp MED, Dental Direkt GmbH, Germany)

The design of the trial bodies, with dimensions of 2 × 2 × 25 mm and a longitudinal channel of 1 × 1.2 × 25 mm, was accomplished using Blender 2.8 software. Subsequently, ExoCAD v2.4 and the software of the CORiTEC® 350i CAM machine, manufactured by imes-icore GmbH, Germany, were utilized to mill the Ots. Upon release from the pins attaching them to the PMMA disk, the Ots were inspected using a caliper with an accuracy of 0.01 mm, and any necessary adjustments were made using a dental motor and milling cutter. The Ots were then arranged in the appliance, with threads stretched in the middle of each body and fixed ("backed") using a self-polymerizing material for PNPC (Dentalon Plus), prepared according to the manufacturer's instructions. The fixation was achieved by pressing the material with a glass plate onto the matrix, followed by clamping with a weight of 1 kg, and allowing it to polymerize for 10 min.

2.2.3. Experimental Bodies Fabricated from Light-Polymerizing Additive Manufacturing through CAD/CAM (Temporary CB Resin, FormLabs, USA) Were Also Included in the Study

The design of the trial bodies, with dimensions of 2 × 2 × 25 mm and a longitudinal channel of 1 × 1.2 × 25 mm, was conducted using Blender 2.8 software. Subsequently, ExoCAD v2.4 and FormLabs Inc.'s PreForm software were utilized to prepare the bodies for 3D printing of the specimens using stereolithography additive technology (SLA) in a Form 2 apparatus. As a post-polymerization treatment of the material, washing with isopropyl alcohol (95%) was performed in the Form Wash ultrasonic bath. This was followed by additional polymerization using the Form Cure photopolymerization oven, where the material was irradiated for 20 min at a temperature of 80 °C with ultraviolet light (wavelength 405 nm).

Following their release from the printer platform using a separator disk, the specimens were carefully examined using a caliper with an accuracy of 0.01 mm. Any necessary adjustments were made using a dental motor and milling cutter. Subsequently, the specimens were arranged in the appliance, and the threads were stretched in the middle of each body and secured ("backed") using a self-polymerizing material for provisional non-removable prosthetic constructions (PNPC), specifically Dentalon Plus. This material was prepared according to the manufacturer's instructions. A glass plate was then pressed onto the matrix, and the assembly was clamped with a weight of 1 kg. The specimens were left to polymerize for 10 min.

2.3. The Clinical Materials for the Test Specimens Were Exclusively Investigated as Solid Specimens in Three Distinct Groups

2.3.1. Test Bodies Fabricated from Self-Polymerizing PEMA DENTALON Plus (Kulzer, Germany)

Following the cleaning of the apparatus, the PNPC material (both powder and liquid components) was manually mixed according to the manufacturer's guidelines. Subsequently, the mixture was placed within the polymerization channels of the apparatus and firmly pressed by hand using a glass plate until it fully adhered to the sides of the channels. The glass plate was then pressed down with a weight of 1 kg until complete polymerization occurred, which typically took approximately 10 min. Upon removal of the test bodies, any connections to the drainage channels were severed, and any excess polymerized material was carefully trimmed away.

2.3.2. The Test Bodies Were Composed of Light-Cured Composite (Revotek LC, GC, Japan)

Following the apparatus's cleaning process, the PNPC material (composite with a doughy consistency) was deposited into the polymerization channels of the device. Subsequently, it was firmly pressed by hand using a glass plate until it adhered to the side edges of the channels. To prevent the inclusion of air pockets in the future test bodies, the pressing was conducted on a powered vibrating table. The apparatus, along with the glass plate, was then inserted into a laboratory light polymerizer, specifically the HiLight Power model (Kulzer, Germany), where polymerization occurred for a duration of 180 s. Afterward, the test bodies were removed from the apparatus, the connections to the drainage channels were severed, and any excess polymerized material was carefully trimmed away. Finally, each test body was calibrated to ISO 10477:2020 dimensions using a 0.01 mm caliper.

2.3.3. The Experimental Bodies Were Comprised of Double-Polymerizing TempSpan (Pentron, USA)

After cleaning the instrument, the PNPC material (a two-component composite in a cartridge, extruded through a mixing nozzle in a 1:1 ratio) was dispensed into the polymerization channels of the device. Subsequently, it was firmly pressed by hand using a glass plate until it adhered to the side walls of the channels. To prevent the inclusion of air pockets in the future test bodies, the pressing was conducted on a powered vibrating table. The apparatus, along with the glass plate, was then inserted into a laboratory light polymerizer, specifically the HiLight Power model (Kulzer, Germany), where polymerization occurred for a duration of 180 s. After removing the test bodies from the apparatus, the connections to the drainage channels were severed, and any excess polymerized material was carefully trimmed away.

Each test body was calibrated to ISO 10477:2020 dimensions using a 0.01 mm caliper.

Following the creation of all sub-groups' (N = 21) test specimens, half of the test specimens from each sub-group (N = 30) were stored in distilled water at room temperature for 24 h.

2.4. Three-Point Flexural Tests

The flexural tests were performed using a universal testing machine (MultiTest 2.5-I, Mecmesin Ltd., UK) calibrated to provide a constant cross-head speed of (1.0 +/− 0.3) mm/min and loading rate of (50 +/− 16) N/min. The radius of the support rollers and the loading was 2 mm and the distance between the centers of the rollers was 20 mm. The mechanical tests were conducted at room temperature (23 ± 2 °C) and 50 ± 5% relative humidity.

2.5. Statistical Methods

The statistical programs IBM SPSS Statistics for Windows (Version 27.0, 2020) and Minitab (21.4, 2023) were used for the analysis and graphical representation of the data.

The physical and mechanical characteristics of the laboratory and clinical test fixtures made of dental composites for non-removable prosthetic constructions (PNPCs) represent the dependent variables in this analysis, including (1) flexural strength (FS/MPa); (2) maximum force before fracture (Fmax/N); and (3) modulus of elasticity (E/MPa).

The influence of the independent variables' reinforcement, polymer material, and storage method was investigated using the Generalized Linear Models (GLMs) method, which allows the effect of one independent variable to be analyzed while statistically controlling for the effect of the remaining ones. The measures of central tendency were represented by the estimated marginal means (ESMs) and corresponding standard deviations (SDs).

The physico-mechanical characteristics were influenced by several independent variables, including reinforcement type, polymer material, and storage method. To analyze the impact of each independent variable while controlling for the others, the Generalized Linear Models (GLMs) method was employed. The GLM allows for the assessment of the influence of one independent variable while accounting for the effects of the other variables simultaneously.

Following the testing of the overall effect of the independent variables, a pairwise post hoc analysis was conducted using the Bonferroni multiple comparison test. This analysis aimed to identify statistically significant differences between the various categories within each independent variable. For instance, in the case of reinforcement type, six categories were considered: (1) without reinforcement; (2) Fiberglass (Fiber Splint Polydentia One Layer); (3) Polyethylene thread (Ribbond Regular, 4.0 mm); (4) Metal multiwire triple-twisted wire for splinting (Leone, 015″); (5) Aesthetic ligature wire (Leone S.p.a. 012″); and (6) Fiberglass thread coated with light-cured composite (Interlig, Angelus, 8.5 × 0.2 mm). Through GLM analysis, it was determined whether the type of reinforcement significantly affected the physico-mechanical characteristics of the test specimens.

In the post hoc pairwise analysis, each type of reinforcement was systematically compared against the others to identify significant differences. Specifically, each reinforcement type was matched with all other types, resulting in a total of 15 pairwise comparisons. For instance, type 1 was compared with types 2, 3, 4, 5, and 6 (five comparisons), followed by type 2 being compared with types 3, 4, 5, and 6 (four comparisons), and so forth. This process ensured a comprehensive assessment of the impact of reinforcement type on the observed outcomes.

Similarly, an analogous post hoc pairwise analysis was conducted for polymer species, involving six species and resulting in 15 pairwise comparisons. However, for the storage method variable, which comprised two categories, a pairwise post hoc analysis was unnecessary. The main trends and significant differences identified through these analyses were visually represented using interval plots depicting the means and individual values.

All statistical analyses were conducted with a predetermined Type I error level of alpha = 5%. The results were deemed statistically significant if $p < 0.05$, indicating a high level of confidence in the observed effects.

3. Results

3.1. The Statistical Processing Using the Generalized Linear Models (GMLs) Method Revealed the Influence of Different Types of Reinforcement on the Physico-Mechanical Characteristics of Laboratory and Clinical Test Specimens Made of Dental Composites

The independent variable "reinforcement" was categorized as follows:

- ➢ Without reinforcement;
- ➢ Fiberglass thread (Fiber Splint Polydentia One Layer);
- ➢ Polyethylene thread (Ribbond Regular, 4.0 mm);
- ➢ Metal multiwire triple-twisted splint wire (Leone, 015″);
- ➢ Aesthetic ligature wire (Leone S.p.a., 012″);
- ➢ Fiberglass thread coated with light-cured composite (Interlig, Angelus, 8.5 × 0.2 mm).

The results present adjusted average values (estimated marginal means) after accounting for the effects of polymer type and storage method. Figures 3–5 depict graphical representations of the average values in descending order, along with the distribution of individual measurements for each type of reinforcement. These visualizations provide insights into the relative performance of different reinforcement types across various physico-mechanical characteristics.

3.1.1. Flexural Strength (FS/MPa)

The statistical analysis revealed a significant effect of the type of reinforcement on flexural strength (FS/MPa), with a *p*-value of <0.001. Among the various reinforcement types, Fiberglass thread coated with the light-cured composite (Interlig, Angelus, 8.5 × 0.2 mm) exhibited the highest flexural strength (82.82 ± 16.76 MPa), while composites without reinforcement showed the lowest flexural strength (68.30 ± 13.15 MPa).

The flexural strengths of the reinforcement types, arranged in descending order, are as follows (Figure 3):

- Fiberglass thread (Fiber Splint Polydentia One Layer): 79.65 ± 12.79 MPa;
- Polyethylene thread (Ribbond Regular 4.0 mm): 79.25 ± 11.80 MPa;
- Metal multiwire triple-twisted splinting wire (Leone, 015″): 75.35 ± 11.09 MPa;
- Aesthetic ligature wire (Leone S.p.a., 012″): 69.05 ± 9.45 MPa.

Out of the 15 pairwise comparisons conducted between individual reinforcement categories, 13 showed significant differences, with significance levels between $p > 0.05$ and $p > 0.001$, according to the Bonferroni test. However, two comparisons with similar mean values did not show significant differences: (1) Fiberglass thread (Fiber Splint Polydentia One Layer) and Polyethylene thread (Ribbon Regular 4.0 mm) ($p = 0.935$); (2) Aesthetic ligature wire (Leone S.p.a., 012”) and no reinforcement ($p = 0.648$).

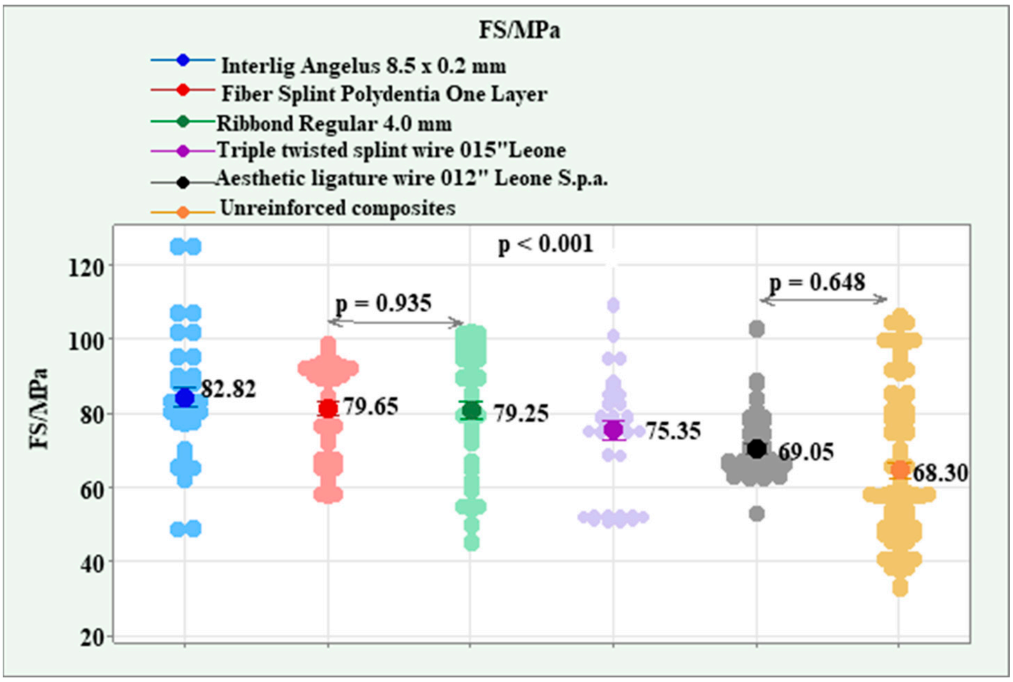


Figure 3. Effect of reinforcement types on flexural strength (FS/MPa).

3.1.2. Maximum Force before Fracture (Fmax/N)

The analysis of the maximum force before fracture (Fmax/N) revealed patterns similar to those observed for flexural strength (FS/MPa). Firstly, there was a significant overall effect of reinforcement on Fmax/N, with a *p*-value of <0.001. Once again, Fiberglass thread coated with the light-polymerizing composite (Interlig, Angelus, 8.5 × 0.2 mm) demonstrated the highest Fmax/N value (22.10 ± 4.49 N), while composites without reinforcement exhibited the lowest (18.21 ± 5.50 N).

The ordering of reinforcement types based on average Fmax/N values was as follows (Figure 4):

- ➢ Fiberglass thread (Fiber Splint Polydentia One Layer): 21.24 ± 3.41 N;
- ➢ Polyethylene thread (Ribbond Regular, 4.0 mm): 21.13 ± 4.49 N;
- ➢ Metal multiwire triple-twisted wire for splinting (Leone, 015″): 19.69 ± 4.89 N;
- ➢ Aesthetic ligature wire (Leone S.p.a., 012″): 18.21 ± 2.53 N.

Out of the 15 pairwise comparisons conducted, 13 showed significant differences between reinforcement types, with significance levels ranging from $p < 0.05$ to $p < 0.001$, according to the Bonferroni test. However, two comparisons revealed similar mean values of Fmax/N and therefore showed no significant differences: (1) Fiberglass thread (Fiber Splint Polydentia One Layer) and Polyethylene thread (Ribbond Regular, 4.0 mm) (p = 0.825); (2) Aesthetic ligature wire (Leone S.p.a., 012″) and no reinforcement (p = 0.694).

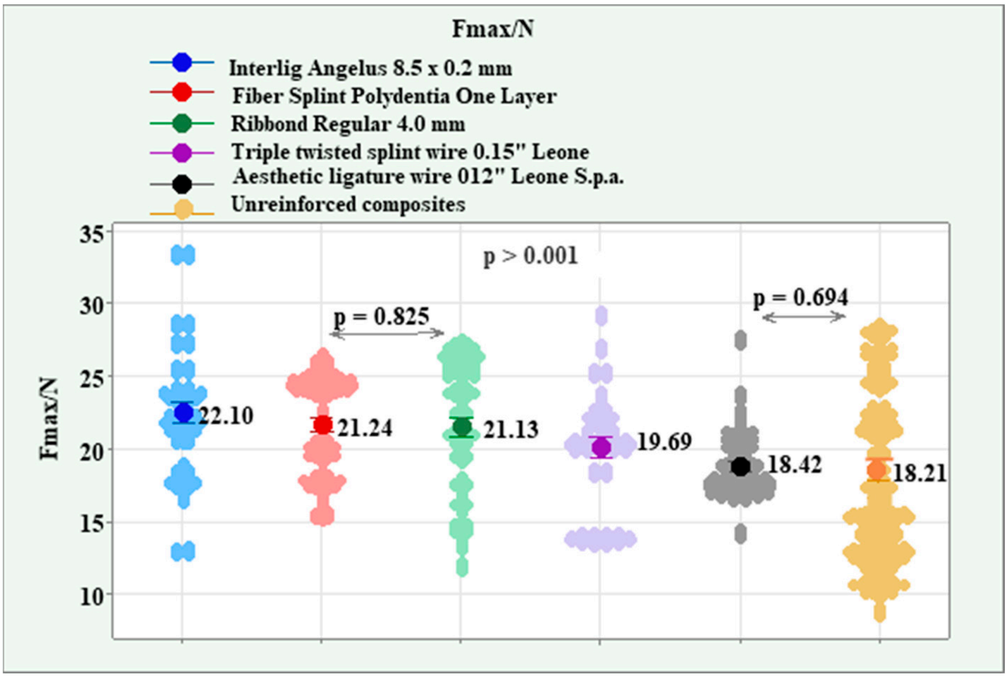


Figure 4. Effect of reinforcement types on maximum strength before fracture (Fmax/N).

3.1.3. Modulus of Elasticity (E/MPa)

The analysis of the modulus of elasticity (E/MPa) revealed a significant overall influence of the reinforcement factor, with a p-value of <0.001. The highest average value was observed for Fiber Splint Polydentia One Layer (8823.77 ± 1456 MPa), while composites without reinforcement exhibited the lowest (7091.05 ± 1848 MPa).

The ordering of reinforcement types based on average modulus of elasticity values was as follows (Figure 5):

- ➢ Fiberglass thread (Fiber Splint Polydentia One Layer): 8823.77 ± 1456 MPa;
- ➢ Polyethylene thread (Ribbond Regular, 4.0 mm): 8159.59 ± 1446 MPa;
- ➢ Fiberglass thread coated with light-cured composite (Interlig, Angelus, 8.5 × 0.2 mm): 8076.73 ± 972 MPa;
- ➢ Metal multiwire triple-twisted splinting wire (Leone, 015″): 7796.42 ± 999 MPa;
- ➢ Aesthetic Ligature Wire (Leone S.p.a., 012″): 7230.31 ± 647 MPa.

Out of the 15 pairwise comparisons conducted, 13 showed significant differences between reinforcement types, with significance levels ranging from $p < 0.05$ to $p < 0.001$, according to the Bonferroni test. However, two comparisons revealed similar mean values of a modulus of elasticity and therefore showed no significant differences: (1) Polyethylene thread (Ribbond Regular, 4.0 mm) and Fiberglass thread coated with light-cured composite

(Interlig, Angelus, 8.5 × 0.2 mm) (p = 0.572); (2) Aesthetic ligature wire (Leone S.p.a., 012″) and no reinforcement (p = 0.618).

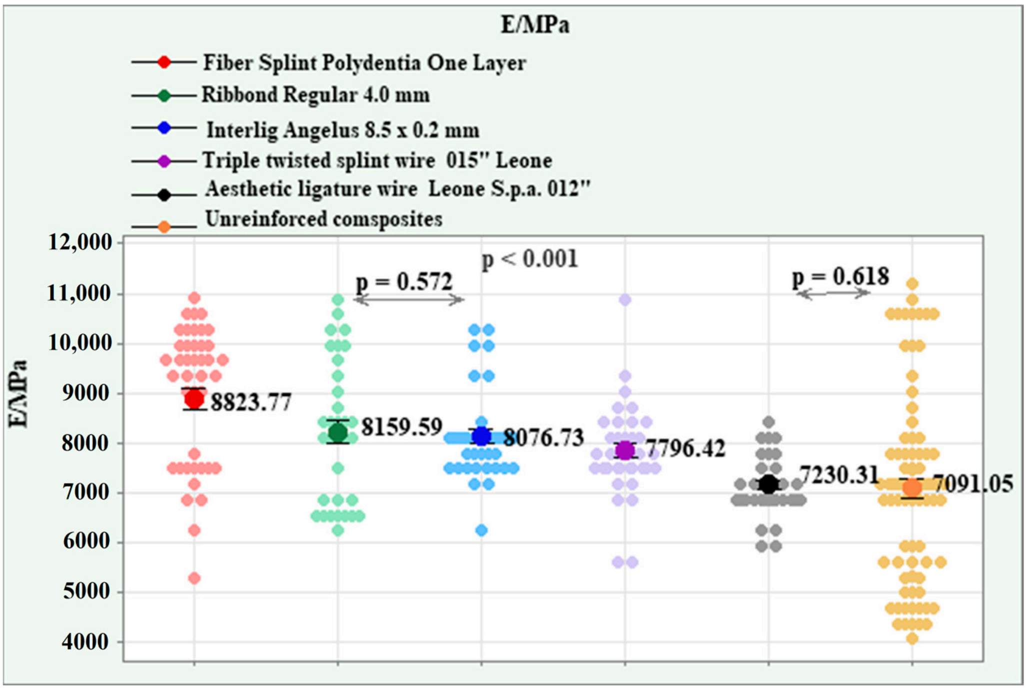


Figure 5. Effect of reinforcement types on modulus of elasticity (E/MPa).

3.2. Influence of Polymer Material on Physico-Mechanical Characteristics

The analysis investigated the influence of different polymer materials on the physico-mechanical characteristics of laboratory and clinical test specimens of dental composites. The independent variable, polymer material, was categorized as follows:

- ➢ Heat-cured PMMA (Superpont C+B, Spofa Dental, Czech Republic);
- ➢ Factory polymerized for subtractive fabrication via CAD/CAM PMMA (DD temp MED, Dental Direkt GmbH, Germany);
- ➢ Light-cured for additive manufacturing via CAD/CAM (Temporary CB Resin, Form-Labs, USA);
- ➢ Self-polymerizing PEMA (DENTALON plus, Kulzer, Germany);
- ➢ Light-cured composite (Revotek LC, GC, Japan);
- ➢ Light- and self-cured (dual-cured) (TempSpan, Pentron, USA).

The results presented are adjusted average values (estimated marginal means) after controlling for the effects of reinforcement type and storage method. Figures 6–8 illustrate graphs displaying the mean values in descending order, along with the distribution of individual dimensions for each type of polymer material.

3.2.1. Flexural Strength (FS/MPa)

The statistical analysis revealed a significant relationship between the type of polymer material and flexural strength (FS/MPa), with a p-value < 0.001 (Figure 6). The highest FS/MPa value (83.56 ± 15.35) was observed for the factory polymerized material (CAD/CAM PMMA, DD temp MED, Dental Direkt GmbH, Germany).

Conversely, the lowest FS/MPa value (40.16 ± 4.59) was found for the light-cured composite (Revotek LC, GC, Japan). In descending order between these extremes were the following materials (Figure 6):

- ➢ Light-curedfor additive manufacturing via CAD/CAM Temporary CB Resin, Form-Labs, USA (80.11 ± 14.69);
- ➢ Heat-cured PMMA (Superpont C+B, Spofa Dental, Czech Republic) (73.13 ± 17.08);

- ➢ Light- and self-cured (dual-cured) TempSpan, Pentron, USA (55.13 ± 5.43);
- ➢ Self-polymerizing PEMA (DENTALON plus, Kulzer, Germany) (40.16 ± 4.59).

All 15 comparisons exhibited significant differences between polymer material types, with p-values < 0.001 for 13 comparisons and p-values < 0.01 for 2 comparisons.

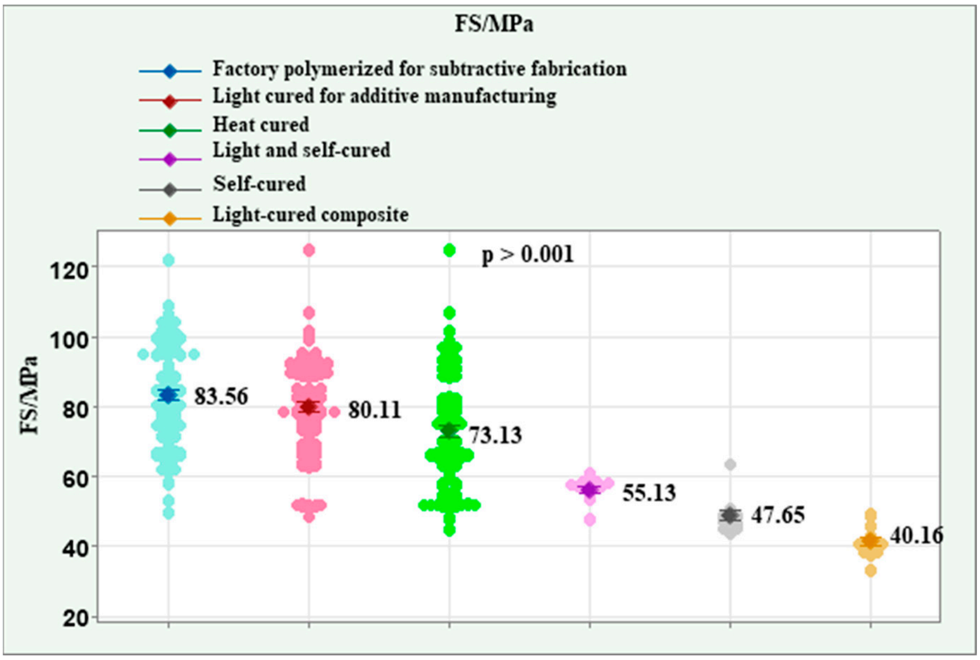


Figure 6. Effect of polymer types on flexural strength (FS/MPa).

3.2.2. Maximum Force before Fracture (Fmax/N)

This type of polymer exhibited a significant impact on the maximum force before fracture (Fmax/N), with a p-value < 0.001. The results mirror those of FS/MPa.

Once again, the highest Fmax/N value (22.29 ± 4.09) was observed with the factory polymerized material (CAD/CAM PMMA, DD temp MED, Dental Direkt GmbH, Germany). Conversely, the lowest value (10.71 ± 1.04) was attributed to the light-cured composite (Revotek LC, GC, Japan). In descending order between these extremes were the following materials (Figure 7):

- ➢ Light-cured for additive manufacturing via CAD/CAM (Temporary CB Resin, FormLabs, USA) (21.36 ± 3.92);
- ➢ Heat-cured PMMA (Superpont C+B, Spofa Dental, Czech Republic) (19.50 ± 4.56);
- ➢ Light- and self-cured (dual-cured) (TempSpan, Pentron, USA) (14.70 ± 0.95);
- ➢ Self-polymerizing PEMA (DENTALON plus, Kulzer, Germany) (12.68 ± 1.47).

All 15 comparisons demonstrated significant differences between polymer material types at $p \leq 0.001$.

3.2.3. Modulus of Elasticity (E/MPa)

The type of polymer material exhibited a significant association with the modulus of elasticity (E/MPa), with a p-value < 0.001. Unlike the previous dimensions, the highest value of E/MPa (8823.12 ± 358) was observed for the heat-polymerizing material (PMMA Superpont C+B, Spofa Dental, Czech Republic).

On the other hand, the lowest value (4539.37 ± 83.50) was again attributed to the light-cured composite (Revotek LC, GC, Japan).

The remaining polymer types demonstrated the following average values of E/MPa, (Figure 8):

- ➢ Light-cured for additive manufacturing via CAD/CAM (Temporary CB Resin, Form-Labs, USA) (7875.25 ± 353);
- ➢ Factory polymerized material (CAD/CAM PMMA, DD temp MED, Dental Direkt GmbH, Germany) (7631.24 ± 352);
- ➢ Light- and self-cured (Dual-cured) (TempSpan, Pentron, USA) (6940.81 ± 83.50);
- ➢ Self-polymerizing PEMA DENTALON plus (Kulzer, Germany) (5758.24 ± 83.30).

All 15 pairwise comparisons demonstrated significant differences between polymer material types at $p \leq 0.001$.

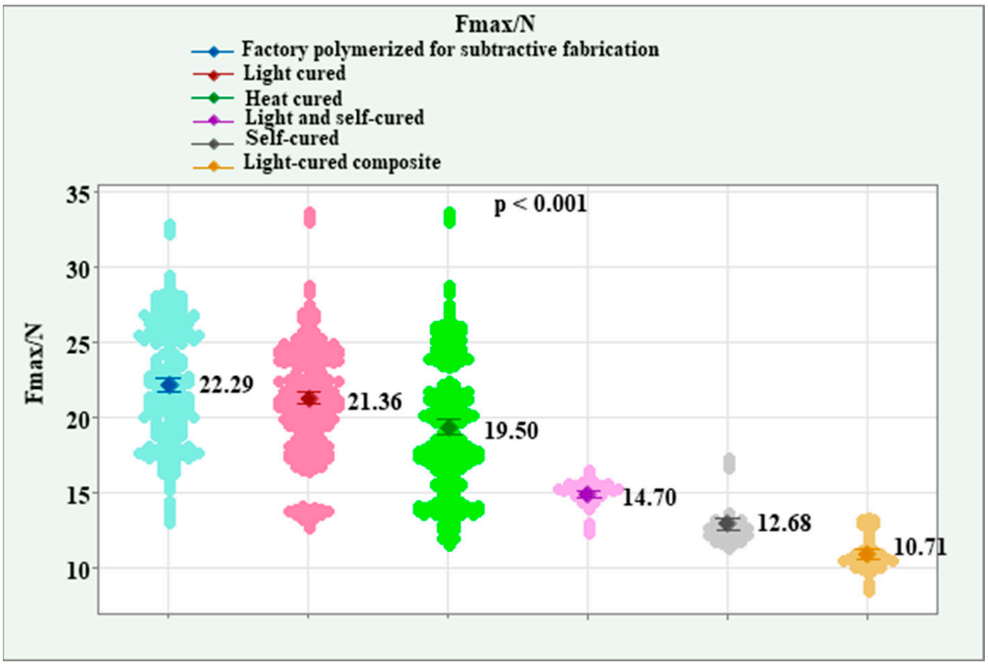


Figure 7. Effect of polymer types on maximum strength before fracture (Fmax/N).

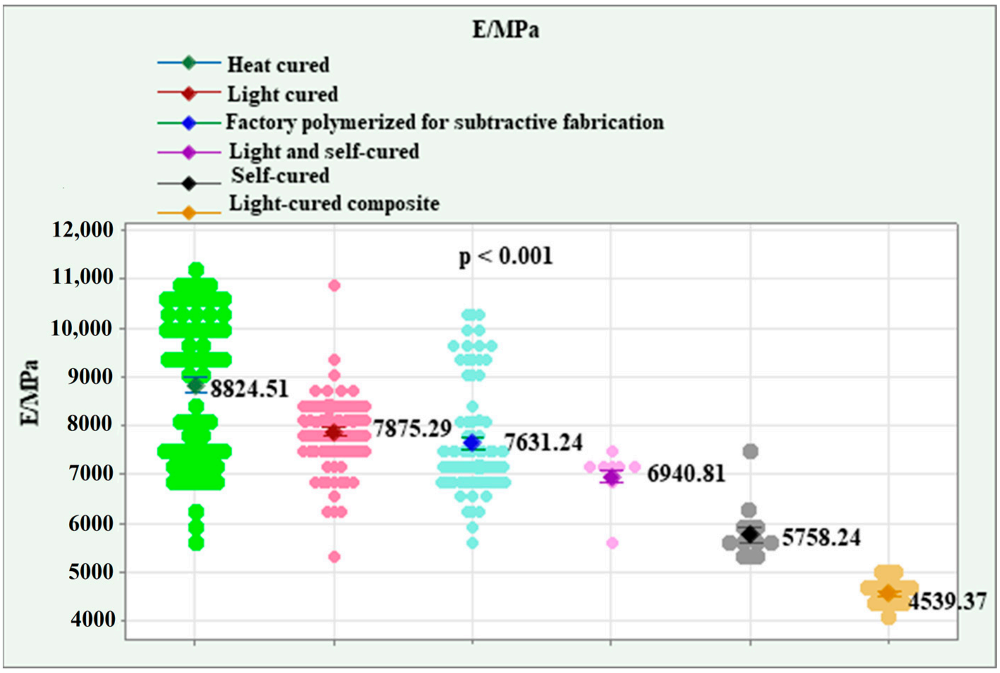


Figure 8. Effect of polymer types on modulus of elasticity (E/MPa).

3.3. Influence of the Method of Storage on Physico-Mechanical Characteristics

The method of storage serves as the third independent variable, comprising two conditions:

➢ Storage at room temperature;
➢ Storage in distilled water at room temperature.

The storage method did not have a large effect on the physico-mechanical properties that were studied (p = 0.226 for FS/MPa, p = 0.229 for Fmax/N, and p = 0.064 for E/MPa). This was after statistical control was applied to the effects of the other two variables (reinforcement and polymer). All three indicators exhibited similar values for both storage methods, as depicted in Table 3.

Table 3. Influence of the method of storage on the physico-mechanical characteristics of laboratory and clinical test specimens of dental composites.

Physico-Mechanical Characteristics	Storage at Room Temperature Estimated Marginal Mean (SD)	Storage in Distilled Water at Room Temperature Estimated Marginal Mean (SD)	p-Value
Flexural strength (FS/MPa)	75.06 (17.96)	73.87 (19.23)	0.226
Maximum force before fracture (Fmax/N)	20.017 (4.80)	19.70 (5.13)	0.229
Modulus of elasticity (E/MPa)	7855 (1530)	7689 (1522)	0.064

The estimated marginal mean is the arithmetic mean value after correction for the influence of the type of reinforcement and the type of polymer.

3.4. Summary of the Main Trends

The present study found a significant influence of the type of reinforcement and the type of polymer material on the physico-mechanical characteristics of laboratory and clinical test specimens of dental composites, including flexural strength (FS/MPa), maximum force before fracture (Fmax/N), and modulus of elasticity (E/MPa). On the other hand, the method of storage did not show a significant influence on the physico-mechanical characteristics. Table 4 provides a summary of the main trends observed for different types of reinforcements in terms of flexural strength (FS/MPa), maximum force before fracture (Fmax/N), and modulus of elasticity (E/MPa). Notably, when controlling for the type of polymer material, optimal values for flexural strength and maximum force before fracture were consistently associated with specific types of reinforcement.

Table 4. Main trends regarding the physico-mechanical characteristics of the test specimens according to the type of reinforcement.

Main Trends	Reinforcement
Flexural strength (FS/MPa) and maximum strength before fracture (Fmax/N)	
Highest values	➢ Fiberglass thread coated with light-cured composite (Interlig, Angelus, 8.5 × 0.2 mm)
Second largest values	➢ Fiberglass strand (Fiber Splint Polydentia One Layer) ➢ Polyethylene thread (Ribbond Regular, 4.0 mm)
Elasticity (E/MPa)	Reinforcement
Highest values	➢ Fiberglass thread (Fiber Splint Polydentia One Layer)
Second largest values	➢ Polyethylene thread (Ribbond Regular, 4.0 mm) ➢ Fiberglass thread coated with light-cured composite (Interlig, Angelus, 8.5 × 0.2 mm)

Table 5 summarizes the main trends for the types of polymer materials regarding flexural strength (FS/MPa), ultimate strength before fracture (Fmax/N), and elasticity ((E/MPa). Similar to the type of reinforcement, flexural strength (FS/MPa) and maximum strength before fracture (Fmax/N) showed optimal values for the same type of polymers when the effect of the type of reinforcement was statistically controlled.

Table 5. Summary of the main trends regarding the physico-mechanical characteristics of the test specimens according to the type of polymer material.

Main Trends	Polymeric Material
Flexural strength (FS/MPa) and maximum strength before fracture (Fmax/N)	
Highest values	➢ Factory polymerized material CAD/CAM PMMA (DD temp MED, Dental Direkt GmbH, Germany)
Second largest values	➢ Light-cured for additive manufacturing CAD/CAM (Temporary CB Resin, FormLabs, USA) ➢ Heat-polymerizing PMMA (Superpont C+B, Spofa Dental, Czech Republic)
Elasticity (E/MPa)	Polymeric material
Highest values	➢ Heat-polymerizing material PMMA (Superpont C+B, Spofa Dental, Czech Republic)
Second largest values	➢ Light-cured for additive manufacturing CAD/CAM (Temporary CB Resin, FormLabs, USA) ➢ Factory polymerized material CAD/CAM PMMA (DD temp MED, Dental Direkt GmbH, Germany)

The comparison of the strength properties (compressive strength, ultimate strength before fracturing, and elastic modulus) of the test specimens of three types of laboratory dental polymers for PNPCs (heat-cured, factory-cured for subtractive manufacturing by CAD/CAM, light-cured for additive manufacturing by CAD/CAM) and three types of clinical dental polymers for PNPCs (self-polymerizing, light-polymerizing, light- and self-polymerizing (double-polymerizing)) showed the following three polymer materials as yielding the best characteristics:

- ➢ Factory-polymerized PMMA material for subtractive CAD/CAM fabrication (DD temp MED, Dental Direkt GmbH, Germany): this material exhibited the best mechanical properties with a flexural strength (FS) of 83.56 ± 15.35 MPa, maximum force before fracturing (Fmax) of 22.29 ± 4.09 N, and an elastic modulus (E) of 7631.24 ± 352 MPa.
- ➢ Light-cured material for additive manufacturing by CAD/CAM (Temporary CB Resin, FormLabs, USA): this material demonstrated strong mechanical properties, with a flexural strength of 80.11 ± 14.69 MPa, maximum force before fracturing of 21.36 ± 3.92 N, and an elastic modulus of 7875.25 ± 353 MPa.
- ➢ Heat-polymerizing PMMA (Superpont C+B by Spofa Dental, Czech Republic): despite being slightly lower in performance compared to the top two materials, it still showed notable mechanical properties, with a flexural strength of 73.13 ± 17.08 MPa, maximum force before fracturing of 19.50 ± 4.56 N, and an elastic modulus of 8823.12 ± 358 MPa.

The clinical materials for PNPCs were ranked lower and therefore do not appear in the top three materials.

In terms of reinforcement materials, the arrangement of reinforcing strands separately in descending order is as follows:

1. Glass thread coated with light-cured composite (Interlig, 8.5 × 0.2 mm) (Angelus, Brazil) (FS = 82.82 ± 16.76 MPa; Fmax = 22.10 ± 4.49 N; E = 8076.73 ± 972);
2. Fiber Splint One Layer (Polydentia, Switzerland) (FS = 79.65 ± 12.79 MPa; Fmax = 21.24 ± 3.41 N; E = 8823.77 ± 1456);

3. Polyethylene thread (Ribbond Regular) (Ribbond Inc., USA) 4.0 mm (FS = 79.25 ± 11.80 MPa; Fmax = 21.13 ± 4.49 N; E = 8159.59 ± 1446).

We explain the results of the reinforcing threads with the better adhesion of the glass threads, previously moistened with a liquid composite, to the polymers for PNPCs.

4. Discussion

Alt et al. [6] investigated the bending quality of provisional bridge structures made on the same matrix but using different materials—conventional ones like PMMAs and composites, as well as PMMA discs manufactured via CAD/CAM technology. They found better maximum fracture force (Fmax) indicators for CAD/CAM PMMAs compared to conventionally made PMMAs, which is confirmed by the data from our laboratory study. In conclusion, the authors mention that, due to the clear advantages of composite materials over PMMAs, it is necessary to develop composite blanks for CAD/CAM milling of provisional structures. This could lead to an improvement in the quality and efficiency of dental constructions, while utilizing more modern and advanced materials and technologies.

In a laboratory study from 2014, Yao et al. [30] compared the bending strength of experimental bodies according to ISO 10477 and the marginal accuracy of provisional crowns made from clinical composite materials for provisional structures with CAD/CAM PMMA (Teilo CAD) and composite material (VITA CAD-Temp). As a result of the investigation, the authors noted the best bending strength indicators for the CAD/CAM PMMA material and the lowest for the composite CAD/CAM material, while digitally fabricated ones exhibited better accuracy. These results, as indicated by the authors, have been confirmed by our laboratory study [30]. Rayyan et al. [32] compared the physical and mechanical qualities (color stability, water absorption, wear resistance, surface hardness, fracture resistance, and microleakage) of CAM-milled crowns made from PMMA with conventional materials for the manual fabrication of provisional structures. The authors found that milled crowns outperformed those made from manual fabrication materials in all aspects except microleakage (where staining does not penetrate any experimental body). They came to the conclusion that CAD/CAM-produced provisional structures exhibited stable physical and mechanical qualities and could be used for long-term provisional constructions. Our results support Rayyan et al.'s conclusions [32].

Alp et al. [33] conducted a laboratory study on the bending strength of experimental bodies according to ISO 10477 using five materials for provisional structures: three CAD/CAM PMMA blanks, one composite, and one conventional PMMA. The authors concluded that the experimental bodies made from CAD/CAM PMMA materials demonstrated higher bending strength values than the composite material, which in turn exhibited higher values than the conventional PMMA. This ranking of materials was confirmed by the data obtained in our laboratory study. In a similar laboratory investigation, Al-Dwairi et al. [35] examined the bending strength, impact strength, and modulus of elasticity of experimental bodies according to ISO 20795 using two types of CAD/CAM PMMAs and one conventional PMMA. Although the study focused on PMMAs for removable prosthodontics, the results align with those of our laboratory study, indicating that subtractive milling methods for pre-cross-linked polymerized PMMAs exhibit the highest mechanical qualities [35].

Abad-Coronel et al. [36] conducted a comparative study between materials for additive and subtractive CAD/CAM provisional prosthodontics. They compared provisional bridge structures made from a single CAD model using CAM milling from PMMAs and 3D printing via rapid prototyping technology. The subtractively manufactured experimental structures exhibited higher values in bending strength tests, which is consistent with the findings of our laboratory investigations.

In a laboratory study from 2022, Pantea et al. [26] compared the compressive strength and bending strength of test specimens made from materials for provisional non-permanent prosthodontics—self-polymerizing PMMA, heat-polymerizing PMMA, and a composite resin for DLP (digital light processing) 3D printing. The printed experimental specimens showed higher elasticity modulus results than the conventional ones, which was also confirmed in our laboratory research.

Mai et al. [37] and Bae et al. [38] found that constructions made with additive methods (SLS, SLA, and PolyJet) were more accurate than those made with subtractive methods.

In 2019, Jasim [39] compared the flexural strength, through three-point bending testing, of provisional bridge constructions made using analog and digital (subtractive) CAD/CAM methods. The better outcomes in the digital method's experimental samples led the author to recommend CAD/CAM subtractive methods for long-term provisional prosthetic treatments and constructions with multiple bridge units.

In a systematic review and meta-analysis of comparative studies between subtractive CAD/CAM materials for provisional non-permanent prosthodontics (PNPCs) and conventional materials, Jain et al. concluded that 3D-printed provisional crowns and materials for removable prosthetics could be used as an alternative to long-term conventional and CAD/CAM subtractive materials [40,41].

5. Conclusions

The present research on the mechanical properties of current materials used in the fabrication of provisional constructions, with or without reinforcement, in dental prosthetics holds significant value for clinical practice, especially in cases of medium- and long-term temporary prosthetic treatments. Moreover, such scientific contributions are lacking, at least to our knowledge.

The selected data subjected to detailed statistical analysis from the present study provide an objective opportunity to systematize a large volume of information. The results obtained through the Generalized Linear Models (GLMs) method indicate that the best mechanical qualities are exhibited by test specimens made using the subtractive digital method with PMMA (DD temp MED, Dental Direkt GmbH, Germany) as the polymer. They are followed by specimens made from light-polymerizing material for additive manufacturing via CAD/CAM (Temporary CB Resin, FormLabs, USA). In terms of the investigated criteria, the heat-polymerizing PMMA Superpont C+B (Spofa Dental, Czech Republic) ranks third.

The best mechanical performance was seen in specimens reinforced with Fiber Splint One Layer (Polydentia, Switzerland), followed by those reinforced with Glass Fibers pretreated with the Interlig composite (Angelus, Brazil). The Ribbond Regular polyethylene fiber (Ribbond Inc., USA) ranked third among the reinforcements of the investigated specimens.

The study demonstrates that reinforcing polymers for provisional laboratory constructions is an accessible and effective way to meet the increased demands for their mechanical qualities. This is particularly significant in cases of medium- and long-term provisional prosthetic treatments where enhanced mechanical resilience of the constructions is required.

6. Patents

Utility model registration certificate number: 4383 U1.

Name: "Apparatus for the production of experimental bodies from polymer materials for crowns and veneers with the possibility of reinforcement".

Author Contributions: Conceptualization, M.D.-G. and I.T.; methodology, T.U.; software, I.G.; validation, T.U. and A.G.; formal analysis, D.S.; investigation, A.G. and S.R.; resources, I.G.; data curation, I.G.; writing—original draft preparation, I.T. and S.R.; writing—review and editing, A.G. and D.S.; visualization, I.T.; supervision, M.D.-G. project administration, T.U. and D.S.; funding acquisition, M.D.-G. and S.R. All authors have read and agreed to the published version of the manuscript.

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