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ORIGINAL RESEARCH

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The effect of restorative material and application timing on the bond strength to primary dentin treated with silver diamine fluoride

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Abstract

Background: This *in vitro* study evaluated the effects of restorative material, specifically resin-modified glass ionomer cement (RMGIC; Fuji II LC, GC Corporation, Japan) compared to bulk-fill flowable composite resin (SDR Plus, Dentsply Sirona, Germany), and the timing of their application timing on the bond strength to artificially demineralized primary dentin treated with 38% silver diamine fluoride (SDF; Riva Star, SDI, Australia). **Methods**: Sixty-eight extracted primary molars with artificially demineralized, flat dentin surfaces were randomly assigned to four groups (n = 17/group) according to restorative material and timing of application: GIC0 (RMGIC—day 0), BF0 (bulk-fill composite—day 0), GIC14 (RMGIC—day 14), and BF14 (bulk-fill composite—day 14). For bulk-fill restorations, a universal adhesive system was applied according to the manufacturer's instructions. Following the SDF application and restoration procedures, all specimens were stored in artificial saliva for 30 days before testing. Macro-shear bond strength (SBS) was measured, fracture types were classified under a stereomicroscope, and selected specimens were further analyzed using scanning electron microscopy (SEM). **Results**: Application timing significantly influenced bond strength, whereas restorative material type showed no significant effect. Restorations placed 14 days after SDF application demonstrated significantly higher bond strength than those placed on day 0 for both RMGIC (p = 0.009) and bulk-fill composite (p = 0.011). The highest mean bond strength was observed in BF14 (5.56 $\pm$ 3.54 MPa; bulk-fill composite—day 14), while the lowest was in GIC0 (1.78 $\pm$ 1.46 MPa; RMGIC—day 0). Although bulk-fill composite demonstrated higher mean values than RMGIC within the same application time, the difference was not statistically significant ($p > 0.05$). **Conclusions**: Bond strength improved when restoration was delayed by two weeks after SDF application. Although the restorative material type did not significantly affect bond strength, application timing should be considered to optimize clinical outcomes.

Keywords

Silver diamine fluoride; Bond strength; Shear bond strength; Resin-modified glass ionomer; Bulk-fill composite

1. Introduction

Minimally invasive approaches have been gaining increasing importance in the management of childhood dental caries, particularly because limited cooperation among younger children often reduces the feasibility of conventional restorative treatments and may necessitate intervention under general anesthesia [1]. This situation creates substantial challenges, including higher treatment costs, limited access to care, and prolonged waiting times; therefore, there is a need to reinforce simpler, more practical, and effective alternative treatment strategies [1, 2].

In response to this need, silver diamine fluoride (SDF) has emerged as a prominent non-invasive treatment option in pediatric dentistry because of its low cost, painless, and rapid application. It has also been shown to be effective in arresting caries progression and lack of aerosol generation [3–5], providing a safe and effective alternative to invasive procedures, particularly for young children and individuals with special healthcare needs. However, SDF primarily inactivates the carious lesion and does not restore lost tooth structure; therefore, placement of restorative materials after SDF application is recommended to restore function, prevent food impaction, and mask potential discoloration [6, 7].

In pediatric dentistry, particularly among young children and individuals with special healthcare needs, where patient cooperation is often limited, the selected restorative material should be easy to apply, quick to adapt, and associated

with minimal technique sensitivity [8]. Accordingly, resin-modified glass ionomer cement (RMGIC) is one of the most commonly preferred materials following SDF application, given its fluoride release, moisture tolerance, and chemical bonding properties [9]. In parallel, bulk-fill flowable composite resins offer notable clinical advantages because they can be placed in a single increment and simplify the restorative procedure, which may be especially beneficial in time-limited clinical settings [10, 11].

Although the effectiveness of SDF in arresting carious lesions is well documented, there is no clear consensus regarding its influence on the bond strength of restorative materials applied afterward. Some studies report that SDF may reduce the effectiveness of adhesive systems by occluding dentinal tubules and altering dentin surface characteristics [12–14], while others indicate that these adverse effects can be minimized through appropriate surface treatments [15–18].

Similarly, there is limited and conflicting evidence regarding whether restorative materials should be applied immediately after SDF treatment or following a defined waiting period [19]. This uncertainty complicates clinical decision-making, especially in young children or those with special healthcare needs who may have limited cooperation, because whether treatment can be completed in a single visit or needs to be staged over time may directly influence bonding success.

Although the effectiveness of SDF in arresting carious lesions has been extensively investigated, most studies assessing its interaction with restorative materials have primarily focused on immediate bonding outcomes [12, 20]. Moreover, a substantial proportion of the available evidence is derived from studies on permanent teeth or includes additional surface pretreatment steps that may not always reflect routine pediatric clinical practice [7, 12]. Consequently, information regarding the bonding performance of restorative materials placed after a delayed period following SDF application on primary dentin remains limited. In addition, comparative data evaluating commonly used, low-technique-sensitive restorative materials in relation to restoration timing after SDF treatment remain scarce [9, 10].

In this context, evaluating the effects of application timing on the bond strength of RMGIC and bulk-fill composite—both commonly used in pediatric patients and considered relatively low in technique sensitivity—has clinical importance. Therefore, the aim of this *in vitro* study was to compare the bond strength of RMGIC and bulk-fill composite restorations applied either immediately (day 0) or 14 days after SDF treatment on demineralized primary teeth.

The null hypotheses of this study were as follows:

1. There is no statistically significant difference in the shear bond strength (SBS) of different restorative materials applied after SDF treatment.

2. The timing of restorative material application following SDF treatment has no statistically significant effect on SBS.

2. Materials and methods

This *in vitro* study was designed to compare the SBS of restorative materials, specifically RMGIC (Fuji II LC Capsule, GC Corporation, Japan) and bulk-fill flowable composite resin (SDR Plus, Dentsply Sirona, Germany), applied at different time intervals to demineralized dentin surfaces of primary teeth treated with 38% SDF (batch no. 1218197, Riva Star Step 1, SDI Limited, Bayswater, VIC, Australia) (Fig. 1). The study was conducted between August 2024 and December 2024.

2.1 Sample size calculation

The study sample size was calculated using G*Power 3.1 software (Heinrich Heine University, Düsseldorf, NRW, Germany) based on data reported by Aldowsari *et al.* [20]. Using an alpha error level of 0.05, a beta error level of 0.20 (power = 80%), and an effect size of 0.8, a total of 68 specimens (17 per group) was determined to be sufficient. To account for potential specimen loss, 80 primary teeth were initially included in the study.

2.2 Specimen selection and preparation

In this study, extracted primary molars were used, either removed for orthodontic reasons or naturally exfoliated due to physiological root resorption. The inclusion criteria were caries-free, untreated primary molars obtained through physiological means. Teeth with carious lesions, structural defects, or a history of restorative or endodontic procedures were excluded. Debris on the extracted teeth was removed using a polishing brush, and the specimens were stored in 0.5% thymol solution until testing. The extracted teeth were stored in thymol solution for short-term disinfection during specimen collection, which was completed within approximately two weeks, and prolonged thymol exposure was avoided.

All specimens were embedded in autopolymerizing acrylic resin up to the cementoenamel junction using silicone molds. To obtain a flat dentin surface, each tooth was sectioned parallel to the occlusal plane using a water-cooled low-speed precision cutting device (Micracut 125 Low Speed Precision Cutter, Metkon, Bursa, Türkiye).

This *in vitro* study was conducted following institutional ethical guidelines for the use of extracted human teeth.

2.3 Demineralization and silver diamine fluoride (SDF) application protocol

A demineralization solution was prepared to create artificial caries-like lesions on primary dentin. The solution consisted of 2.2 mM $CaCl_2 \cdot 2H_2O$, 2.2 mM KH_2PO_4, and 0.05 M acetic acid, with the pH adjusted to 4.4 using 10 M KOH. All specimens were immersed in this solution for 5 days at 37 °C, following previously published recommendations [21]. The demineralization solution was not renewed during these 5 days to maintain consistent demineralization conditions [21].

After demineralization, each specimen was treated with 38% SDF solution. The SDF-treated surfaces were gently air dried without rinsing, allowing evaluation of a simplified and clinically relevant SDF protocol. Specimens that were scheduled for restorative procedures 14 days after SDF treatment were stored in artificial saliva at 37 °C, with the pH adjusted to 7 throughout the storage period. The artificial saliva was prepared using the following formulation per 1 L of solution: 0.4 g NaCl, 0.4 g KCl, 0.795 g $CaCl_2 \cdot 2H_2O$, 0.69

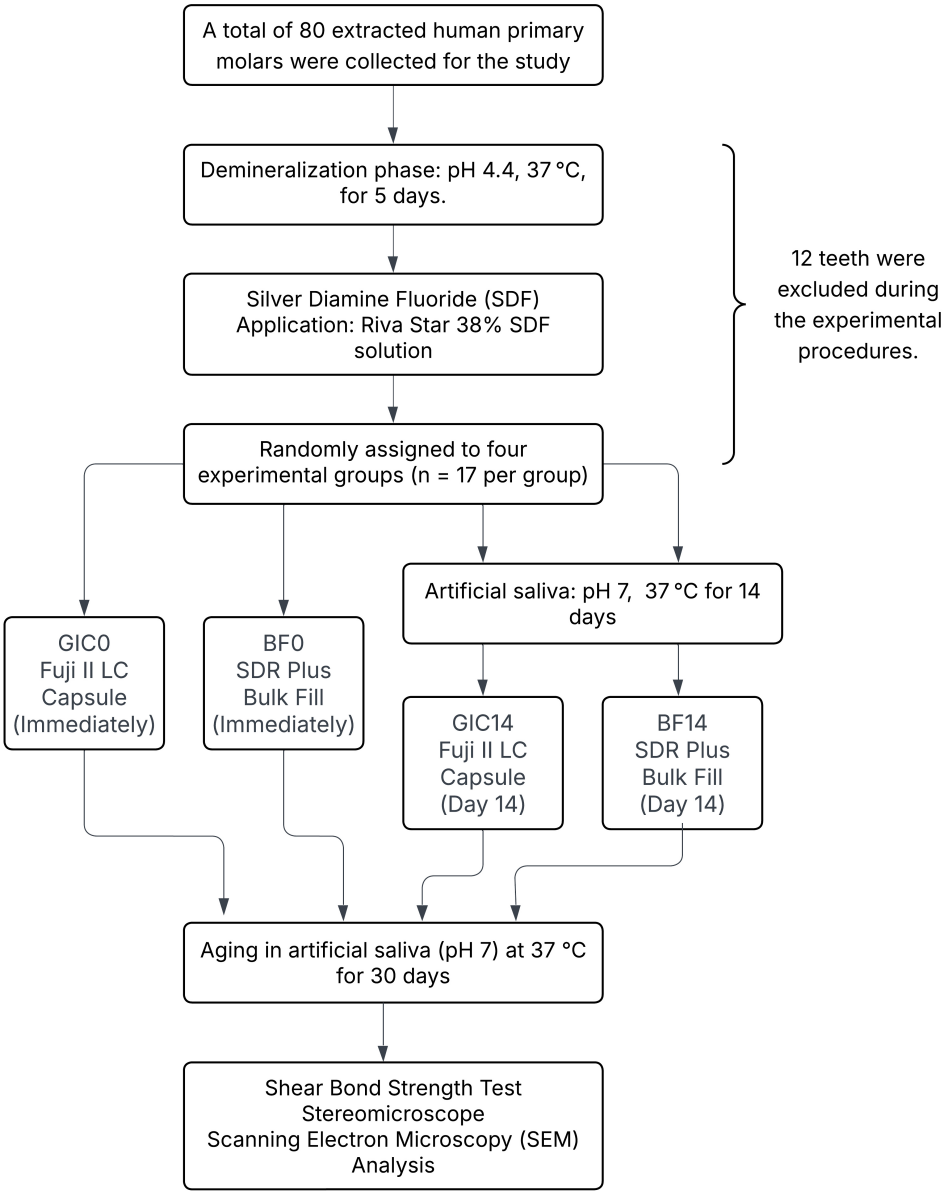

FIGURE 1. Flowchart of the *in vitro* study design and group allocation. GIC0: resin-modified glass ionomer cement—day 0; BF0: bulk-fill composite—day 0; GIC14: resin-modified glass ionomer cement—day 14; BF14: bulk-fill composite—day 14.

g $NaH_2PO_4 \cdot H_2O$, and 0.005 g $Na_2S \cdot 9H_2O$ [22].

2.4 Restorative material application procedure and group allocation

The properties of the restorative materials used in this study are presented in Table 1.

The specimens were randomly assigned to four groups using computer-assisted randomization:

• GIC0: RMGIC applied immediately (Day 0) after SDF application.

• BF0: Bulk-fill composite applied immediately (Day 0) after SDF application.

• GIC14: RMGIC applied on Day 14 after SDF application.

• BF14: Bulk-fill composite applied on Day 14 after SDF application.

Before the RMGIC application, a cavity conditioner (batch no. 2304111, GC Corporation, Tokyo, Japan) was applied to the designated 3 mm bonding area. The material was then injected into a cylindrical mold (3 mm internal diameter and 4 mm height) and light-cured for 20 s. For bulk-fill composite restorations, surface treatment was performed using Prime & Bond Universal adhesive (batch no. 2402000703, Dentsply Sirona, Konstanz, BW, Germany), after which the composite was injected into the same mold and light-cured for 20 s (Fig. 2). This adhesive protocol was selected according to the manufacturer's instructions and applied in self-etch mode without an additional phosphoric acid etching step to reflect a simplified and clinically applicable bonding approach.

To standardize the bonding area, a cylindrical mold (3 mm internal diameter) was positioned on the dentin surface before surface pretreatment. The cavity conditioner or adhesive was applied only within the mold area, and the restorative material was subsequently injected into the mold and light-cured. All restorative materials were light-cured using a light-curing unit (LED.B, Woodpecker Medical Instruments Co., Ltd., Guilin,

TABLE 1. Materials used, their composition, purpose, and application protocols.

Material Name/Manufacturer	Type/Composition	Application Purpose/Applied Group(s)	Application Protocol
Riva Star (Step 1) SDI Dental Ltd. (Australia)	38% Silver Diamine Fluoride (SDF) solution	Application of SDF to demineralized dentin (All groups)	- Dry the surface - Apply to dentin using a microbrush (~20 s) (1 drop per 5 teeth) - Gently air dry after 1 minute - No rinsing
Fuji II LC Capsule GC Corporation (Japan)	Resin-modified glass ionomer cement (RMGIC)	Restorative material (GIC0 and GIC14)	- Activate capsule - Mix for 10 seconds - Apply to the tooth - Light-cure for 20 seconds
SDR Plus Bulk-Fill Dentsply Sirona (Germany)	Bulk-fill Flowable composite resin	Restorative material (BF0 and BF14)	- Apply directly from the syringe onto the tooth - Light-cure for 20 seconds
Cavity Conditioner GC Corporation (Japan)	20% Polyacrylic acid solution	Dentin surface conditioning before RMGIC application (GIC0 and GIC14)	- Apply with a microbrush - Wait for 10 seconds - Rinse with water
Prime&Bond Universal Dentsply Sirona (Germany)	Universal adhesive (acetone-based)	Adhesive agent prior to bulk-fill composite application (BF0 and BF14)	- Apply with a microbrush - Air-dry for 5 seconds - Light-cure for 20 seconds

GIC0: resin-modified glass ionomer cement—day 0; BF0: bulk-fill composite—day 0; GIC14: resin-modified glass ionomer cement—day 14; BF14: bulk-fill composite—day 14.

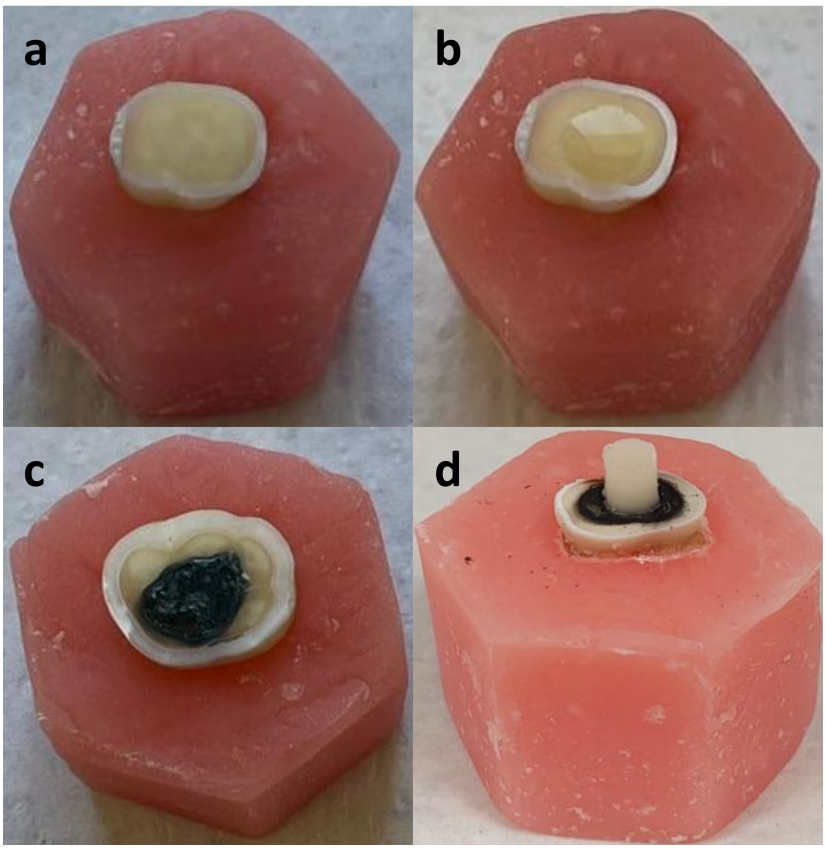

FIGURE 2. Specimen preparation and treatment procedures. (a) Prepared dentin section embedded in acrylic resin. (b) Application of SDF to the designated area. (c) Appearance of the dentin surface after silver diamine fluoride (SDF) application. (d) Appearance of specimens after restorative material application.

Guangxi, China) with an irradiance of approximately 1000–1200 mW/cm^2, in accordance with the manufacturer's instructions. All restorative procedures were performed by a single operator following standardized manufacturer instructions to minimize operator-dependent variability.

Following these procedures, all specimens were aged in artificial saliva (pH 7) at 37 °C for 30 days. During specimen preparation and the subsequent experimental procedures, 12 specimens were excluded because of technical failures related to restorative material application, and no fractures involving the tooth structure were observed. The study was therefore completed with 68 specimens (n = 17 per group). After group allocation, no pre-test failures occurred before SBS testing.

2.5 Bond strength testing

After the aging process, the specimens were mounted in an Instron Universal Testing Machine (Model 3382, Instron Corp, Canton, MA, USA) for SBS testing. A shear force was applied perpendicular to the restorative material using a chisel-shaped metal blade at a crosshead speed of 0.5 mm/min until failure occurred. The maximum load at failure was recorded in Newtons (N), and SBS was then calculated in megapascals (MPa) by dividing the failure load by the bonded surface area. A macro-SBS test was performed. To standardize the bonding area across specimens, a cylindrical mold with an internal diameter of 3 mm was used, corresponding to a bonding area of 7.07 mm^2 ($A = \pi r^2$).

2.6 Fracture surface evaluation

The fracture surfaces of all specimens were examined under a stereomicroscope (SZ-4045 ESD, Olympus Corporation, Tokyo, Japan) at 40× magnification. The failure modes were classified into three categories: adhesive, cohesive, and mixed. Adhesive and mixed failures were determined based on stereomicroscopic inspection of the debonded surfaces, following commonly used criteria in bond strength studies. This evaluation was performed by a single experienced examiner who was not involved in the restorative procedures. Formal examiner calibration and blinding were not performed; however, fracture mode assessment was conducted as a descriptive analysis to support the SBS results rather than as a primary outcome measure.

2.7 Scanning electron microscope (SEM) analysis

Two specimens were randomly selected from each group and prepared for SEM analysis at the MERLAB Laboratory of Karadeniz Technical University. The surfaces were gold-coated, and SEM images were obtained using an EVO LS10 system (Zeiss, Oberkochen, BW, Germany) at 100× and 1000× magnifications. SEM analysis was performed to provide representative surface observations and was not used for failure mode classification.

2.8 Statistical analysis

Data were analyzed using SPSS for Windows version 23.0 (SPSS Inc., Chicago, IL, USA). The Shapiro-Wilk test was used to assess normality. Descriptive statistics were reported as mean, standard deviation, median, minimum, and maximum values, and median and interquartile range (IQR) were additionally provided to better describe the distribution of non-normally distributed data. Group comparisons were performed using the Kruskal-Wallis test, and the Mann-Whitney U test with Bonferroni correction was applied for pairwise comparisons. The wide minimum to maximum ranges reflects observed extreme values in groups with limited sample size and were therefore interpreted in conjunction with the median and IQR. A p-value < 0.05 was considered statistically significant.

3. Results

The SBS values differed significantly among the groups. Restoration timing significantly influenced bond strength, whereas the type of restorative material did not show a statistically significant effect under the tested conditions.

Among all groups, the highest mean SBS value was observed in the group restored with bulk-fill composite 14 days after SDF application (5.56 ± 3.54 MPa), while the lowest mean SBS value was recorded in the group in which RMGIC was applied immediately after SDF treatment (1.78 ± 1.46 MPa).

In both restorative material groups, restorations performed 14 days after SDF application demonstrated significantly higher SBS values than those performed immediately (Day 0) (RMGIC: $p = 0.009$; bulk-fill composite: $p = 0.011$). However, when compared within the same application time, although the bulk-fill composite groups showed higher mean values than the RMGIC groups, the difference was not statistically significant ($p > 0.05$).

The detailed statistical data for each group are presented in Table 2, and a comparative graph of the SBS values is shown in Fig. 3.

Following the SBS test, fracture surfaces were examined under a stereomicroscope and classified as adhesive, mixed, or cohesive failure. Overall, adhesive failure was the most frequently observed mode across all groups. An exception was noted in the GIC0 group, in which mixed failures occurred more frequently than adhesive failures. In the remaining groups, adhesive failures were followed by mixed failures, and no cohesive failures were observed in any specimen (Table 3).

When the distribution of failure modes was evaluated by restorative material, adhesive failures predominated in the bulk-fill composite groups, whereas the RMGIC groups showed similar proportions of adhesive and mixed failures (Table 3, Fig. 4).

4. Discussion

In this *in vitro* study, the SBS of two different restorative materials applied after treatment with 38% SDF was evaluated, together with the effect of restoration timing (day 0 and day 14) on SBS. The results demonstrated that restoration timing had a statistically significant effect on SBS, whereas restorative material type did not show a statistically significant difference under the tested conditions. Accordingly, the null hypothesis stating that "the timing of restorative material application

TABLE 2. Shear bond strength values of the groups and intergroup comparisons.

Group	n	Mean ± SD (MPa)	Median (IQR) (MPa)	Min–Max (MPa)	Statistical Comparison
GIC0	17	1.78 ± 1.46	1.29 (1.9)	0.2–5.8	GIC0[1] < GIC14 ($p = 0.009$*)
BF0	17	2.64 ± 2.33	2.40 (2.5)	0.4–8.6	BF0[2] < BF14 ($p = 0.011$*)
GIC14	17	4.32 ± 3.57	3.73 (4.1)	0.5–14.8	GIC14 > GIC0[1] ($p = 0.009$*)
BF14	17	5.56 ± 3.54	5.06 (5.6)	1.2–12.4	BF14 > BF0[2] ($p = 0.011$*)
					GIC0 *vs.* BF0 and GIC14 *vs.* BF14: not significant ($p > 0.05$)

[1]*Comparison between GIC0 and GIC14.* [2]*Comparison between BF0 and BF14.*
Statistical analysis: Pairwise comparisons were performed using the Mann-Whitney U test with Bonferroni correction.
**$p < 0.05$ indicates statistical significance.*
IQR (interquartile range) values are reported as Q3–Q1 and reflect data dispersion in non-normally distributed samples.
Minimum–maximum values represent observed extremes and may include individual outlier measurements.
SD: standard deviation; GIC0: resin-modified glass ionomer cement—day 0; BF0: bulk-fill composite—day 0; GIC14: resin-modified glass ionomer cement—day 14; BF14: bulk-fill composite—day 14.

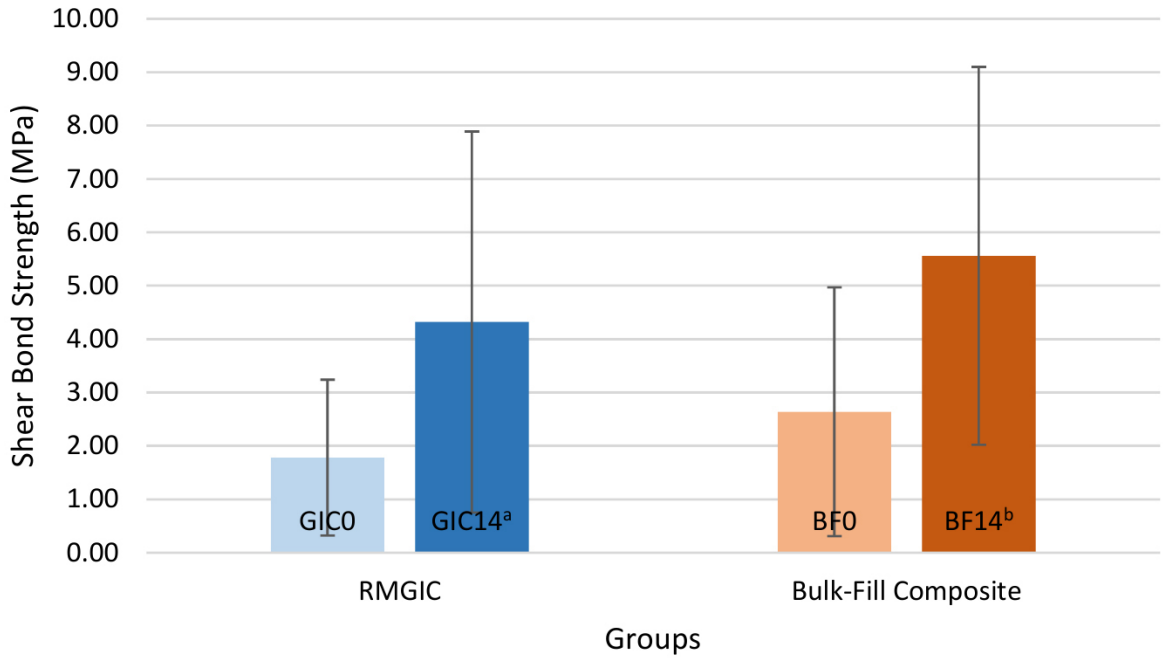

FIGURE 3. Shear bond strength of restorative materials applied immediately and 14 days after SDF treatment. The bars represent mean shear bond strength values (MPa), and error bars indicate standard deviation (SD). Group codes indicate restorative material and application timing (GIC0 and BF0: immediate restoration; GIC14 and BF14: restoration after 14 days). Different lowercase letters indicate statistically significant differences between groups ($p < 0.05$). [a]GIC0–GIC14; $p = 0.009$, [b]BF0–BF14; $p = 0.011$. RMGIC: resin-modified glass ionomer cement; GIC0: resin-modified glass ionomer cement—day 0; BF0: bulk-fill composite—day 0; GIC14: resin-modified glass ionomer cement—day 14; BF14: bulk-fill composite—day 14.

TABLE 3. Distribution of fracture types.

Group	n	Adhesive Failure n (%)	Mixed Failure n (%)	Cohesive Failure n (%)
GIC0	17	8 (47.1%)	9 (52.9%)	0 (0.0%)
BF0	17	15 (88.2%)	2 (11.8%)	0 (0.0%)
GIC14	17	10 (58.8%)	7 (41.2%)	0 (0.0%)
BF14	17	12 (70.6%)	5 (29.4%)	0 (0.0%)

GIC0: resin-modified glass ionomer cement—day 0; BF0: bulk-fill composite—day 0; GIC14: resin-modified glass ionomer cement—day 14; BF14: bulk-fill composite—day 14.

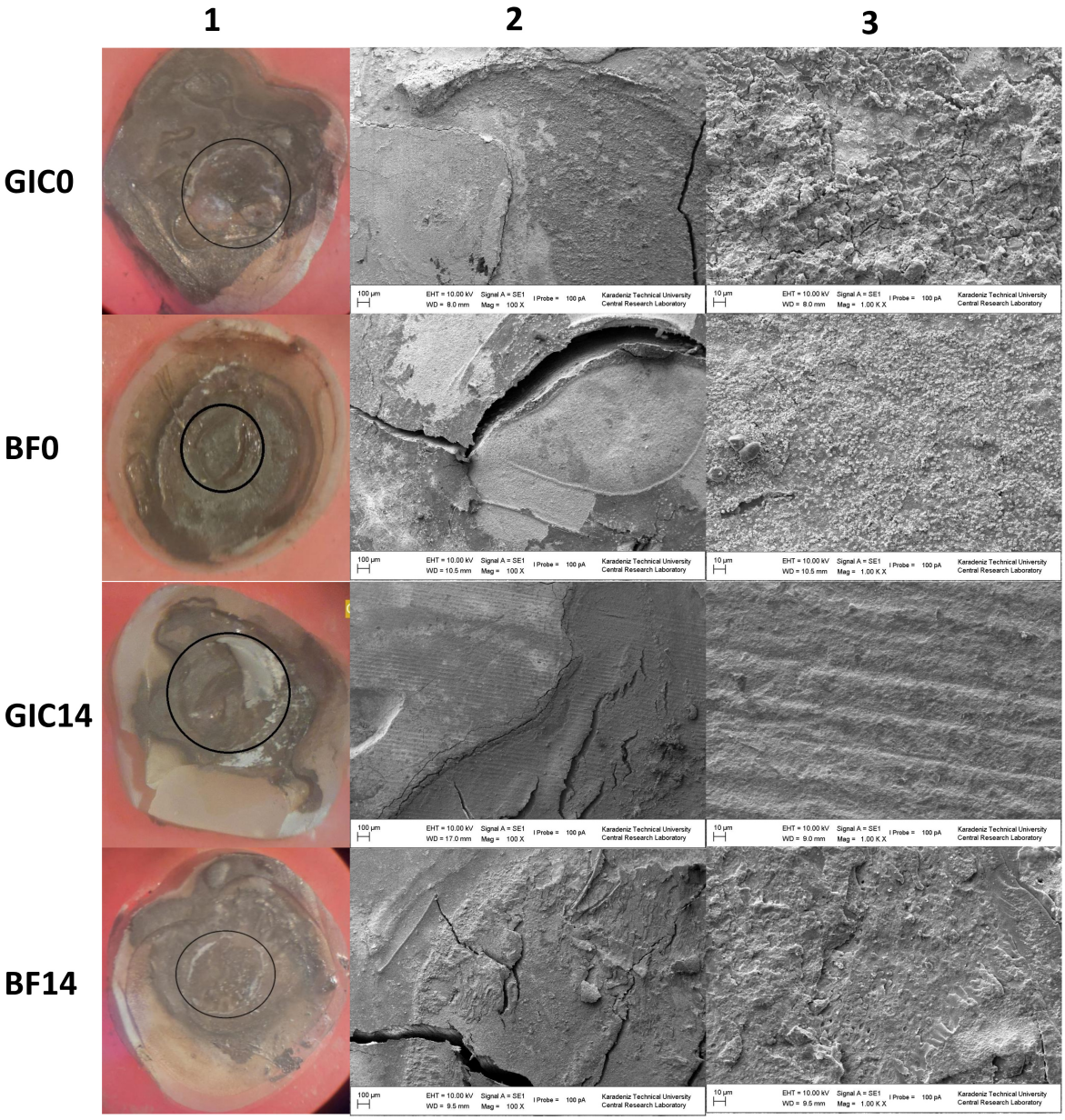

FIGURE 4. Micromorphological evaluation of restored specimens. Representative stereomicroscopic and SEM micrographs of the debonded surfaces obtained after the shear bond strength test for each experimental group are shown. Images are presented at three magnifications: (1) a 40× stereomicroscopic view showing the standardized bonding area (circled), (2) an SEM image at 100× magnification, and (3) an SEM image at 1000× magnification. The specimen shown in BF0 illustrates an adhesive failure pattern, whereas the specimens shown in the other groups illustrate mixed failure patterns. GIC0: resin-modified glass ionomer cement—day 0; BF0: bulk-fill composite—day 0; GIC14: resin-modified glass ionomer cement—day 14; BF14: bulk-fill composite—day 14; EHT: electron high tension (accelerating voltage); WD: working distance; SE: secondary electron; Mag: magnification.

following SDF treatment has no statistically significant effect on SBS" was rejected, while the null hypothesis proposing that "there is no statistically significant difference in SBS values between different restorative materials applied after SDF treatment" could not be rejected within the scope of the tested protocols.

Although the microtensile bond strength (μTBS) test theoretically provides high sensitivity for evaluating bond strength, it is also associated with increased specimen loss and potential methodological reliability concerns, particularly because primary teeth have limited dentin thickness and a relatively fragile structure [23]. Therefore, in the present study, the SBS test was preferred for comparative evaluation because of its practical applicability and its widespread use in the literature [24–26]. Nevertheless, limitations of the SBS test, including the non-homogeneous distribution of stress, should be taken into account, and the results should be interpreted primarily through intergroup comparisons rather than as absolute bond strength values.

In this study, only Step 1 of the Riva Star system (38% SDF) was applied, and the potassium iodide stage (Step 2) was not included. This approach was adopted because discoloration

control was not among the objectives of the study, and the primary aim was to evaluate the effect of SDF on bond strength to demineralized primary tooth dentin. Considering that potassium iodide application may alter the structure of precipitates formed on the dentin surface and thereby influence adhesive interactions [6, 27], the present findings should be interpreted specifically within the context of the Step 1 SDF application protocol.

A static demineralization model was used to create standardized caries-like lesions. This model enabled the acquisition of a controlled and reproducible demineralized dentin surface, thereby reducing inter-sample variability. Although dynamic pH-cycling models may better simulate intraoral conditions [28], static models remain widely used in *in vitro* studies because of their practical applicability and their ability to provide consistent demineralization outcomes [29]. Nevertheless, it should be acknowledged that this approach does not fully reflect the biological complexity of clinically active caries.

The selection of a 30-day aging period in neutral pH artificial saliva was based on its frequent use as a short-term chemical aging protocol in bond strength studies [19, 20, 25]. Although this approach provides standardized storage conditions, it does not fully replicate the dynamic oral environment, particularly in pediatric patients with high caries activity. Previous studies have reported that, while artificial saliva storage may allow some degree of mineral exchange, it cannot reproduce the thermal stresses and cyclic loading conditions encountered *in vivo* [30]. Accordingly, aging methods such as thermocycling and mechanical loading are generally considered more clinically relevant, especially when the long-term durability of adhesive bonds is being evaluated [31]. However, within the context of the present study, the 30-day storage period was intended to provide a basic level of chemical aging while minimizing variables introduced by more complex *in vitro* simulations.

Difficulties associated with direct bonding to SDF-treated dentin have been well documented. In particular, 38% SDF applied without rinsing can leave mineral precipitates composed of silver- and phosphate-containing components on the dentin surface, and these deposits may occlude dentinal tubules and limit adhesive interactions [32]. Nevertheless, functional monomers present in modern universal adhesive systems, such as 10-methacryloyloxdecyl dihydrogen phosphate (10-MDP), are capable of chemical bonding and may still interact, although to a limited extent, with this modified surface; at the same time, they may contribute to micromechanical retention through adaptation to dentin morphology. Although these mechanisms may not achieve ideal bond strength levels, they can still contribute to measurable and potentially clinically relevant bonding values [33, 34]. Therefore, the ability of the universal adhesive system used in the present study to achieve bonding after SDF application without rinsing may be related to the chemical and physical bonding capacity of these functional monomers. However, the literature also suggests that this simplified protocol may limit bond strength, and the findings should therefore be interpreted with caution [35].

Consistent with these mechanistic considerations, previous studies have reported variable effects of SDF on dentin bonding, with outcomes influenced by the restorative material used and the specific application protocol [35, 36]. Fröhlich *et al.* [34] reported that SDF application did not affect the bond strength of glass ionomer cements to dentin, whereas it could adversely influence the bonding performance of adhesive systems. Other studies have suggested that combining SDF with potassium iodide (SDF-KI) may increase the bond strength of RMGIC [15], and that incorporating SDF into glass ionomer cement may enhance bonding to enamel and dentin margins without increasing microleakage [37]. In contrast, adverse effects have also been reported with certain SDF application methods; for example, when SDF is used as a rinsing agent, reduced bond strength between root dentin and fiber posts has been demonstrated [38].

Our findings also suggest that the effects of SDF on dentin bonding mechanisms may vary according to the restorative material used, the surface treatment applied, and the specific application protocol. Aldowsari *et al.* [20] compared the bond strength of different restorative materials in permanent molars treated with 38% SDF and reported that bulk-fill composite exhibited higher bond strength values than RMGIC. Similarly, in the present study, higher SBS values were obtained in the bulk-fill composite group than in the RMGIC group; however, this difference was not statistically significant. This pattern may be related to the physico-mechanical properties of bulk-fill composites, including low viscosity, reduced polymerization shrinkage stress, and a low elastic modulus, which may support stress distribution at the bonded interface [39–41]. In contrast, despite the fluoride release and chemical bonding potential of RMGIC to dentin, RMGIC has been reported to be disadvantaged in terms of bond strength because of its relatively inferior mechanical properties and the presence of internal microporosities within the material [42].

In this study, a 14-day waiting period was selected because it represents a clinically feasible recall interval in pediatric dentistry. This duration may allow mineral deposition and surface stabilization to occur on the dentin surface following SDF application [43], while also providing a realistic approach for staged treatment in children with limited cooperation [44]. In addition, this interval is consistent with previous studies reporting improved bond strength with delayed restorations [19, 45].

In a study evaluating the effect of restoration timing on bond strength after SDF application, restorations placed immediately after SDF treatment were reported to show reduced bond strength, whereas waiting for 24 hours and performing surface polishing significantly improved bonding performance [32]. In another study, delaying the restoration was shown to enhance bond strength by promoting mineral deposition, with restorations placed after 15 days providing particularly stable outcomes [45]. Our findings align with these reports, because in both the RMGIC and bulk-fill groups, restorations performed 14 days after SDF application demonstrated significantly higher bond strength than restorations placed immediately (day 0) ($p < 0.05$). These results indicate that restoration timing after SDF treatment is a critical factor for clinical success.

SEM analyses further supported these findings, revealing a more irregular and particulate dentin surface morphology in specimens restored immediately after SDF application, whereas a more compact and homogeneous surface structure

was observed in specimens allowed to mature for 14 days. This difference may be related to increased mineral deposition and improved surface stabilization over time.

In this study, the fracture types of RMGIC and bulk-fill composite restorations applied at different time intervals after SDF treatment were analyzed. Fracture mode analysis is an important tool for identifying weak points within the bonded complex, because adhesive failures indicate insufficient bonding between the restorative material and dentin, whereas mixed failures may reflect a more balanced stress distribution at the bonding interface. Importantly, these patterns are influenced not only by bond strength but also by the mechanical properties of the restorative material and the morphological condition of the bonding surface.

In the GIC0 (RMGIC) group, in which restorations were placed immediately after SDF application, mixed failures (52.9%) were slightly more frequent than adhesive failures (47.1%). This finding suggests that RMGIC may have provided limited micromechanical retention to dentin despite chemical alterations at the surface. In contrast, the BF0 (bulk-fill composite) group exhibited a markedly high rate of adhesive failures (88.2%), indicating that the bulk-fill composite was unable to achieve adequate bonding to the SDF-treated dentin surface under the tested protocol. Consistent with this observation, previous studies have reported that bonding failures in bulk-fill composite restorations placed after SDF treatment frequently occur at the adhesive interface [34].

For restorations placed 14 days after SDF application, the GIC14 group showed an increase in adhesive failures to 58.8%, accompanied by a decrease in mixed failures to 41.2%. This shift may indicate that, despite higher bond strength values, the bonding interface remained the weakest component of the system. In the BF14 group, however, the proportion of mixed failures increased (11.8% to 29.4%), and adhesive failures decreased (88.2% to 70.6%) compared with the BF0 group, suggesting that delayed application may have contributed to the relative stabilization of the bonding surface in the bulk-fill composite group. Nevertheless, the predominance of adhesive failures in both material groups suggests that SDF may still limit interfacial bonding, even when restorations are delayed [33].

When fracture mode analysis and bond strength are considered together, distinct material-specific patterns become apparent. In the bulk-fill groups, despite the higher bond strength values, most failures were adhesive in nature, which suggests that, given the high cohesive strength of the material, fracture tended to concentrate at the interface as the weakest link of the system. In the RMGIC groups, failures were more evenly distributed; in particular, the predominance of mixed failures in the GIC0 group suggests that crack propagation could occur both within the material and at the interface. Taken together, these findings indicate that a direct relationship between bond strength and fracture mode cannot always be assumed, because this relationship is influenced by multiple variables, including material type, bonding strategy, and surface conditions [27].

The findings of the present study may contribute to clinical decision-making regarding restoration timing and restorative material selection, particularly in pediatric patients with limited cooperation. The use of primary teeth accounts for their distinct morphological and histological characteristics and therefore enhances the clinical relevance of the data for pediatric dentistry. In addition, the relatively large sample size and the combined evaluation of SBS together with micromorphological analyses using SEM represent important methodological strengths.

However, this study was performed under *in vitro* conditions, and the direct generalizability of the findings to the clinical oral environment is therefore limited. The aging process was performed using artificial saliva at neutral pH only, and clinical stress factors such as salivary dynamics, biofilm formation, thermal fluctuations, and masticatory forces were not simulated. This is particularly relevant for pediatric patients with high caries activity, in whom the intraoral environment is typically more acidic and biologically complex. In addition, the use of artificially demineralized sound primary teeth rather than naturally carious dentin may not fully reproduce the structural and biological complexity of clinical lesions, which may influence the translational value of the results. Only two restorative materials (RMGIC and bulk-fill composite) and a single universal adhesive system were evaluated, which limits extrapolation to other material and adhesive combinations. No surface roughening was performed in the bulk-fill composite groups, whereas material-specific pretreatment protocols were applied in the RMGIC groups, and these differences may have influenced bonding behavior. Fracture mode analysis was presented descriptively without statistical evaluation, which restricts the quantitative assessment of potential relationships between bond strength and fracture type. Moreover, the relatively large bonding area with a diameter of 3 mm may have influenced stress distribution at the interface and increased the tendency toward adhesive failures. Finally, the absence of a control group without SDF application precludes direct comparison between SDF-treated and untreated dentin surfaces; therefore, it remains unclear whether delayed restoration achieves performance comparable to that of dentin not treated with SDF. This limitation also restricts the interpretation of whether the improvement in bond strength observed after 14 days is attributable solely to maturation processes or whether it reflects recovery from an initial reduction associated with SDF treatment. Future studies should include untreated controls to clarify whether SDF impairs adhesion or primarily delays the development of optimal bonding conditions.

5. Conclusions

Within the limitations of this *in vitro* study, the timing of restorative procedures following SDF application was found to influence the SBS to demineralized primary tooth dentin under the tested conditions. Specifically, delaying restoration for 14 days resulted in higher bond strength values than immediate restoration. However, the performance of restorative materials should be interpreted in the context of the applied surface pretreatments and adhesive protocols, and the findings of the present study are limited to the specific materials and application procedures evaluated.

AVAILABILITY OF DATA AND MATERIALS

The datasets used during the current study are available from the corresponding author on reasonable request.

AUTHOR CONTRIBUTIONS

MY—Contributed to experimental design; performed the experiments in partial fulfillment of requirements for a degree; carried out specimen preparation and restorative procedures; collected and analyzed data; wrote the manuscript; approved the final version. ÖFG—Conceived the original idea and hypothesis; led the study concept; contributed to experimental design; supervised methodology; contributed substantially to the discussion; proofread and revised the manuscript; approved the final version. MAİ—Contributed substantially to the discussion and interpretation of results; proofread and revised the manuscript for intellectual content; approved the final version.

ETHICS APPROVAL AND CONSENT TO PARTICIPATE

Ethical approval for this study was obtained from the Scientific Research Ethics Committee of Karadeniz Technical University Faculty of Medicine on 21 July 2024, under protocol number 2024/28. As this study was conducted entirely *in vitro*, no human participants were involved, and therefore informed consent was not required.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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