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ORIGINAL RESEARCH

In vitro evaluation of compressive strength and microleakage of stainless steel and BioFLX crowns used for restoring primary molar teeth

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Abstract

Background: The restoration of primary molar teeth requires crowns with adequate mechanical strength and marginal sealing ability. This *in vitro* study aimed to compare the compressive strength and microleakage of stainless-steel crowns (SSC) and BioFLX crowns used for restoring primary molar teeth. **Methods**: Forty-eight typodont primary mandibular second molar teeth were divided into two groups (n = 24) according to crown type: SSC and BioFLX. Each group was further subdivided into compressive strength and microleakage subgroups (n = 12). All teeth were prepared using standardized protocols and cemented with resin-modified glass ionomer cement. After thermocycling for 10,000 cycles between 5 °C and 55 °C, compressive strength was measured using a universal testing machine. Microleakage was evaluated by 0.5% basic fuchsin dye penetration under 25× magnification using a dental microscope, and measurements were performed with ImageJ software. Data were analyzed using independent t-tests with a significance level set at $p < 0.05$. **Results**: SSC crowns exhibited significantly higher compressive strength (56.07 ± 10.48 MPa) than BioFLX crowns (46.17 ± 10.57 MPa) ($p = 0.032$). Microleakage analysis revealed lower dye penetration in SSCs (11.65 ± 0.53%) compared with BioFLX crowns (12.56 ± 0.88%) ($p = 0.006$). **Conclusions**: Although stainless-steel crowns demonstrated superior compressive strength and marginal seal, the microleakage values of BioFLX crowns were within ranges reported for esthetic pediatric crowns with documented clinical success. Considering their comparable dye-penetration percentages and ability to withstand forces exceeding typical pediatric masticatory loads, BioFLX crowns may be regarded as a clinically acceptable esthetic alternative for the restoration of primary molars under standardized *in vitro* conditions.

Keywords

Stainless-steel crown; BioFLX crown; Primary molar; Compressive strength; Microleakage; Pediatric dentistry

1. Introduction

Dental caries remains one of the most prevalent chronic diseases in children, significantly affecting oral health, comfort, and quality of life, causing pain, infection, and tooth loss [1–3]. When multiple surfaces of primary molars are involved, full-coverage restorations are preferred for maintaining tooth integrity and function [4, 5].

Since their introduction by Humphrey in 1950, stainless-steel crowns (SSCs) have been the gold standard for restoring extensively damaged primary molars due to their superior durability, simplicity of application, and cost-effectiveness [6–9]. While stainless-steel crowns continue to serve as the benchmark for durability and marginal sealing, the rising preference for metal-free restorations in pediatric dentistry has shifted clinical decision-making toward a compromise between aesthetics and mechanical performance [10, 11].

To address these concerns, newer aesthetic full-coverage alternatives, such as zirconia, composite, and hybrid polymer-based crowns, have been developed. Among these, BioFLX crowns are a hybrid resin polymer material designed to combine esthetic appeal with adequate mechanical strength [12].

Numerous studies have assessed the mechanical performance, marginal fit, and microleakage of various pediatric crown materials [13–15]. However, direct comparisons between stainless-steel crowns and BioFLX crowns, utilizing standardized protocols for tooth preparation, cementation, thermocycling, and testing, remain limited. Therefore, this *in vitro* study aims to comparatively evaluate the compressive strength and microleakage of stainless-steel and BioFLX crowns used for the restoration of primary molars.

2. Materials and methods

2.1 Sample selection and grouping

This study involved forty-eight typodont mandibular second primary molars. Sample size was determined using G*Power 3.1 Software (Heinrich Heine University Düsseldorf, Düsseldorf, NRW, Germany). For both compressive strength and microleakage tests, effect sizes were calculated as 0.97–0.98 with an alpha level of 0.05 and power of 0.8, requiring 12 specimens per group. Thus, 24 specimens per test (n = 48 total) were prepared.

Samples were divided into two groups (n = 24 each). Group 1: Stainless-steel crowns (Kids Crown; Shinhung, Seoul, Korea; Fig. 1), and Group 2: BioFLX crowns (Kids-e-Dental LLP, Mumbai, India; Fig. 2). Each group was further subdivided into 12 samples for compressive strength testing and 12 for microleakage analysis.

FIGURE 1. Stainless-steel crowns (Kids Crown; Shinhung, Seoul, Korea).

FIGURE 2. BioFLX crowns (Kids-e-Dental LLP, Mumbai, India).

2.2 Tooth preparation

All teeth were prepared by a single operator using extra-fine-grit football-shaped and flame-shaped diamond burs (Acurata GmbH & Co KG, Germany) under water cooling. Crown sizes were selected based on mesiodistal measurements obtained with a periodontal probe.

A standardized reduction of 1–1.5 mm occlusally and 1 mm on buccal, lingual, and proximal surfaces was performed. All line angles were rounded, and margins extended approximately 1 mm below the artificial gingival line. Standardization of preparation depth was achieved by using the bur diameter as a reference, creating guiding grooves and connecting them to maintain uniform reduction. The adequacy of preparation, occlusal clearance, and marginal adaptation were verified on the phantom jaws before proceeding.

A single silicon preparation guide was fabricated using C-type addition silicone impression material (Zetaplus; Zhermack, Rovigo, Italy) and used for all 48 specimens to standardize tooth reduction and specimen geometry. All tooth preparations were performed by a single experienced operator to eliminate inter-operator variability. Although formal intra-operator reliability testing was not conducted, the use of a silicone index and bur-diameter-guided reduction minimized preparation variability across specimens.

The space corresponding to the pulp chamber and root canal region of each typodont tooth was filled with light-cured flowable composite resin (AeliteFlo; Bisco Inc., USA) and light-cured for 40 seconds using an LED curing unit (Ivoclar Vivadent LED Beam; Ivoclar Vivadent AG, Schaan, Liechtenstein) to mimic dentin support and to prevent dye penetration during the microleakage test.

Following tooth preparation, crowns were cemented with a resin-modified glass ionomer cement (FujiCEM™ Evolve; GC Corp., Japan), which is widely used for cementation of prefabricated pediatric crowns and offers fluoride release, chemical adhesion to tooth structure, adequate working time, and favorable clinical outcomes [4]. Fig. 3 illustrates the cementation procedure performed on typodont teeth using resin-modified glass ionomer cement.

FIGURE 3. Cementation procedure on typodont teeth using resin-modified glass ionomer cement.

A brief tack-curing step (3 seconds per surface) was performed to facilitate excess cement removal and improve marginal adaptation, consistent with manufacturer recommendations and previous pediatric crown studies, without interfering with the cement's final chemical polymerization. During cement setting, a standardized axial load of 5 kg was applied for 4 minutes and 30 seconds to simulate clinical seating pressure generated by finger pressure or patient biting during crown cementation, as reported in previous *in vitro* studies evaluating pediatric crowns [7].

2.3 Thermocycling

All specimens were subjected to 10,000 thermocycles between 5 °C and 55 °C, with a 30-second dwell time in each bath, and a 10-second transfer interval. Approximately 10,000 thermocycles have been reported to simulate nearly one year of intraoral thermal aging under clinical conditions [7].

2.4 Compressive strength test

The parameters used for compressive strength testing were selected to simulate axial loading conditions commonly applied in laboratory studies evaluating full-coverage restorations.

Each specimen was embedded in self-cure polymethyl methacrylate (PMMA) resin (Imicryl SC®, Konya, Turkiye) using cylindrical molds (12 mm × 15 mm), leaving 1 mm of the crown margin exposed. Compressive strength testing was performed using a universal testing machine (Instron 3345; Instron Corp., Norwood, MA, USA; device ID: 3345J7324) at a crosshead speed of 1 mm/min until failure occurred (Fig. 4). The maximum load at failure (N) recorded by the universal testing machine was converted to compressive strength values (MPa), representing derived stress values rather than raw load measurements. The compressive strength (CS) was calculated in megapascals (MPa) using the formula: $\mathrm{CS} = 4F/\pi d^2$, where F is the maximum load (N), and d is the specimen diameter (mm).

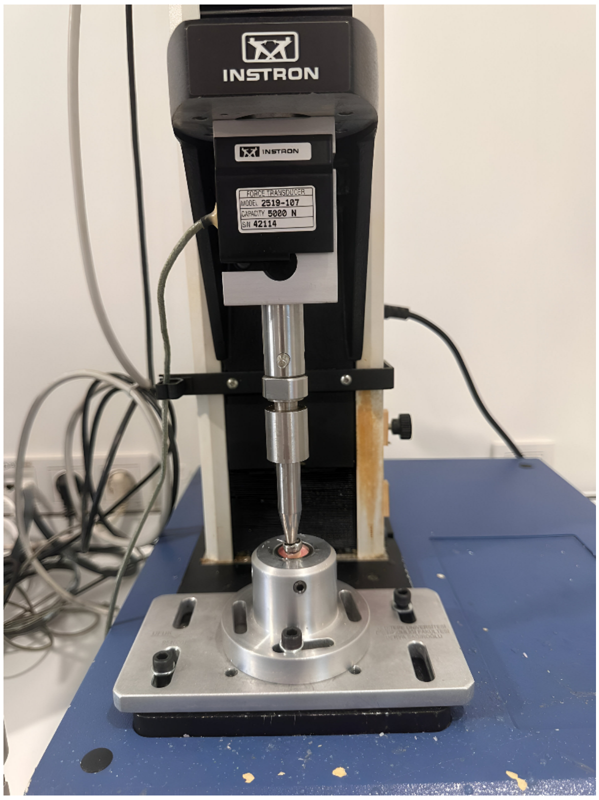

FIGURE 4. Compressive strength testing setup.

2.5 Microleakage evaluation

After thermocycling, the specimens were coated with nail varnish, leaving a 1 mm margin around the crown-tooth interface exposed, and immersed in a 0.5% basic fuchsin dye for 24 hours. After dye immersion, the specimens were sectioned mesiodistally into two halves using a separator disc mounted on a clinical handpiece connected to a micromotor (Acurata GmbH & Co. KG, Thurmansbang, Germany) under continuous water cooling. The central groove of each specimen served as a reference point to ensure standardized sectioning and was examined under a dental microscope (Zeiss OPMI Pico, Carl Zeiss Meditec AG, Jena, TH, Germany) at 25× magnification. Digital images were captured and analyzed using ImageJ software (Version 1.34, NIH, USA). The dye penetration length along the mesial and distal margins was measured, and microleakage (%) was calculated as the ratio of dye penetration length to total cement interface length.

2.6 Statistical analysis

Data analysis was conducted using NCSS 2007 (Version 2007; Number Cruncher Statistical System, Kaysville, UT, USA). Descriptive statistics (mean (M) ± standard deviation (SD)) were calculated for all variables. Data normality was assessed with the Shapiro-Wilk test, and intergroup comparisons were made using independent *t*-tests. Statistical significance was set at $p < 0.05$.

3. Results

3.1 Compressive strength values (MPa)

SSC crowns demonstrated significantly higher compressive strength compared with BioFLX crowns (p = 0.032) (Table 1). In addition to higher mean compressive strength, stainless-steel crowns demonstrated a narrower distribution of values, indicating more consistent mechanical behavior. BioFLX crowns exhibited greater variability; however, all specimens withstood loads exceeding reported pediatric bite forces.

3.2 Microleakage values

BioFLX crowns exhibited greater microleakage compared to SSCs, with significant differences observed in dye penetration (p = 0.026) and dye/cement ratio (p = 0.006) (Table 2). Although BioFLX crowns demonstrated statistically higher dye penetration, the absolute difference between groups was relatively small (<1%), and substantial overlap was observed between distributions, suggesting that the observed difference may be of limited clinical relevance. The distribution of microleakage values among groups is shown in Fig. 5.

Fig. 5 demonstrates that while stainless-steel crowns showed a more clustered distribution of microleakage values, BioFLX crowns exhibited a slightly broader spread. Despite partial overlap between groups, the overall distribution supports the statistically significant difference observed between crown types.

4. Discussion

This *in vitro* study compared the compressive strength and microleakage of stainless-steel and BioFLX crowns used for restoring primary molar teeth. The results demonstrated that stainless-steel crowns possessed significantly greater compressive strength and lower microleakage than BioFLX crowns. Despite these differences, BioFLX crowns demonstrated mechanical and marginal performance comparable to that reported for esthetic pediatric crown systems under standardized *in vitro* conditions, suggesting their potential as an esthetic alternative to stainless-steel crowns.

Compressive strength is a critical mechanical property for full-coverage restorations, as it reflects their ability to withstand occlusal forces during mastication. Although masticatory forces in children are lower than those observed in adults, they still generate considerable vertical loads on primary teeth. Mean bite forces in pediatric populations have been reported to range from approximately 186.2 N in 3–5-year-old boys and 203.4 N in girls of the same age group to 309.5 ± 193.75 N in boys aged 7–20 years and 219 ± 144.21 N in girls [16]. In the present study, both stainless-steel and BioFLX crowns demonstrated resistance levels exceeding the reported masticatory forces under standardized *in vitro* conditions.

Their metallic structure, characterized by a high modulus of elasticity and ductility, allows for uniform stress distribution under occlusal load and resistance to permanent deformation [17, 18]. This explains why SSCs have remained the gold standard for full-coverage restorations of extensively carious or pulpotomized primary molars for more than seven decades. The biocompatibility and minimal cytotoxicity of preformed stainless-steel crowns have also been well established, reinforcing their safety for long-term intraoral use [19, 20].

By contrast, BioFLX crowns, composed of a hybrid polymeric matrix, exhibited lower compressive strength, which may be attributed to the material's viscoelastic properties. Polymers and resin-based materials typically exhibit elastic deformation under masticatory loads, resulting in reduced ultimate compressive resistance compared to metals [18]. It may be hypothesized that the viscoelastic behavior of the polymeric matrix contributes to stress distribution and marginal behavior; however, these mechanisms were not directly evaluated and should be confirmed by future mechanical and thermal analyses.

Thermocycling is widely used to simulate the thermal stresses dental materials experience in the oral environment. Although the ISO/TS 11405 standard considers 500 thermocycles between 5 °C and 55 °C sufficient for artificial aging, previous investigations have suggested that a higher number of cycles may better reflect clinical conditions [21]. In this context, approximately 10,000 thermocycles have been reported to correspond to nearly one year of intraoral thermal aging under *in vivo* conditions [22]. Therefore, the application of 10,000 thermocycles in the present study was intended to provide a more clinically relevant aging protocol

TABLE 1. Derived compressive strength values (MPa) calculated from maximum load at failure.

Group	Stainless-Steel Crown (M ± SD)	BioFLX Crown (M ± SD)	p value
Compressive Strength (MPa)	56.07 ± 10.48	46.17 ± 10.57	0.032*

**Independent t-test; significance at p < 0.05. M: Mean; SD: standard deviation.*

TABLE 2. Microleakage results.

Parameter	SSC Group (M ± SD)	BioFLX Group (M ± SD)	p-value
Dye Penetration (mm)	56.90 ± 3.15	61.08 ± 5.21	0.026*
Total Cement (mm)	488.29 ± 10.48	486.10 ± 13.42	0.660
Dye Penetration/Total Cement (%)	11.65 ± 0.53	12.56 ± 0.88	0.006*

**Independent t-test; significance at p < 0.05. SSC: stainless-steel crowns; M: Mean; SD: standard deviation.*

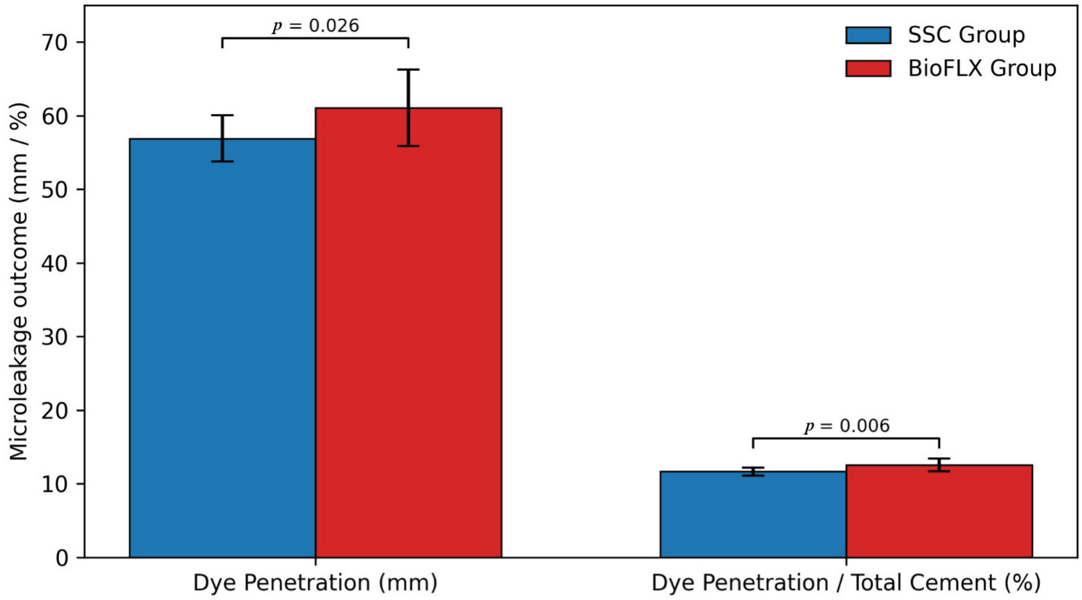

FIGURE 5. Microleakage values distribution within groups. SSC: stainless-steel crowns.

for evaluating the compressive strength and marginal sealing of pediatric crowns.

In a recent thermomechanical aging study, Abo-Elsoud *et al.* [18] (2024) reported that BioFLX crowns demonstrated intermediate fracture resistance, higher than zirconia but lower than stainless-steel, confirming the balance between resilience and flexibility inherent in polymer-based designs. This flexibility may slightly reduce compressive resistance while increasing marginal gaps under loading, potentially explaining the higher microleakage values observed.

Although no universally accepted numeric threshold exists for microleakage or compressive strength in pediatric crowns, the values observed for BioFLX crowns in the present study are comparable to those reported for esthetic crown systems that have demonstrated favorable clinical performance. Specifically, compressive strength values exceeding reported pediatric masticatory forces and microleakage percentages similar to those of zirconia and resin-based crowns suggest that the observed performance falls within clinically acceptable ranges reported in the literature. Similar to findings by Patil *et al.* [23] (2024) and Abo-Elsoud *et al.* [18] (2024), BioFLX crowns demonstrate that new-generation esthetic crown systems can offer functional and visually pleasing alternatives without severely compromising mechanical performance [18, 23].

The microleakage results in this study also favored SSCs, which showed significantly less dye penetration compared to BioFLX crowns. Adequate marginal sealing is essential in pediatric full-coverage restorations to prevent bacterial leakage, secondary caries, and pulpal irritation [24].

The rigid metallic nature of SSCs facilitates consistent marginal crimping and may contribute to reduced marginal discrepancies after cementation. In contrast, the underlying factors responsible for the slightly higher microleakage observed in BioFLX crowns were not directly investigated in the present study. It may be hypothesized that differences in internal surface characteristics, polymer flexibility, or thermal expansion behavior between the crown material and the luting cement could influence marginal stability during thermocycling. However, these explanations should be interpreted as speculative, and further studies incorporating direct mechanical and thermal analyses are required to clarify their potential role in microleakage. Nevertheless, He J *et al.* [25] (2024) highlighted that the choice of luting cement and its elastic modulus can also influence interfacial stress distribution and sealing ability, suggesting that optimized cementation protocols may mitigate microleakage in BioFLX restorations.

Although *in vitro* results clearly favored SSCs, clinical studies have consistently shown that BioFLX crowns perform satisfactorily in the oral environment and can serve as functional alternatives to SSCs in pediatric patients [23, 26, 27]. Patil *et al.* [23] (2024) conducted a 12-month split-mouth randomized clinical trial and found comparable success rates between SSCs and BioFLX crowns for retention, gingival health, and anatomic form, with SSCs showing only a slight advantage in retention. Similarly, Adelhafez and Dhar (2025) reported that stainless-steel, zirconia, and BioFLX crowns demonstrated favorable clinical performance after 1 year of follow-up, with stainless-steel crowns showing marginally superior retention [27]. These clinical findings are consistent with the present study's results, indicating that although stainless-steel crowns provide superior mechanical performance, BioFLX crowns may serve as a viable esthetic alternative when esthetic considerations are prioritized.

From an aesthetic perspective, BioFLX crowns present a significant advantage over SSCs. The metallic appearance of SSCs often causes parental dissatisfaction and self-consciousness in children [27]. BioFLX crowns, by contrast, provide a tooth-colored, translucent finish closely mimicking natural enamel, improving patient and parent acceptance. Their polymeric matrix also allows easier contouring and chairside adjustment than the brittle, non-modifiable structure of zirconia crowns. Amer (2025) emphasized that BioFLX crowns offer favorable clinical outcomes (retention rates of 92–98%) with the additional benefit of superior esthetics. However, surface staining and long-term wear remain potential limitations that require further research [15].

Thermocycling in this study simulated thermal fluctuations of the oral environment, providing realistic aging conditions comparable to one year of intraoral function. Abo-Elsoud *et al.* [18] (2024) confirmed that thermomechanical aging significantly affects marginal adaptation and fracture resistance, particularly in polymeric crown systems. While such *in vitro* models are essential for standardization, they cannot replicate the complex biological environment of the oral cavity, including saliva, pH variations, and masticatory fatigue. Therefore, long-term clinical studies are necessary to validate the laboratory results and assess color stability, wear, retention, and parental satisfaction.

Several limitations of the present study should be acknowledged. First, typodont teeth were used instead of extracted human teeth to ensure uniformity; however, natural tooth structure might influence cement penetration and bond strength. Second, only one luting cement type was evaluated; using alternative cements, such as resins or bioactive materials, may affect microleakage outcomes. Third, the compressive strength test measured static loads; fatigue and cyclic loading tests could provide more realistic insights into long-term clinical performance. Fourth, the experimental setting did not fully replicate the physiological oral environment. In particular, the absence of artificial saliva represents a limitation, as salivary contamination and humidity may influence cementation quality and marginal sealing, particularly in pediatric clinical settings where moisture control is challenging. Future research combining finite element analysis and *in vivo* evaluations could offer a more comprehensive understanding of stress distribution, material wear, and failure modes of BioFLX crowns.

Overall, the results of the present study align with recent literature demonstrating that SSCs remain the most durable and well-sealed option for restoring primary molars [24, 26, 27]. Nevertheless, BioFLX crowns provide a favorable balance between function and esthetics, making them an appealing choice for children and parents seeking metal-free restorations. As the demand for esthetic pediatric treatments continues to increase, materials like BioFLX crowns are expected to play an increasingly important role in modern pediatric dental care, provided that long-term clinical data continue to support their mechanical and biological performance [15–27].

5. Conclusions

Within the limitations of this *in vitro* study, the following conclusions can be drawn:

1. Stainless-steel crowns showed higher compressive strength and lower microleakage than BioFLX crowns.

2. BioFLX crowns demonstrated acceptable *in vitro* performance comparable to other esthetic pediatric crowns.

3. BioFLX crowns may be considered an esthetic alternative to stainless-steel crowns; however, further clinical evidence is required.

AVAILABILITY OF DATA AND MATERIALS

The datasets generated and/or analyzed during the current study and the materials used are available from the corresponding author upon reasonable request.

AUTHOR CONTRIBUTIONS

MAB—designed the research study, performed all experimental procedures, collected the data, and conducted the statistical analysis. ESE—contributed to manuscript writing, provided critical revisions, and supervised the research process. MÖK—provided conceptual guidance and critically reviewed the manuscript. All authors contributed to editorial changes in the manuscript. All authors read and approved the final manuscript.

ETHICS APPROVAL AND CONSENT TO PARTICIPATE

Not applicable.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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