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Research Article

Flexual Strength And Artificial Aging Of 3d Printable Permanent Restoration Reinforced With Zirconium Oxide And Magnesium Oxide.

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Abstract: Background: The long-term mechanical performance of printed resin materials is a concern, and the importance of three-dimensional (3D) printing in restorative dentistry is increasing. The addition of reinforcement materials such as zirconium oxide (ZrO_2) and magnesium oxide (MgO) can enhance the strength and durability of these materials. Objective: The flexural strength of 3D-printable permanent restorative resin (PRR) with ZrO_2 and MgO was assessed before and after artificial aging. ***Materials and Methods***: An experimental study was conducted in vitro from January 2026 to June 2026. Forty specimens were divided equally into four groups: control resin, ZrO_2-reinforced resin, MgO-reinforced resin, and combined ZrO_2 + MgO-reinforced resin. The flexural strength was measured by the three-point bending test before and after artificial aging. Artificial aging was performed by thermal cycling (5°C to 55°C, 10,000 cycles). ***Results***: The mean flexural strength before aging and after aging was highest for the ZrO_2 + MgO group (129 and 111 MPa, respectively). The lowest values were obtained for the control group, from 105 MPa to 89 MPa following aging. Artificial aging decreased the flexural strength of all groups, but the reinforced groups had higher flexural strength than the control group. ***Conclusion***: The flexural properties of the 3D-printable permanent restorative resin were enhanced by ZrO_2 and MgO reinforcement, and the composite reinforcement of ZrO_2 and MgO gave the best result.

Keywords: 3D printing; flexural strength; zirconium oxide; magnesium oxide; dental resin; artificial aging; permanent restoration.

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INTRODUCTION

In recent years, additive manufacturing has been revolutionizing restorative dentistry, providing the ability to create customized dental restorations that are more efficient to produce, more accurate in digital form, and less wasteful in materials. Due to their ability to be fabricated directly from digital design, 3-dimensional (3D) printed resin-based materials are being investigated for permanent and interim restorations. However, their mechanical properties are dependent on printing orientation, material composition, polymerization, and aging (1). In the same way, print orientation and thermal ageing have been found to influence the flexural strength of 3D printed restorative materials reinforced with zirconia (2). The flexural strength is especially significant since dentinal restorations are subjected to repeated functional forces during chewing (3).

Accelerated aging studies have also shown that changes in flexural strength and surface properties of 3D-printed IRMs have occurred, highlighting the need to assess the materials under simulated clinical conditions (4). The addition of ceramic and inorganic nanoparticles to resin-based materials is a promising method for enhancing mechanical properties and durability. The use of ceramics in digitally fabricated restorations has grown, and the ceramic-reinforced composites offer the processing benefits of resin systems and the desirable mechanical properties of ceramics (5). Meanwhile, more sophisticated 3D-printed resin-based prostheses are being developed, using microcrack self-healing, among others, and the ongoing development of printed dental materials is striving to enhance their structural stability and durability (6).

Artificial aging is significant in the evaluation of permanent restorative materials since the restorations may be subjected to repeated thermal, moisture, and mechanical stresses during clinical service. Studies on 3D-printed fixed implant prostheses have demonstrated that the strength of fractures is dependent on age, and that the design of prostheses and reinforcement strategies also impact the strength of fractures (7). Another way to enhance the performance of the resin could be by using nanoparticle reinforcement. Magnesium oxide and zirconium dioxide nanoparticles have been studied in acrylic denture-base

materials, where they were shown to be effective in changing the mechanical properties of polymer-based dental materials (8). Zirconium oxide is a well-known reinforcing material with favorable biocompatibility, chemical stability, fracture resistance, and high strength, which is useful in dentistry. When added to resin systems, it can enhance mechanical resistance and contribute to increased durability of the restoration (9). Its wide use in dentistry is also linked to its excellent mechanical, esthetic, and biological characteristics (10).

When combined with resin materials with zirconium oxide, magnesium oxide can give complementary reinforcement. Studies of the effect of the nanoparticles of magnesium oxide and zirconium dioxide on acrylic resin, which is used in dentistry, give evidence of how these particles can affect the performance of the polymers (11). Moreover, flexural strength tests of the denture-base resin fabricated by 3D printing have shown that material composition and repair methods can affect the mechanical properties, which is why it's important to understand how materials interact when evaluating denture-base resin restorations (12). Long-term performance of 3D-printed permanent restorations is also dependent on their clinical procedures and environmental reactions. Research on 3D-printed permanent composite crowns has investigated the impact of pretreatment and artificial aging on the retention of these materials, and showed that clinical performance can not only be evaluated by initial material properties (13).

Artificial aging has also been reported to affect the physical and mechanical properties of 3D-printed denture-base materials, further justifying the use of aging protocols when assessing the performance of digitally fabricated restorative materials (14,15). Surface deformation and mechanical wear can also be associated with clinical procedures, as shown in studies regarding the influence of carbide burs on monolithic zirconia crowns (16). The results highlight the need to assess restorative materials in a context that mimics their clinical application. Restorative dentistry is now more and more concerned with the material composition, mechanical properties, and clinical longevity. Recent reviews have highlighted the importance of choosing restorative materials based on their mechanical, physical, biological, and clinical properties (17). With the advent of dental nanocomposites, resin systems have been developed specifically for 3D-printed crown and bridge restorations to enhance their performance for permanent use (18).

Therefore, the development of 3D-printed resin-based nanocomposites is an important field of prosthetic dentistry, especially when good flexural strength and durability are needed. However, artificial aging can alter the physical and mechanical properties of CAD-CAM polymeric materials, demonstrating the importance of assessing changes over simulated service periods (19). Therefore, evaluating the flexural strength of 3D-printable permanent restorative resin reinforced with zirconium oxide and magnesium oxide before and after artificial aging is important for determining its mechanical stability and potential suitability for durable permanent dental restorations.

Objective: To test the flexural strength of a 3D-printed permanent restorative resin reinforced with zirconium oxide and magnesium oxide and determine the changes in mechanical properties after artificial aging.

MATERIALS AND METHODS

Study Design: In-vitro experimental laboratory study.

Study Setting: Dental Materials Research Laboratory/Prosthodontics Laboratory of a dental institution.

Study Duration: This study was carried out for 6 months (January 2026 to June 2026).

Sample Size: Forty specimens were prepared. The samples were divided into four groups: Control Resin (no reinforcement), Zirconium Oxide-reinforced Resin, Magnesium Oxide-reinforced Resin, and Zirconium Oxide + Magnesium Oxide-reinforced Resin. This was followed by an evaluation of each group both before and after artificial aging.

Sample Technique: The specimens were selected using a **purposive sampling technique** based on pre-defined eligibility criteria. To minimize variations due to specimen preparation, standardized specimens were fabricated using the same 3D-printing system and printing parameters.

Inclusion criteria: The study included specimens made of the 3D-printable permanent restorative resin selected. Only specimens that met the pre-established dimensions and exhibited no cracks, voids, warpage, delamination, or manufacturing defects were included. Specimens reinforced with the specified zirconium oxide and/or magnesium oxide were also included in the specimens of the respective experimental group.

Exclusion criteria: Specimens that had cracks, fractures, surface defects, and/or incomplete printing, dimensional abnormalities, excessive warpage, delamination, or other defects related to fabrication were not included. Samples that failed

to meet the specified dimensions or that were damaged during finishing, polishing, artificial ageing, or handling were also rejected for mechanical testing.

METHODS

The permanent restorative resin was selected for 3D-printing and prepared as per the manufacturer's instructions. The resin was modified with zirconium oxide and magnesium oxide nanoparticles in the pre-designed experimental groups, and the unmodified resin was used as the control. The computer-aided design software was used to design the standardized rectangular specimens, which were then 3D printed with controlled printing parameters. The specimens were printed, washed, post-cured, and finished as per the manufacturer's recommendations. The specimens were inspected for any visible defects, and the dimensions were checked prior to testing. Three-point bending was used to measure the baseline flexural strength in accordance with the relevant ISO standard. The rest were artificially aged by controlled thermal cycling to mimic the changes that occur during oral service. Thermal cycling was performed in a thermocycling unit with distilled water baths at temperatures of 5°C and 55°C, which are the extremes of cold and hot ingestion in the oral cavity as commonly found in laboratory studies (20,21). All specimens were placed in each bath for a dwell time of 30 s, and transferred between baths for 10 s to minimize equilibration with ambient temperature. A total of 10,000 cycles were completed, which is equivalent to about 1 year of clinical service (20). As there is no universal standard for the thermal cycling procedure of restorative materials (21), the parameters were chosen from those generally reported in literature and based on ISO/TS 11405. The flexural strength was measured using a three-point bending test after the aging process. The maximum load at fracture was determined, and flexural strength values were calculated and compared with each other for the experimental groups before and after artificial aging.

RESULTS

Forty specimens, equally divided among four groups (n = 10 each), were subjected to both pre- and post-artificial aging testing, and all passed the dimensional and quality requirements set. Table 1 and Figure 1 show descriptive statistics. Results are presented as mean ± standard deviation (SD) and 95% confidence interval. Welch's independent-samples t-test was used to analyze between-group differences, and Cohen's d was calculated as a standardized effect size, with a value of <0.5 regarded as a small effect and <0.8 as a moderate effect.

The mean flexural strength increased gradually from the unreinforced control (105 ± 6.8 MPa) to the resin reinforced with MgO (114 ± 6.9 MPa), ZrO_2 (118 ± 7.2 MPa) and a combination of ZrO_2 and MgO (129 ± 7.5 MPa) at baseline. The artificial aging led to a decrease in flexural strength in all groups, namely 16 MPa (control), 17 MPa (ZrO_2), 17 MPa (MgO), and 18 MPa (ZrO_2 + MgO). The relative reductions were very small, from 14.0% in the combined group to 15.2% in the control group, and the strength retained was 84.8% to 86.0%, respectively. The standard deviation of the within-group variability was low and was similar among the groups (SD 6.5-7.5 MPa, coefficient of variation 5.8%-8.0%), which suggests consistent fabrication and testing of specimens. The 95% confidence intervals of the control and combined groups did not overlap at either time point (before aging: 100.1–109.9 vs 123.6–134.4 MPa; after aging: 83.9–94.1 vs 105.8–116.2 MPa).

Table 1. Descriptive statistics of flexural strength before and after artificial aging

Group	n	Before aging Mean ± SD (MPa)	95% CI	After aging Mean ± SD (MPa)	95% CI	Absolute loss (MPa)	Reduction (%)	Retention (%)
Control	10	105 ± 6.8	100.1–109.9	89 ± 7.1	83.9–94.1	16	15.2	84.8
ZrO_2	10	118 ± 7.2	112.8–123.2	101 ± 6.5	96.4–105.6	17	14.4	85.6
MgO	10	114 ± 6.9	109.1–118.9	97 ± 7.0	92.0–102.0	17	14.9	85.1
ZrO_2 + MgO	10	129 ± 7.5	123.6–134.4	111 ± 7.3	105.8–116.2	18	14.0	86.0

SD, standard deviation; CI, confidence interval (t-distribution, df = 9). Retention = after-aging mean ÷ before-aging mean × 100.

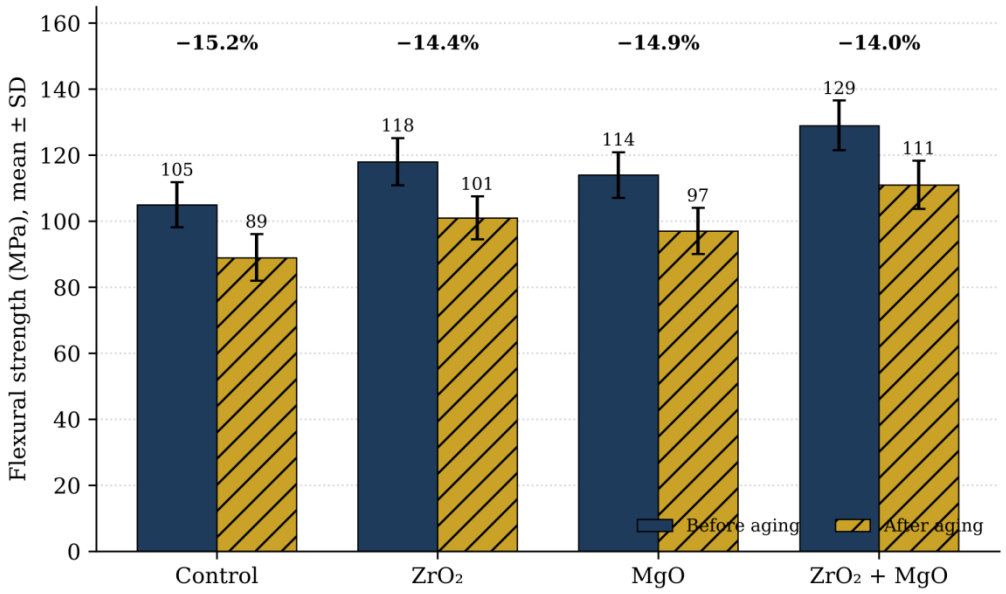

Figure 1. Flexural strength of the experimental resins before and after artificial aging Bars show mean ± SD; percentages above bars indicate relative reduction after aging.

The flexural strength of the reinforced groups was higher than the control group at both times (Table 2). The differences before and after aging were +13 MPa for ZrO_2, +9 MPa for MgO, and +24 MPa for the combined formulation. Effect sizes were large across the board (Cohen's d = 1.13–3.35), and group summary statistics were used to calculate Welch's t-tests at each time point, which showed that all reinforced groups differed significantly from the control ($p \leq 0.021$).

Table 2. Comparison of reinforced groups with the unreinforced control

Group vs control	Before aging Δ MPa (%)	Cohen's d	p	After aging Δ MPa (%)	Cohen's d	p
ZrO_2	+13 (+12.4%)	1.86	<0.001	+12 (+13.5%)	1.76	<0.001
MgO	+9 (+8.6%)	1.31	0.009	+8 (+9.0%)	1.13	0.021
ZrO_2 + MgO	+24 (+22.9%)	3.35	<0.001	+22 (+24.7%)	3.06	<0.001

Δ, mean difference from control; p-values from Welch's independent-samples t-test calculated from group means, SDs and n = 10.

The most effective formulation was the one containing ZrO_2 + MgO, which was 22.9% and 24.7% stronger than the control before and after aging, respectively. The relative performance of the materials remained the same at both assessments (ZrO_2 + MgO > ZrO_2 > MgO > control), suggesting that aging did not affect the relative performance of the materials. Interestingly, the aged combined resin (111 MPa) was still higher than the non-aged control (105 MPa), while the aged ZrO_2 (101 MPa) and MgO (97 MPa) resins were lower. Each formulation's percentage of the combined post-aging strength is shown in Figure 2, and the combined resin provides the highest percentage.

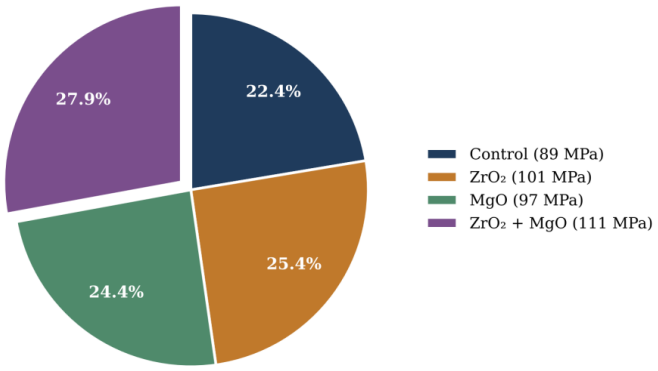

Figure 2. Proportional contribution of each group to the summed post-aging mean flexural strength Percentages are calculated from post-aging mean values (total = 398 MPa).

Head-to-head comparisons between reinforcement strategies are shown in Table 3. The combination of the two fillers was superior to both single-filler resins at both time points, while ZrO_2 was superior to MgO alone after 4 MPa (after aging, p = 0.202).

Table 3. Pairwise comparison between reinforcement strategies

Comparison	Before aging Δ MPa (%)	Cohen's d	p	After aging Δ MPa (%)	Cohen's d	p
ZrO_2 + MgO vs ZrO_2	+11 (9.3%)	1.50	0.004	+10 (9.9%)	1.45	0.005
ZrO_2 + MgO vs MgO	+15 (13.2%)	2.08	<0.001	+14 (14.4%)	1.96	<0.001
ZrO_2 vs MgO	+4 (3.5%)	0.57	0.221	+4 (4.1%)	0.59	0.202

Percentages are relative to the second group named in each comparison.

The combined resin was significantly stronger than ZrO_2 alone, by 11 MPa (9.3%) before aging and 10 MPa (9.3%) after aging, and significantly stronger than MgO alone, by 15 MPa (13.2%) before aging and 14 MPa (13.2%) after aging (Table 3, Cohen's d > 1.4, and significant pairwise differences). Overall, the flexural strength of the materials with the nanoparticles was higher than that of the materials without the nanoparticles, and the loss in flexural strength due to artificial aging was comparable for all the materials (14.0%–15.2%). The results suggest that the dual-filler resin provided the best mechanical properties in both cases, while the ZrO_2 and MgO fillers enhanced the bending resistance without affecting the aging degradation pattern.

DISCUSSION

In the present in-vitro study, the effect of 3D-printable permanent restorative resin with ZrO_2, with MgO, and with both ZrO_2 and MgO on flexural strength before and after artificial aging was evaluated. The result showed that at both evaluation periods, all the formulations containing nanoparticles had higher flexural strength than the control. The mean flexural strength of the combined ZrO_2 + MgO formulation was the highest, 129 MPa before aging and 111 MPa after aging, while the control group had the lowest value, 105 MPa before aging and 89 MPa after aging (1). The enhancement of the reinforced groups could be attributed to the interaction between inorganic particles and the surrounding polymer matrix. If reinforced appropriately, reinforcing particles can help to enhance stress distribution and limit bending deformation (2). Likewise, changes in printing direction and artificial aging have been correlated with flexural strength and modulus changes, suggesting that the fabrication condition should be taken into account when assessing reinforced dental materials (3).

All experimental groups showed a decrease in flexural strength as a result of artificial aging. For the control group, the reduction was from 105 MPa to 89 MPa, and for the combined ZrO_2 + MgO group, it was from 129 MPa to 111 MPa. The individual reinforcement groups also showed reductions, ZrO_2 from 118 MPa to 101 MPa, and MgO from 114 MPa to 97 MPa. The results show that reinforcement has enhanced the overall strength of material but could not entirely stop the degradation due to aging. The thermal cycles (10,000) applied in this aging protocol (5°C to 55°C) are thought to reflect approximately 1 year of clinical use (20), and so the reductions seen are not necessarily a measure of long-term clinical performance. A previous study with 3D-printed interim restorative materials has shown that there were changes in flexural strength and surface characteristics after accelerated ageing, which highlighted the need to assess the mechanical properties of restorative materials beyond their initial properties (4). Moreover, the growing ceramic-reinforced resin composite development is evidence of the attempt to achieve the manufacturing benefits of polymer materials and the desirable mechanical properties of inorganic reinforcement (5).

The overall performance of the combined nanoparticle formulation was the best with the highest initial strength and post-aging strength. It was about 14.0% less after artificial aging than the control, which was 15.2%. The absolute loss of strength in the combined group was 18 MPa, but this was still 13% of the original strength compared to 16 MPa in the control. However, these results alone do not support a synergistic interaction since the study did not directly examine the interactions between the two types of nanoparticles. The study of advanced resin-based dental prostheses, which seeks to reduce the occurrence of microcracks and material degradation, also highlights the interest in enhancing the durability of printed dental materials (6). Further, studies of 3D-printed fixed implant prostheses have revealed that the fracture strength may be affected by aging, design of the structure, and reinforcement methods (7). The results highlight the need to take into account the material composition and environmental exposure over a long period when designing permanent restorative systems.

The present results also help in the development of the knowledge of inorganic nanoparticle reinforcement of dental polymers. Magnesium oxide and zirconium dioxide nanoparticles were previously studied in acrylic denture-base resin, which showed that the addition of these materials could affect the mechanical properties of the acrylic polymer (8). This offers some support to help determine whether similar reinforcement methods can be used for 3D-printable restorative resins; differences between acrylic denture-base materials and permanent restorative resins should be recognised. Furthermore, it

has been shown that the flexural strength of 3D-printed denture-base resin may be influenced by the type of repair material and repair method (9,10). The strength results of the ZrO_2-containing groups are higher, which is in accordance with the interest in zirconia as a dental restorative material (11). Likewise, studies involving 3D-printed permanent composite crowns have pointed out the impact of artificial aging and pretreatment procedures on the retention of the restoration (12). Research into 3D-printed denture-base materials has also shown that the physical and mechanical properties of these materials can change as a result of aging (13).

The impact of finishing and clinical instrumentation on restoration integrity is another important factor. The current study focused on flexural strength but surface properties can also affect the response of dental restorations in clinical service. Studies comparing carbide burs and monolithic zirconia crowns have demonstrated the importance of the surface deformation that occurs during instrumentation when assessing restorative material integrity (14). Thus, the enhancement in strength after the incorporation of nanoparticles cannot be assumed independently of the surface treatment, finishing process, and stresses on the final restoration. Modern methods of selecting materials for restorations increasingly focus on mechanical, physical, biological, and clinical properties, with the focus not being on one laboratory test (15). In this context, the use of zirconium oxide in dentistry is still very relevant due to its known strength, chemical resistance, fracture resistance and good biological properties (16). The biological response and clinical suitability of the individual reinforced resin formulations investigated in the present study, however, needs to be investigated separately.

Another area of advanced research in the field of digitally manufactured restorative dentistry is the development of advanced resin-based nanocomposites. The experimental dental nanocomposites have been examined for use in 3D printed crowns and bridges to enhance properties that are desirable for permanent prostheses (17). The progress of 3D-printed resin-based nanocomposite systems suggests ongoing research and development of the performance and durability of additively manufactured dental prostheses (18). But even products produced by known and proven digital manufacturing methods, such as polymeric materials, can undergo physical and mechanical changes after environmental exposure, so artificial aging is still a key factor (19). Thus, initial and post-aging measurements are more informative of the behaviour of a restorative material than baseline measurements alone.

There are a number of caveats to note in interpreting the present findings. Mechanical results may vary depending on the concentration of nanoparticles, particle size distribution, and mixing methods. Aging was also limited to thermal cycling in water, and because there is no universally accepted thermal cycling protocol (21), differences in cycle number, dwell time, and temperature range may limit direct comparison with other studies. In addition, the investigation was limited to flexural strength and other clinically relevant properties were not assessed, such as fracture toughness, fatigue resistance, water absorption, surface roughness, wear behaviour, and biological responses. Concentrations of various nanoparticles, combinations of nanoparticles, longer aging times, cyclic mechanical loading and simulated oral conditions should therefore be investigated in the future. Routine permanent restorative use of the reinforced formulations will also require clinical investigations.

CONCLUSION

Based on the present in-vitro study, the authors found that permanent restorative resin reinforced with 3D zirconium oxide and magnesium oxide enhanced flexural strength as compared to unreinforced resin. The zirconium oxide and magnesium oxide mixture had the highest flexural strength before and after artificial aging. However, the flexural strength of the reinforced groups remained higher than the control group after aging, indicating greater resistance to mechanical deterioration caused by aging. The use of Zirconium oxide alone showed a higher reinforcing power than Magnesium oxide alone, and the combined use gave the best overall results. Based on these results, it can be concluded that the reinforcement using zirconium oxide and magnesium oxide may enhance the mechanical properties of 3D-printable permanent restorative resins and could be considered for use in long-term 3D-printed dental restorations.

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