Original Article

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The effects of cyclic loading on flexural strength and wear resistance of injectable and conventional resin composites

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Objective: To evaluate the flexural strength and wear resistance of injectable and conventional resin composites after cyclic loading.

Materials and Methods: Three resin composites were evaluated: Filtek Z350XT (FZX), Beautifil Injectable X (BIX), and G-aenial Universal Injectable (GUI). Mini-flexural bar specimens (12 × 2 × 2 mm) were fabricated using Teflon molds and light-cured with a polywave LED unit. After 24 hours storage in a light-proof container, half of the specimens were tested directly, while the remaining half underwent cyclic loading (2.25 N, 60 Hz, 250,000 cycles) in distilled water. Flexural strength was determined using a three-point bending test with a 10-mm span at a crosshead speed of 0.5 mm/min. Wear resistance was assessed by wear volume loss measurement after cyclic loading.

Results: FZX showed the highest flexural strength under both non-cyclic and cyclic conditions (159.30 ± 5.66 MPa and 147.50 ± 9.12 MPa, respectively). The injectable composites demonstrated lower flexural strength values, with GUI showing slightly higher values than BIX. Cyclic loading reduced the flexural strength of all tested materials. For wear resistance, FZX exhibited the lowest wear volume loss (0.009±0.001 mm^3), whereas BIX and GUI showed higher values (0.028 ± 0.008 mm^3 and 0.033 ± 0.011 mm^3, respectively), with no significant difference between the two injectable composites. The correlation analysis demonstrated a moderate negative relationship between wear volume loss and cyclic flexural strength (R^2=0.487), indicating that materials with lower wear tended to exhibit higher flexural strength.

Conclusion: Cyclic loading reduced the flexural strength of all tested composites. The conventional composite, FZX, demonstrated superior flexural strength and wear resistance compared with the injectable composites. Higher cyclic flexural strength was associated with lower wear volume loss.

Keywords: composite resins, dental restoration wear, fatigue, flexural strength

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Introduction

Resin composites are commonly used for posterior restorations due to their aesthetic appeal and the ability for direct placement [1, 2]. In recent years, injectable composites have emerged as an alternative to traditional composites, offering enhanced handling and adaptability [3]. However, concerns persist regarding their mechanical performance, especially in stress-bearing posterior areas.

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Flexural strength is a crucial mechanical property that indicates a material's capacity to resist functional loading without fracturing [4]. Additionally, wear resistance is vital for maintaining occlusal stability and the longevity of restorations [5]. These properties are particularly significant in posterior restorations, which are subject to complex masticatory forces [6].

Cyclic loading is frequently used to simulate intraoral conditions and assess the durability of restorative materials [7]. Previous studies have shown that cyclic loading can diminish the mechanical properties of resin composites, including flexural strength, and increase wear [3, 6]. However, the comparative performance of injectable composites versus conventional composites under these conditions is not fully understood. Moreover, the relationship between flexural strength and wear resistance has not been completely clarified. While materials with higher flexural strength are generally anticipated to have better wear resistance, this relationship is affected by various factors, such as filler content, resin matrix composition, and material structure [8, 9].

Therefore, the main research question of this study is whether cyclic loading impacts the flexural strength and wear resistance of injectable composites compared to conventional composites.

The purpose of this study was to evaluate the effects of cyclic loading on the flexural strength and wear resistance of injectable and conventional resin composites. The null hypotheses were: 1) cyclic loading would not affect the flexural strength of the tested materials; 2) cyclic loading would not affect the wear resistance of the tested materials; and 3) there would be no difference in flexural strength and wear resistance between injectable and conventional resin composites.

Materials and Methods

Three restorative resin composites were investigated: one conventional composite, Filtek Z350XT (3M ESPE, St. Paul, MN, USA), and two injectable composites, Beautifil Injectable X (Shofu Inc., Kyoto, Japan) and G-aenial Universal Injectable (GC Corp., Tokyo, Japan). All tested composites were shade A2. Material compositions are summarized in Table 1.

For the evaluation of flexural strength, mini-flexural bar specimens measuring 12 × 2 × 2 mm were prepared using customized Teflon molds (n=8/group). Mini-bars were selected instead of 25-mm ISO bars because shorter specimens have been reported to provide more uniform light exposure and polymerization along their length and to better approximate the dimensions of stress-bearing regions in posterior restorations [10-12]. Each material was placed in a single increment, covered with polyester strips and glass slides, and light-cured using a polywave LED curing unit (Bluephase N; Ivoclar Vivadent, Schaan, Liechtenstein; 1,200 mW/cm², 385–515 nm). Two overlapping 40-second irradiations were applied on each side of the specimen to ensure complete polymerization. After curing, the excess material on the side areas was removed using 500-grit silicon carbide paper, ensuring that the top and bottom surfaces were not touched. The final dimensions were then confirmed with a digital caliper. The specimen preparation procedure is illustrated in Figure 1.

Table 1 Materials used in this study.

Type of material	Name and shade	Composition	Filler rate wt%/vol%	Filler size	Manufacturer
Conventional resin composite					
Nanofilled	Filtek Z350 XT (A2 Body)	Organic matrix: Bis-GMA, Bis-EMA, UDMA, TEGDMA Fillers : Silica nanocluster, cluster	78.5/63.3	Nanocluster: 0.075 μm Cluster: 0.64 - 1.4 μm	3M ESPE, St.Paul, Minnesota, United States
Flowable resin composites					
Nanohybrid	Beautifil Injectable X (A2)	Fillers : S-PRG based on fluoroboroaluminosilicate glass and multi-functional glass fillers with total coverage silane treatment	64/42	400 nm	Shofu, Kyoto, Japan
Nanofilled	G-aenial Universal Injectable (A2)	Organic matrix: Bis-EMA, tricyclodecanedimethanol dimethacrylate, neopentyl glycol dimethacrylate, UDMA, 6-tertbutyl-2,4-dimethylphenol, TEGDMA Fillers: Barium glass, silica	69/50	150 nm	GC Corporation, Tokyo, Japan

Bis-GMA: bisphenol A glycidyl methacrylate, Bis-EMA: bisphenol A ethoxylate methacrylate, UDMA: urethane dimethacrylate, TEGDMA: triethyleneglycol dimethacrylate, S-PRG: surface pre-reacted glass.

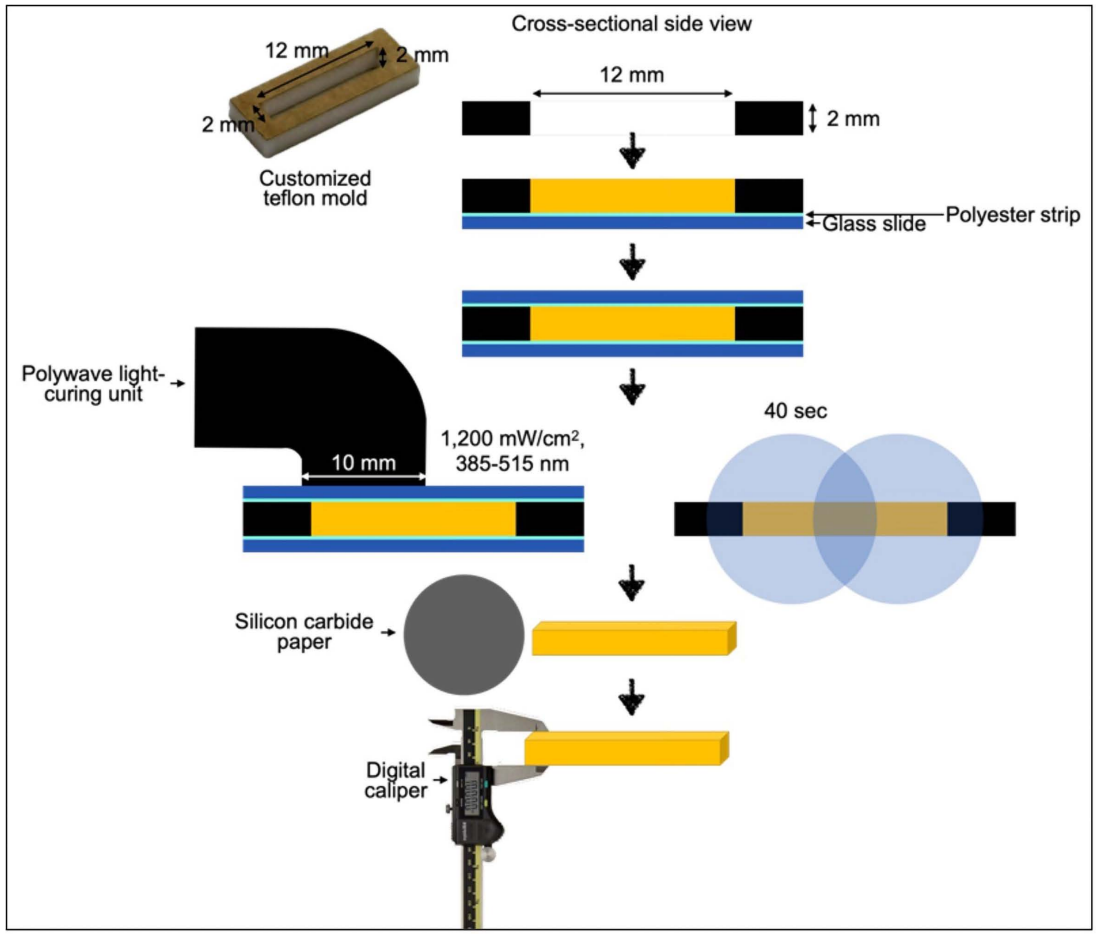


Figure 1 Specimen preparation procedure

All specimens were stored in a light-proof container at room temperature for 24 hours before testing. The specimens were then divided into two subgroups: non-cyclic loading and cyclic loading. For the cyclic loading condition, specimens were subjected to 250,000 loading cycles at 2.25 N and 60 Hz in distilled water, using a V-shaped stainless-steel antagonist that repeatedly slid across the specimen surface to generate two-body wear and simulate functional masticatory loading.

Flexural strength was measured using a three-point bending test in a universal testing machine (Lloyd Instruments, Hants, England) with a support span of 10 mm and a crosshead speed of 0.5 mm/min until fracture. Flexural strength values were calculated from the maximum fracture load using the following formula, $\sigma = \frac{3PL}{2BH^2}$ in these formulas the following parameters are used: σ = Flexural strength (MPa), P = Maximum load exerted on the specimen (N), L = Distance between the supports (mm), B = Width of the specimen (mm), and H = Height of the specimen (mm).

For wear evaluation, post-cyclic specimens were analyzed using a 3D laser measuring microscope (OLS5100-SAF, Olympus, Nagano, Japan), and wear volume loss was calculated as the integrated volume of the wear track relative to the adjacent unworn reference surface on each specimen. Normality test was assessed using the Komogorov-Smirnov test, and homogeneity of

variances was checked with Levene's test. Flexural strength and wear data were analyzed using two-way and one-way ANOVA, respectively, followed by Dunnett T3 multiple comparisons. Statistical significance was set at $\alpha = 0.05$. Statistical analyses were performed using IBM SPSS Statistics 29.0 for Windows (StudentDiscounts.com, Orem, UT, USA).

Sample size was calculated using nQuery Advisor version 6.01 (Statistical Solutions Ltd., Cork, Ireland) with 80% power and a significance level of 0.05. Using mean and standard deviation values from François P et al. [6] and Lapaschaone N and Maneenut C [3], the required sample size was determined to be 8 specimens per group, which was adopted for this study.

Results

The flexural strength values of all tested materials under non-cyclic and cyclic conditions are presented in Table 2. Means and standard deviations were recorded for each group. Under non-cyclic conditions, the flexural strength values were 159.30 ± 5.66 MPa for FZX, 123.01 ± 4.55 MPa for BIX, and 129.26 ± 4.87 MPa for GUI. After cyclic loading, the corresponding values decreased to 147.50 ± 9.12 MPa for FZX, 117.23 ± 1.22 MPa for BIX, and 121.75 ± 7.87 MPa for GUI, respectively.

Two-way ANOVA revealed significant effects of material type ($p < 0.05$) and cyclic condition ($p < 0.05$) on flexural strength, without a significant interaction between these two factors ($p = 0.365$). According to multiple comparisons, FZX demonstrated significantly higher flexural strength than both BIX and GUI groups under both testing conditions ($p < 0.05$). Cyclic loading significantly reduced the flexural strength of all tested materials ($p < 0.05$). No statistically significant difference was observed between BIX and GUI in the cyclic condition ($p \geq 0.05$). The flexural strength of GUI was significantly higher than that of BIX in the non-cyclic condition ($p < 0.05$).

The wear volume loss values after cyclic loading are presented in Table 3, while the representative images of wear tracks following cyclic loading are shown in Figure 2. The means and standard deviations for wear volume loss were 0.009 ± 0.001 mm^3 for FZX, 0.028 ± 0.008 mm^3 for BIX, and 0.033 ± 0.011 mm^3 for GUI. One-way ANOVA revealed a significant difference in wear volume loss among the tested materials ($p < 0.05$). Multiple comparison analysis indicated that FZX exhibited significantly lower wear volume loss compared to both BIX and GUI ($p < 0.05$), whereas no statistically significant difference was found between BIX and GUI ($p > 0.05$). Figure 2 illustrates the representative wear tracks observed using three-dimensional profilometry after cyclic loading. The images show that

Table 2 Flexural strength of all tested materials.

Tested materials	Flexural strength (MPa)	
	Non-cyclic	Cyclic
Filtek Z350 XT (FZX)	$159.30 \pm 5.66^{a, A}$	$147.50 \pm 9.12^{b, A}$
Beautifil Injectable X (BIX)	$123.01 \pm 4.55^{a, C}$	$117.23 \pm 1.22^{b, B}$
G-aenial Universal Injectable (GUI)	$129.26 \pm 4.87^{a, B}$	$121.75 \pm 7.87^{b, B}$

The same lowercase letter indicates no statistically significant difference between groups within the same row ($p \geq 0.05$). The same uppercase letter indicates no statistically significant difference between groups within the same column ($p \geq 0.05$).

Table 3 Wear volume loss after cyclic loading.

Tested materials	Wear volume loss (mm^3)
Filtek Z350 XT (FZX)	0.009 ± 0.001^b
Beautifil Injectable X (BIX)	0.028 ± 0.008^a
G-aenial Universal Injectable (GUI)	0.033 ± 0.011^a

The same letter indicates no statistically significant difference between groups ($p \geq 0.05$).

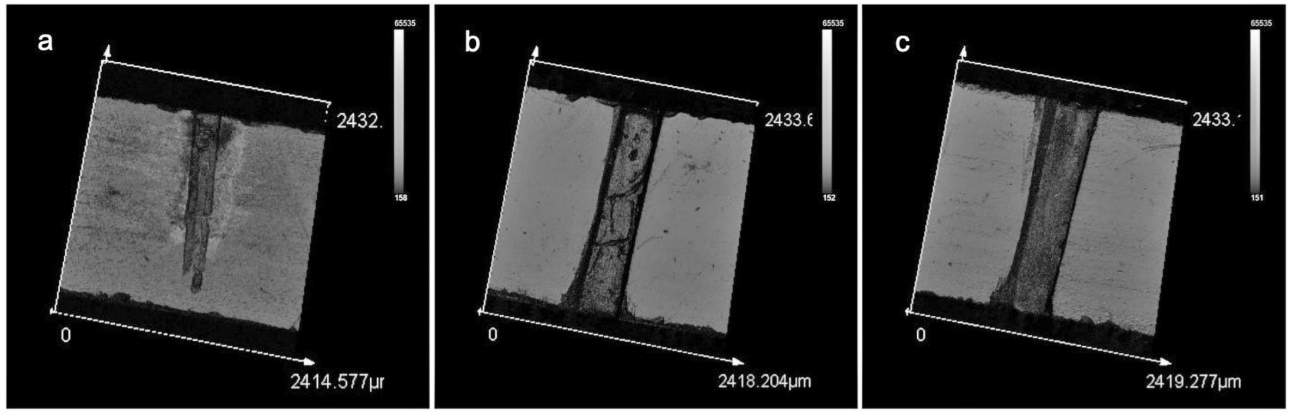


Figure 2 Wear track images after cyclic loading (a = FZX, b = BIX, c = GUI).

FZX had the shallowest wear, followed by BIX and GUI, which displayed nearly identical wear patterns.

For the correlation analysis, a statistically significant negative correlation was observed between wear volume loss and flexural strength after cyclic loading ($p < 0.05$). The coefficient of determination (R^2) was 0.487, indicating that approximately 48.7% of the variation in post-cyclic flexural strength could be explained by wear volume loss. This relationship was further evaluated using linear regression analysis, resulting in the equation: $y=1.48 \times 10^2 - 8.3 \times 10^{-6}x$, where y represents flexural strength after cyclic loading and x represents wear volume loss.

Discussion

This study evaluated the effects of cyclic loading on the flexural strength and wear resistance of injectable and conventional resin composites for posterior restorations. FZX showed the highest flexural strength under both non-cyclic and cyclic conditions (159.30 ± 5.66 MPa and 147.50 ± 9.12 MPa, respectively), whereas BIX and GUI demonstrated lower values. Cyclic loading significantly reduced the flexural strength of all tested materials. Wear volume loss was lowest for FZX (0.009 ± 0.001 mm^3), while higher values were observed for BIX (0.028 ± 0.008 mm^3) and GUI (0.033 ± 0.011 mm^3), with no significant difference between the two injectable composites. Therefore, the first null hypothesis that cyclic loading would not affect flexural strength was rejected. The second null hypothesis that no difference in wear resistance would exist among the tested materials was also rejected. However, no significant difference in wear resistance was found between the two injectable composites. A moderate negative correlation was observed between post-cyclic flexural strength and wear

volume loss, indicating that materials with higher flexural strength tended to exhibit lower wear. Therefore, the third null hypothesis that injectable and conventional composites would demonstrate similar mechanical performance was rejected.

Flexural strength is one of the most important mechanical properties for resin-based restorative materials, particularly in posterior stress-bearing areas where restorations are subjected to repeated tensile, compressive, and shear forces during mastication [4]. According to ISO4049, polymer-based restorative materials intended for occlusal load-bearing applications should demonstrate a minimum flexural strength of 80 MPa [13]. In the present study, all tested materials exceeded this threshold under both non-cyclic and cyclic conditions, indicating that each material possesses a baseline mechanical performance considered acceptable for posterior clinical use. Importantly, this suggests that, despite the statistically lower flexural strength of the injectable composites compared with the conventional control, both injectable materials remain mechanically viable for posterior restorations within the limits of this in vitro model.

Among the tested composites, FZX demonstrated the highest flexural strength before and after cyclic loading. This superior performance may be associated with its nanofilled/nanocluster filler technology, optimized filler distribution, and effective silane coupling between filler particles and resin matrix, which improve stress transfer and resistance to crack propagation [14]. Previous studies have reported that composites with smaller and more homogeneously distributed fillers often exhibit enhanced mechanical properties because localized stress concentration is reduced and filler reinforcement becomes more efficient [15, 16]. In addition, FZX contains a high-viscosity Bis-GMA/UDMA/Bis-EMA–based resin matrix, which is relatively hydrophobic and highly cross-linked, resulting in lower water sorption and reduced hydrolytic degradation over time [17, 18]. In contrast, injectable composites generally require a greater proportion of low-viscosity monomers to maintain flowability, which may increase water uptake and matrix plasticization [19, 20]. These combined compositional factors, rather than filler loading alone, are likely to contribute to the higher flexural strength of FZX compared with the injectable composites.

The injectable composites, GUI and BIX, showed lower flexural strength values than the conventional composite, although both remained above the ISO requirement. Injectable materials have been developed to combine improved handling with mechanical properties comparable to conventional composites [3]. However, to maintain flowability, these materials generally require a greater resin matrix fraction or modified rheological systems, which may reduce stiffness and resistance to bending stresses [21]. This may explain why their flexural strength values were lower than those of FZX.

The two injectable composites differ not only in filler loading but also in filler technology and resin matrix composition. BIX is a nanohybrid S-PRG–based injectable composite with a relatively lower filler content and an ion-releasing glass filler system designed to enhance handling and bioactive properties [22, 23]. In contrast, GUI is a nanofilled injectable composite with higher filler loading and a Bis-EMA/UDMA-based matrix formulated to provide a more rigid network [24]. These differences in filler morphology, filler content, and matrix composition are likely to influence stress distribution, water sorption, fatigue behavior, and ultimately the flexural and wear responses of the materials. Interestingly, GUI showed slightly higher flexural strength than BIX under both conditions; however, this difference reached statistical significance only

in the non-cyclic condition. This pattern suggests that GUI may be more susceptible to fatigue-related degradation, such as matrix softening or filler–matrix debonding, leading to a greater reduction in flexural strength under repeated loading, whereas BIX experienced a relatively smaller loss of strength. Thus, while GUI provided a higher initial flexural strength, BIX appeared to maintain its flexural performance more stably after cyclic loading under the conditions tested.

Cyclic loading protocols are commonly selected to approximate long-term masticatory function under accelerated laboratory conditions. Previous studies have suggested that approximately 1,200,000 chewing cycles may represent about five years of clinical service [25], whereas loading frequencies around 2 Hz correspond to the maximum physiological chewing rate in humans [26]. Because prolonged low-frequency fatigue testing is highly time-consuming, accelerated protocols using higher frequencies have been proposed. Based on these considerations, the present loading regimen was selected to simulate approximately one year of mastication while maintaining practical experimental duration and clinically relevant fatigue conditions.

Cyclic loading significantly reduced the flexural strength of all tested materials. Repetitive loading may induce fatigue-related damage, including filler-matrix debonding, propagation of internal microcracks, hydrolytic softening of the resin matrix, and accumulation of subcritical defects [9, 27]. Such mechanisms progressively weaken the material structure and reduce its resistance to fracture [8]. Nevertheless, FZX maintained the highest post-cyclic flexural strength, suggesting better fatigue tolerance and structural stability under simulated functional loading.

Wear resistance is another key determinant of the long-term success of posterior restorations. Excessive material loss may result in occlusal disharmony, loss of anatomical contour, compromised proximal contact, increased plaque retention, and eventual restoration failure [5].

In the present study, FZX exhibited the lowest wear volume loss and significantly better wear resistance than both injectable composites. This finding may be explained by its high filler loading, nanocluster filler system, and strong filler-matrix integration, which enhance surface hardness and reduce matrix removal during repetitive contact [14, 28]. The presence of well-bonded nanosized fillers may also help maintain a protective superficial layer during wear, thereby limiting filler plucking and surface breakdown [29].

The injectable composites demonstrated greater wear volume loss, although no significant difference was observed between BIX and GUI. This may be related to their higher resin matrix proportion compared with conventional composites, which may make them more susceptible to matrix abrasion and subsequent filler exposure [30]. Once the surrounding resin matrix is removed, unsupported fillers may be dislodged, accelerating surface loss.

Although injectable composites showed lower wear resistance in the present study, their wear values should be interpreted in relation to their potential clinical advantages, including superior cavity adaptation, easier placement, and reduced void formation. These handling benefits may be valuable in minimally invasive posterior restorations or small to moderate cavities where extreme occlusal loading is less critical.

Correlation analysis revealed a moderate negative relationship between post-cyclic flexural strength and wear volume loss, indicating that materials with higher resistance to bending stress tended to show lower wear. This suggests that structural integrity and resistance to deformation may contribute to improved wear performance.

However, because the correlation was only moderate, wear behavior is likely influenced by additional factors such as filler hardness, particle size, surface roughness evolution, elastic modulus, and degradation of the resin matrix over time [6]. Therefore, wear resistance cannot be predicted solely from flexural strength.

This study has several limitations. As an in vitro investigation, the cyclic loading protocol cannot fully reproduce the complex oral environment, where thermal changes, pH fluctuation, saliva, enzymatic degradation, and multidirectional mastication occur simultaneously. In addition, only three composite materials were evaluated. Future studies should include a wider range of restorative materials, long-term aging protocols, thermomechanical loading, and clinical trials to confirm the long-term performance of injectable composites in posterior applications.

Conclusion

Within the limitations of this in vitro study, the tested injectable and conventional resin composites exhibited different flexural strength and wear resistance properties after cyclic loading. The conventional composite, FZX, demonstrated the highest flexural strength and the greatest wear resistance under the present testing conditions. The injectable composites showed lower flexural strength and higher wear volume loss, although all materials maintained flexural strength values above the minimum requirement specified by ISO4049 for posterior restorative applications. Among the injectable materials, GUI and BIX exhibited comparable overall performance. A moderate negative relationship was observed between post-cyclic flexural strength and wear volume loss, suggesting that materials with greater mechanical strength tended to demonstrate lower wear. These findings indicate that highly filled injectable composites may be considered for posterior restorations when improved handling and cavity adaptation are desired, whereas conventional composites may remain preferable in high stress-bearing areas requiring superior mechanical durability.

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