REVIEW ARTICLE

Effect of Topical Fluoride on Composite Bonding Strength: A Narrative Literature Review

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Abstract

Topical fluoride materials are used in dentistry to prevent caries. Composite adhesive resins are commonly used to restore primary and permanent teeth. The interaction between fluoride agents and resin adhesives remains challenging. Hence, this review explores the effect of fluoride agents on the adhesive bond strength of teeth restored with composite. This paper reviews the effect of sodium fluoride, acidulated phosphate fluoride, titanium tetrafluoride, stannous fluoride, and silver diamine fluoride and their application methods, timing, and interactions with adhesives. The effect of fluoride agents on bond strength varies based on concentration and acidity. The weakening of the bond occurs through surface precipitation and etching-induced modifications. Fluoride formulations with neutral pH and lower concentration, with timely application, preserve the bond strength.

Key words: Adhesives, bond strength, composite resin, topical fluorides, varnish

INTRODUCTION

Topical fluoride presents a great challenge to adhesive restorations in restorative dentistry.[1] Topical fluorides, such as gels, varnishes, foams, and solutions, prevent dental caries by several mechanisms. These include promoting remineralization and inhibiting cariogenic bacteria, thereby making enamel resistant to acid attack.[2,3] Composite resins are mainly used for direct fillings and sealing pits and fissures. They are also used in orthodontic bracket bonding, which requires strong adhesion to enamel and dentin.[4,5] The problem arises when topical fluoride application interferes with the adhesive mechanism. Fluoride can modify the tooth surface, disrupting acid etching, resin tag formation, and ultimately affecting adhesive bond strength.[6,7]

The interaction between topically applied fluoride and composite bonding remains inconsistent and scarce.[8] Recently, sodium fluoride (NaF), titanium tetrafluoride (TiF_4), stannous fluoride (SnF_2), and silver diamine fluoride (SDF) have been studied for their chemical properties and uses.[9-11] The complex interaction between fluoride and bonding depends on many factors: Type and concentration of fluoride, properties of the tooth surface (enamel vs. dentin, primary vs. permanent, sound vs. demineralized), and the adhesive system used (etch-and-rinse, self-etch, universal).[12,13] Strong fluoride formulations used immediately before bonding can reduce bond strength due to effects, such as fluoride-compound surface deposits, changes in etching patterns, and disrupted resin monomer penetration.[13,14] However, neutral, low-concentration fluoride agents and proper timing often maintain or improve bond strength.[1,12]

Progress in adhesive technology has raised concerns about its compatibility with fluoride bonding. The growing application of SDF to arrest caries in children and the elderly encourages further research into how it affects future restorations. This review paper explores the effects of topical fluoride on adhesive bond strength. It discusses how fluoride agents, substrate factors, timing, and concentration interact with the bond strength of adhesives. This paper analyzes *in vitro* studies, systematic reviews, and emerging clinical studies

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published mainly from 2020 to 2025. It guides clinicians on preventive fluoride treatments and adhesive dentistry.

BACKGROUND AND THEORETICAL FOUNDATIONS

Fluoride mechanisms in caries prevention

Multiple mechanisms are involved in the anticaries effect of topical fluorides. These include the formation of acid-resistant fluorapatite and fluor hydroxyapatite crystals.[15,16] It also inhibits bacterial glycolysis and enhances remineralization of early carious lesions.[17,18] These beneficial effects depend on elevated fluoride concentrations that are achieved through various delivery vehicles, such as gels (1.23% Acidulated phosphate fluoride [APF] or 2% neutralNaF), varnishes (5% NaF), foams, and solutions. Higher fluoride concentrations are used in professional applications (1.23% APF to 38% SDF) than in over-the-counter products. This results in high fluoride uptake and more substantial surface modifications.[19,20] These surface modifications to resist caries might complicate adhesive bonding, leading to a clinical challenge between preventive and restorative objectives.[3]

Adhesive bonding principles

Effective adhesive bonding to tooth structure depends on forming a hybrid layer in dentin or micromechanical interlocking in enamel. These ensure retention and a proper marginal seal.[21,22] In enamel bonding, phosphoric acid (usually 30–40%) etches the surface by dissolving hydroxyapatite crystals, forming microporosities of 5–50 micrometers. These microporosities permit resin penetration and mechanical interlocking.[23] The formation of adhesive resin tags in close contact with the etched enamel yields adequate bond strength (20–40 MPa) for clinical success.[24] Dentin bonding uses either an etch-and-rinse or a self-etch approach to modify the dentin and facilitate resin infiltration.[25] Universal adhesives are the newest type of bonding agents, offering multiple application modes (etch-and-rinse, self-etch, or selective enamel etch) and compatibility with various substrates and restorative materials. The surface pre-treatment of topical fluoride can affect universal adhesives in clinical practice.[5]

Potential fluoride-bonding interactions

The physical barrier (calcium fluoride [CaF_2], fluorapatite, or metal fluorides) formed by topical fluoride application may interfere with adhesive bonding. This barrier may affect etching and resin infiltration, and ultimate bonding.[13,18] Surface energy and wettability affect adhesive spread.[6] APF alters the mineral phase composition, affecting etching patterns.[5] Fluoride occludes dentinal tubules and reduces the bonding surface area.[16] Some fluoride treatments improve substrate integrity or have little impact at the proper concentration. The significance of these interactions varies with the fluoride used, its concentration, and pH. Fluoride application timing, substrate characteristics, and the adhesive system used can affect the adhesive bonding. Understanding these interactions is crucial to improving caries prevention and restoration.[3] The conceptual framework for the study is shown in Figure 1.

METHODOLOGY

Articles on the effects of topical fluorides and adhesive bonding were searched in Google Scholar and PubMed using relevant keywords. Full-text articles were retrieved after abstract screening. *In vitro*, review articles and clinical studies were considered for the review. English-language publications between 2020 and 2025 were evaluated. The impact of NaF, APF, TiF4, SnF2, and SDF on adhesive bond strength was discussed.

RESULTS

This narrative review included 61 articles published in the past 5 years (2020–2025). Studies reporting on fluoride-enamel surface interactions, etching patterns, and adhesion principles were evaluated. All reported articles were summarized in Table 1, and key findings were presented and discussed.

DISCUSSION

Fluoride agent types and their effects on bond strength

NaF

Neutral NaF is available on the market as a 2% gel and a 5% varnish for clinical use. The impact on composite bond strength varies by situation. Farzaneh *et al*. (2014) examined the bond strength after applying a 2% neutral NaF gel for 4 min before etching and observed no significant difference in shear bond strength between the fluoride-treated and control groups.[1] This indicated that neutral NaF does not compromise enamel bonding when applied before acid etching. Similarly, Biria *et al*. (2019) found no significant decrease in shear bond strength after NaF application in primary teeth compared with APF.[2] Scanning electron microscopy revealed the formation of a thin, symmetric surface layer with neutral NaF, whereas APF created irregular precipitates. Thus, explaining the better bonding profile of NaF varnish. In contrast, Ortiz-Ruiz *et al*. (2018) observed a reduction in shear bond strength on intact enamel if bonding was performed 24 h after fluoride varnish application. The bond strength became normal after 7 days. Moreover, improved bond strength was noted 24 h after mechanical polishing. This suggests that the varnish layer acts as a physical barrier.[3] The use of a universal adhesive had a greater negative impact on intact enamel than

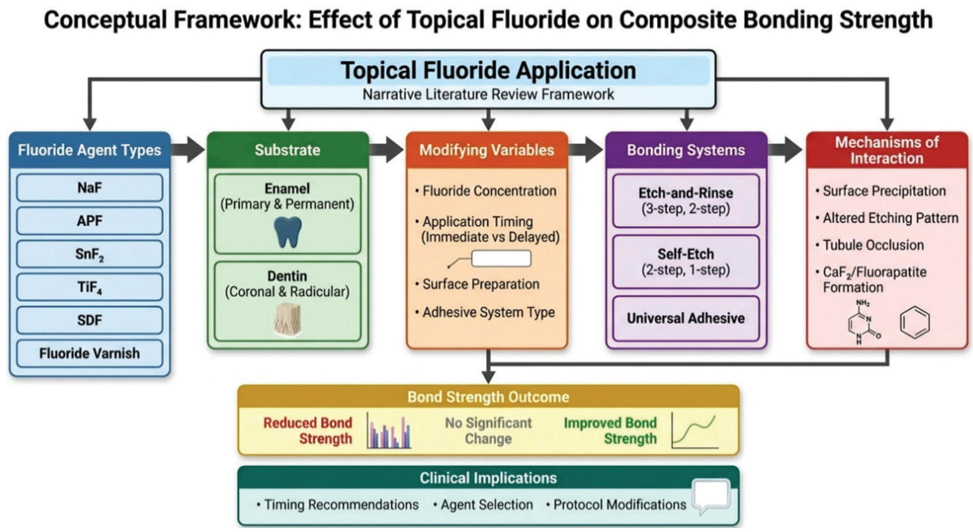

Figure 1: Conceptual framework of the review

Table 1: Summary of the studies published from 2020 to 2025

No.	Author(s), Year	Fluoride Agent	Substrate	Adhesive system	Key finding
1	Ko *et al*., 2020[26]	38% SDF	Dentin (permanent)	Self-etch adhesive	"TBS and interfacial morphology were influenced by SDF concentration; slope-shaped acid-base resistance zone formation was unique to SDF-treated groups."
2	Markham *et al*., 2020[27]	38% SDF	Enamel & dentin	Universal adhesive (SE)	"SDF application significantly reduced bond stability dentin uTBS with SDF (14.8–20.9 MPa) was weaker than controls (19.3–36.1 MPa)."
3	Firouzmandi *et al*., 2020[28]	SDF	Enamel and dentin	Etch-and-rinse	"SDF initially increased bond strength to caries-affected dentin, but this benefit disappeared after artificial ageing."
4	Pirmoradian *et al*., 2020[29]	Fluoride-containing adhesive	Enamel and dentin	Fluoride-releasing SE adhesive	"Fluoride released from adhesive systems declined significantly and adversely influenced bond strength and resin–dentin interface durability."
5	Panahandeh *et al*., 2020[13]	1.23% APF	Enamel	Composite adhesive	"TiF_4 alone and combined with CO_2 laser decreased uSBS APF alone and with laser did not significantly affect uSBS."
6	Al-Qahtani *et al*., 2021[30]	NaF (varied)	Enamel	Composite adhesive	Higher NaF/KF increased acid resistance; uSBS effects were concentrationspecific.
7	Cifuentes-Jimenez *et al*., 2021[31]	SDF	Dentin	Adhesive system	SDF increased mineralization but negatively affected bond strength.
8	Favaro *et al*., 2021[32]	SDF	Enamel	Composite adhesive	SDF and AgNP agents did not reduce uSBS; adhesive failures predominated.
9	Nhan *et al*., 2021[33]	NaF varnish	Not specified	Ortho bonding	Fluoride varnish did not reduce bracket SBS.
10	Saraswati *et al*., 2021[34]	Fluoride (varied)	Enamel	Totaletch versus SE	Fluoride before totaletch improved strength; SE systems showed fluoriderelated reduction.
11	Tiba *et al*., 2022[35]	SDF (Riva Star)	Enamel and dentin	GIC/composite	SBS remained clinically acceptable; suitable for military dentistry.

(Contd...)

Table 1: *(Continued)*

No.	Author(s), Year	Fluoride Agent	Substrate	Adhesive system	Key finding
12	Eyüboğlu and Kalay 2022[36]	NaF	Enamel and dentin	Universal adhesive	Laser+NaF did not reduce SBS; laser surface changes may offset fluoride effects.
13	Rifai *et al*., 2022[37]	Fluoridereleasing composite	Dentin	Bioactive composite	Activa released less fluoride than Equia Forte; SBS varied.
14	Aldosari *et al*., 2022[38]	SDF	Dentin (demineralized)	RMGIC/composite	Delayed loading (1 week) after SDF increased μTBS.
15	Fernández-Mafé *et al*., 2022[39]	SDF	Enamel and dentin	Multiple adhesives	Dentin more adversely affected than enamel.
16	Khanna *et al*., 2022[40]	APF	Enamel (bleached)	Composite	Fluoride timing critical; McInnes solution restored uSBS best.
17	Akwan *et al*., 2022[41]	APF versus NaF	Enamel	GIC sealant	No SBS difference between APF and NaF.
18	Chauhan *et al*., 2023[42]	Fluoride varnish	Not specified	Ortho bonding	No negative effect on SBS; fluoridereleasing adhesives may add protection.
19	Yousry, 2023[43]	SDF	Dentin (primary and permanent)	Composite	Primary teeth showed lower uTBS due to inhibited resin tags.
20	Khalifa *et al*., 2023[44]	TiF_4 (1–2%)	Enamel	Ortho adhesive	2% TiF_4 improved remineralization and ARI.
21	Cardoso *et al*., 2023[45]	TiF_4 (2.5%)	Dentin	Universal adhesive	No effect on dentin permeability.
22	Joshi *et al*., 2023[46]	SDF	Enamel	Ortho bonding	SBS remained clinically acceptable.
23	Patterson *et al*., 2023[5]	APF; varied F	Enamel & dentin	Universal adhesive	<1000 ppm preserved durability; >1000 ppm harmed dentin bonding.
24	Jabbour *et al*., 2023[47]	SDF	Enamel	Universal adhesive	Phosphoric acid partially restored bond strength.
25	Ahmad *et al*., 2024[48]	SDF	Carious and sound dentin	Universal adhesive	Failure modes varied by adhesive system.
26	Senthilkumar *et al*., 2024[49]	Fluoride varnish	Enamel	Fluoridereleasing ortho adhesive	CPPACP+varnish increased hardness and bond strength.
27	Intajak *et al*., 2024[50]	38% SDF	Sound dentin	Universal adhesive	Calcium-fluoride layer formed; bonding changes were materialdependent.
28	Al-Angari and Alayad 2024[51]	SDF	Enamel and dentin	Multiple cements	SDF increased SBS of KETC cement to demineralized dentin.
29	Abdul-Razzaq *et al*., 2024[52]	SDF	Sound dentin	Composite	NaF preserved SBS; SDF reduced immediate and delayed SBS.
30	Gao *et al*., 2025[53]	Fluoride- releasing self-adhesive	Dentin	Self adhesive materials	Fluoride release and strength declined after water storage.
31	Khataminia *et al*., 2025[54]	SDF±KI± glutathione	Primary dentin	Composite	Adjuncts influenced μSBS; effects depended on adjunct.
32	Pawar *et al*., 2025[55]	SDF	Remineralized dentin	Composite	Cohesive failures predominated; adequate bond strength.
33	Bhardwaj *et al*., 2025[56]	SDF+KI	Enamel and dentin	Composite	SDF+KI improved SBS and microhardness versus SDF alone.
34	Sirichamratsakul *et al*., 2025[57]	Fluoride (varied)	Enamel	Bioactive composite/giomer/resin	All materials showed acceptable SBS; bioactive materials may protect enamel.
35	Öztürk *et al*., 2025[58]	APF varnish	Enamel (artificial lesions)	Ortho adhesive	Nanohydroxyapatite outperformed APF; fluoride varnish had the lowest remineralization.

APF: Acidulated phosphate fluoride, SDF: Silver diamine fluoride, SBS: Shear bond strength, KI: Potassium iodide, TiF_4: Titanium tetrafluoride, NaF: Sodium fluoride, GIC: Glass ionomer, SE: Standard error on demineralized enamel. Frazer *et al*. (2017) reported a significant reduction in bond strength in sealants placed over enamel treated with NaF varnish. However, polishing failed to fully restore bond strength.[4] Thus, reflecting variation in polishing protocols and fluoride agent formulations in studies.[3]

APF

Clinical application requires APF gel at a concentration of 1.23% and a pH of 3.5. The acidic nature of the gel forms surface precipitates that affect bond strength. Yang *et al*. (2021) reported a decrease in the bond strength of orthodontic brackets bonded to enamel with the acid-etch method after APF pre-treatment. Bond strength recovered to the control level after 21 days. Hence, it is recommended to attach the brackets 21 days after APF gel application to achieve better bond strength.[6] Similarly, Meng *et al*. (1998) observed reduced bond strength in acid-etched teeth following APF treatment. Bond strength values were less affected if the APF application was performed before etching.[7] Panahandeh *et al*. (2020) found that neither APF alone nor combined with CO_2 laser significantly affected bond strength between APF and TiF_4.

TiF_4

TiF_4 showed improved caries protection due to its chemical composition. However, its effects on composite bonding are complex and differ from substrate to substrate. 2.5% TiF_4 pre-treatment significantly increased microtensile bond strength to dentin when a two-step etch-and-rinse adhesive system (Adper Single Bond 2) was used, as reported by Tranquilin *et al*. (2016). Most surprisingly, this positive effect was independent of whether TiF_4 was applied before or after phosphoric acid conditioning, and primer/adhesive application mode (active vs. passive) did not influence the outcome.[9] The authors relate the improved bonding to the formation of a titanium-rich surface layer that may assist resin infiltration or provide additional sites for chemical bonding.

In another study, Panahandeh *et al*. (2020) found that the application of 4% TiF_4 reduced the microshear bond strength of composite to enamel significantly, at values of 13.44 MPa for TiF_4 alone and 10.16 MPa when TiF_4 was combined with CO_2 laser, in comparison to 20.66 MPa for controls. The reduction was attributed to crystal deposition on the enamel surface, which precluded penetration by the resin.[13] This divergence is beneficial for dentin and deleterious for the enamel; therefore, tissue type should be an important consideration in the evaluation of fluoride effects.

SnF_2

SnF_2 formulations have been studied primarily in orthodontic bonding applications, with generally positive outcomes. In a model of bonding orthodontic brackets, Chandulal *et al*. (2015) studied 8% SnF_2 gel applied before acid etching. Tensile bond strength between the SnF2-treated and control groups was identical.[8] Hence, SnF_2 may provide antimicrobial benefits without interfering with adhesion.

Patterson *et al*. (2023) evaluated 0.4% SnF_2 pre-treatments with a universal adhesive on enamel and dentin. The findings showed that the etch-and-rinse protocol after SnF_2 pre-treatment achieved the greatest microtensile bond strength on dentin, comparable to the controls.[5] Hence, it was concluded that low-concentration SnF_2 is more compatible with etch-and-rinse protocols on dentin than other modern protocols.

SDF

The use of SDF at 38% concentration to arrest carious lesions poses a challenge to bonding due to the precipitation of silver within the tooth structure. Quock *et al*. (2012) observed no general adverse effect of SDF on bond strength at concentrations typically used in clinical practice, but a significant interaction between SDF concentration and adhesive type (self-etch vs. etch-and-rinse) at one concentration level.[10] This interaction suggests careful selection of the adhesive system when bonding to dentin treated with SDF. In contrast, Fujimori *et al*. (2026) showed superficial silver deposition and significant reduction in dentin bond strength after application of 38% SDF. The removal of 0.1 mm of superficial dentin restored bond strength to a level similar to the control. The bond strength remained unaffected with the use of 3.8% SDF. Furthermore, the combined application of SDF and potassium iodide (KI) formulations reduced the silver deposition.[11] Thus, providing a clinical solution for managing SDF-treated teeth requiring subsequent restorations.

Fluoride varnishes

Fluoride varnishes are used in preventive dentistry and contain 5% NaF in a resin or colophony base. The bonding interference varnishes depend on the timing and surface preparation. Ortiz-Ruiz *et al*. (2018) investigated the effects of varnish application on adhesive bond strength and observed a significant decrease in bond strength within 24 h. However, this bond strength became similar to that of controls after 7 days.[3] Frazer *et al*. (2017) demonstrated a significantly lower bond strength immediately after varnish application.[4] It is clear that fluoride varnish needs to be either removed or allowed to dissolve completely before attempting adhesive procedures.

SUBSTRATE-SPECIFIC CONSIDERATIONS

Enamel bonding

Enamel bonding exhibits greater tolerance to fluoride pre-treatment compared to dentin bonding; however, significant effects may still manifest depending on the fluoride agent and protocol employed. Patterson *et al*. (2023) reported no significant difference in the microtensile bond strength of enamel pre-treated with various fluoride concentrations (1.23% APF, 1.1% neutral NaF, 0.4% SnF_2) compared to dentin using universal adhesive without etching.[5] In contrast, TiF_4 and APF significantly reduced adhesive bond strength.[13,6] These findings indicate that the acid-etching process effectively removes or neutralizes fluoride precipitates on enamel and restores the bonding surface.

Dentin bonding

Dentin bonding is much more susceptible to fluoride interference as compared to enamel bonding. Here, the roles of concentration and adhesive system selected are critical. In a study conducted by Patterson *et al*. (2023), all study variables (fluoride type, concentration, adhesive protocol, aging) significantly affected microtensile bond strength of dentin specimens. Importantly, fluoride concentrations higher than 1000 ppm adversely affected dentin bonding, while those below this threshold showed promise without compromising bond durability.[5] The etch-and-rinse protocol consistently produced higher bond strength values on dentin after fluoride pre-treatment compared to self-etch protocols.

Tranquilin *et al*. (2016) showed that TiF_4 increased dentin bonding with an etch-and-rinse adhesive, suggesting that some fluoride agents positively modify the dentin substrate or hybrid layer formation.[9] This was in direct contrast to what Quock *et al*. (2012) had earlier found, where they demonstrated significant interactions between SDF concentration and adhesive type on dentin bonding, thus proving the complexity of fluoride-dentin-adhesive interactions.[10]

Altinci *et al*. (2018) studied NaF, potassium fluoride, and CaF_2 on dentin microtensile bond strength. They found that neutral or lower-concentration fluoride treatments applied after phosphoric acid etching do not harm the initial or long-term dentin bond strength and can support durability.[12] This finding supports the use of post-etching fluoride application as a strategy to preserve bonding while providing fluoride benefits.

Primary versus permanent teeth

Little evidence exists regarding differences between primary and permanent teeth, although differences in substrate structure suggest the possibility of variation in response to fluoride. Biria *et al*. (2019) reported no significant reduction in microshear bond strength in the enamel of the primary teeth treated with neutral NaF.[2] This could be due to differences in the alterations in enamel morphology of primary and permanent teeth after fluoride application. The primary enamel is thinner and more uniform, influencing fluoride uptake and adhesive bonding.

Immediate versus delayed bonding

The timing between fluoride application and bonding procedures is an important factor affecting bond strength. Yang *et al*. (2021) observed that the bonding procedure performed immediately after application of APF resulted in a significantly reduced shear bond strength. However, bond strength values approached the control level after about 21 days.[6] This recovery indicates slow dissolution of CaF_2 precipitates and the reorganization of the surface mineral phase. A similar temporal pattern of bond strength was observed by Ortiz-Ruiz *et al.* (2018), in which the bond strength of varnish-treated enamel was restored between 24 h and 7 days. Furthermore, mechanical polishing at 24 h expedited the recovery of the bond strength. Thus, avoiding the delayed bonding option.[3] These study findings provide clinical recommendations for delaying adhesive treatments by 1–3 weeks after professional fluoride therapy with APF or varnish, whenever feasible. If immediate bonding is necessary, mechanical surface preparation or neutral, low-concentration fluoride agents should be considered alternatively.

Concentration thresholds

Fluoride levels greatly affect bonding results, with data indicating a threshold near 1000 ppm for dentin bonding. Patterson *et al*. (2023) explicitly identified this threshold, concluding that concentrations of fluoride higher than approximately 1000 ppm adversely affected bonding to dentin with a universal adhesive, while bonding to enamel was tolerant across the whole range tested. Such findings have significant clinical implications, as many professional fluoride products exceed the threshold (1.23% APF = 12,300 ppm; 2% NaF = 9,000 ppm; 5% NaF varnish = 22,600 ppm).[5]

Low-concentration fluoride products, such as the 0.4% SnF_2 tested by Patterson *et al*., produced high values of microtensile bond strength comparable to controls,[5] which may indicate that prescription-strength fluoride products (usually 1,000-5,000 ppm) offer an optimal balance between caries prevention and bonding compatibility.

Surface preparation and removal strategies

In many cases, the bond can be restored by physically removing or altering the fluoride-treated surface. Fujimori *et al*. (2026) showed that removing a 0.1 mm superficial dentin layer after applying 38% SDF completely restores bond strength to the levels of the control.[11] This finding offers a more practical approach for bonding to SDF-treated teeth, although one that should be applied with due clinical judgment in balancing tissue preservation against bonding requirements.

Shear bond strength was improved by mechanical polishing 24 h after application of the fluoride varnish. Although not entirely restored, bonding was not completely restored by polishing, as in the sealant model of Frazer *et al*. (2017). These differences may arise from different polishing protocols (instrument type, duration, pressure) or varnish formulations.[4] Therefore, standard surface preparation protocols should be detailed. These discrepancies could be due to differences in the polishing protocols (instrument type, duration, pressure) or varnish formulations. Thus, they indicate that standardized surface preparation protocols should be further investigated.

Etch-and-rinse systems

Etch-and-rinse (total-etch) adhesive systems typically perform strongly after fluoride pre-treatment, especially when used on dentin substrates. The results of the present study corroborate those of Patterson *et al*. (2023), who found that the etch-and-rinse protocol resulted in the highest microtensile bond strength values to dentin after both control and SnF_2 pre-treatment.[5] This probably shows how well the phosphoric acid etching removes the precipitates of fluoride to create deep microporosities for resin infiltration since it is known to result in aggressive demineralization.

Tranquilin *et al*. (2016) used a two-step etch-and-rinse adhesive (Adper Single Bond 2), and TiF_4 pre-treatment was actually found to enhance dentin bonding, irrespective of application timing.[9] This finding suggests that etch-and-rinse systems may be particularly compatible with certain fluoride agents that modify the dentin substrate favorably.

Self-etch systems

Fluoride pre-treatments have been shown to have more variable responses with self-etch adhesive systems, with evidence of interactions between fluoride concentration and adhesive performance. Quock *et al*. (2012) found a significant interaction between SDF concentration and adhesive type (self-etch vs. etch-and-rinse) at a single concentration level. They stated that self-etch systems might be more sensitive to fluoride-induced surface modifications.[10] The authors explained that in self-etch adhesives, demineralization and infiltration by acidic monomers occur simultaneously; thus, fluoride precipitates may interfere with this process more than with the separate etching step of etch-and-rinse systems.

Endo *et al*. (2014) studied long-term repeated topical fluoride applications in an orthodontic model using a self-etching primer. They found that repeated fluoride applications reduced shear bond strength; however, an adhesion promoter (Transbond Plus) restored bond strength to control levels.[59] This finding suggests that adhesion promoters or primers may compensate for fluoride-induced bonding challenges when using self-etch systems.

Universal adhesives

Universal adhesives are designed to function in both etch-and-rinse and self-etch modes, thereby offering flexibility in managing fluoride-treated substrates. Ortiz-Ruiz *et al*. (2018) used a universal adhesive (Scotchbond Universal) on fluoride varnish-treated enamel and found time-dependent recovery of bond strength.[3] Patterson *et al*. (2023) used a universal adhesive (Prime and Bond Elect) in both etch-and-rinse and self-etch modes, with the former producing superior dentin bonding after fluoride pre-treatment.[5] Eyüboğlu and Kalay (2022) reported no significant effect on the shear bond strength of dentin with universal adhesive treated either NaF alone or a combination of NaF and laser treatments.[36] Using fluoride in combination with laser treatment resulted in tubule occlusion without affecting bonding strength. This indicates that universal adhesives might perform well when paired with neutral fluoride formulations and proper surface preparation.

Fluoride application leads to the formation of several types of surface precipitates that can act as physical barriers to resin infiltration. In a study conducted by Ortiz-Ruiz *et al*. (2018), scanning electron microscopy revealed that fluoride varnish created a homogeneous layer with amorphous surface precipitates on enamel, which correlated with reduced shear bond strength at 24 h.[3] Biria *et al*. (2019) observed entirely different morphology between APF (irregular particles) and neutral NaF (thin uniform coats) on the surfaces of primary enamel. These explain differential effects on bonding, with thicker, more irregular precipitates causing greater interference.[2] These morphological differences could account for the different effects on bonding.

The main precipitate that will form during most fluoride treatments is CaF_2, which will deposit on the tooth surface and within superficial enamel or dentin. While serving as a fluoride reservoir for remineralization, CaF_2 can impede acid penetration during etching and reduce the depth as well as the quality of the etched pattern. The bond strength recovery observed in many studies can be explained by the dissolution of these precipitates over time.

Altered etching patterns

Fluoride pre-treatment can cause a change in the etching pattern produced by phosphoric acid, modifying the microretentive surface necessary for bonding. In the study by Yang *et al*. (2021), APF was found to interfere with phosphoric acid etching, thereby reducing the etch depth and changing the surface topography. Most likely, such interference can be attributed to fluoride's effects on the crystal structure and composition of enamel, as well as on hydroxyapatite and fluorapatite. More recent findings suggest that the interference may be due to fluoride's effects on the crystal structure and composition of enamel, as well as on hydroxyapatite and fluorapatite. The resultant effects will be shorter microporosity and resin tags, hence compromised micromechanical retention.[6] Similarly, Panahandeh *et al*. (2020) stated that the decrease in bond strength after treatment with TiF_4 is due to crystal deposition, which blocks the resin from penetrating well. TiF_4 forms a glaze-like layer of titanium oxide and fluoride compounds – highly resistant to acid dissolution – which accounts for its marked adverse effect on bonding to enamel, despite beneficial effects on dentin.[13]

Tubule occlusion and resin penetration

Fluoride on dentin substrates can occlude dentinal tubules, reducing available surface area for bonding and limiting resin tag formation. Eyüboğlu and Kalay (2022) found tubule occlusion under scanning electron microscopy after NaF treatment combined with Er,Cr:YSGG laser, yet they did not find any reduction in shear bond strength with the universal adhesive.[36] This could be taken as an apparent paradox, in that modern adhesive systems may compensate for reduced tubule penetration by enhancing bonding to inter-tubular dentin or by chemical adhesion mechanisms. On the other hand, TiF_4 may improve dentin bonding by forming a titanium-rich surface layer, which allows better resin infiltration or provides more chemical bonding sites. This finding contrasts with physical occlusion and highlights complex interactions between fluoride and dentin.

Chronologic investigations

Research published in 2020 reported that SDF had a measurable, often negative, effect on adhesive bond strength to dentin. Aye *et al*., noted that tensile bond strength and interfacial morphology were influenced by SDF concentration. Similarly, Markham *et al*. showed that SDF significantly reduced bond strength compared with untreated controls. Contrarily, Firouzmandi *et al*. observed an initial increase in dentin bond strength in caries-affected teeth, but it reduced with aging. Fluoride-containing adhesives showed lower fluoride release and decreased interfacial bond durability. APF and TiF_4 caused substrate-dependent interfacial effects; TiF_4, in particular, when combined with the CO_2 laser, decreased enamel bond strength.[13,26-29]

By 2021, the literature emphasized fluoride concentration, adhesive strategy, and substrate types. NaF showed improved acid resistance without reducing bond strength. SDF consistently demonstrated negative effects on dentin bonding, due to increased deposits that interfered with resin infiltration. Fluoride varnish did not compromise orthodontic bracket bonding. Saraswati *et al*. suggested that fluoride pre-treatment favored total-etch systems, whereas self-etch adhesives exhibited significant reductions in bond strength.[30-34]

In 2022, literature continued to shift toward clinical applicability, examining the effects of timing, laser conditioning, and restorative material selection on fluoride-related outcomes. Delayed loading after SDF application significantly improved microtensile bond strength; immediate restoration may not be the best option. Laser-fluoride combinations of Er,Cr:YSGG with NaF sometimes reduced the expected strength loss by altering the surface morphology. Bioactive composites had variable fluoride release and bonding performance. APF and NaF pre-treatments yielded similar results for GIC-based fissure sealants. It was thus concluded that the effect of fluoride is not constant; it highly varies with procedural variables.[36,35-41]

In 2023, the literature identified clinically meaningful thresholds and partial mitigation strategies. Patterson *et al*. set levels below 1000 ppm as those that preserved bond durability; levels above this threshold were adverse to dentin bonding. SDF continued to impair bonding, especially in primary teeth, where Yousry attributed reduced uTBS to inhibited resin tag formation. However, phosphoric acid etching partially restored bond strength in SDF-treated enamel, although adhesive failures remained higher than in untreated controls. TiF_4-containing orthodontic adhesives improved remineralization and bonding durability, and several studies confirmed that SDF and other remineralizing agents did not compromise orthodontic bracket SBS.[42-48]

In 2024, it was increasingly recognized in the literature that the effects of SDF were material-dependent rather than universally detrimental. They reported that SDF created a calcium- and fluoride-rich surface layer that altered bonding behavior depending on the adhesive used. NaF pre-treatment is considered a preventive protocol that does not affect bond strength, even after thermo cycling. In contrast, SDF continually decreased the immediate and delayed bond strength. Using casein phosphopeptide-amorphous calcium phosphate and fluoride varnish together enhances enamel hardness and bonding strength, showing substrate-specific benefits.[49-53]

The 2025 study materials reflected the above shift, while adjuncts modifying SDF were bioactive. Composite giomers and resin composites used for attachments to clear aligners showed acceptable shear bond strength and additional enamel protection. Those adjuncts, such as KI and glutathione, significantly influenced the micro-shear bond strength of SDF-treated primary dentin. The former improved both SBS and microhardness compared with SDF alone. SDF-remineralized dentin showed predominantly cohesive failures, meaning sound internal integration and bonding. Self-adhesive materials, however, released fluoride and showed decreasing bond strength after water storage.[51-58]

CLINICAL IMPLICATIONS AND RECOMMENDATIONS

Timing recommendations

Delay adhesive procedures for 1-3 weeks after professional fluoride application when clinically feasible, particularly after APF gel or fluoride varnish application.[3,6] If immediate bonding is necessary, mechanically remove fluoride varnish through polishing or pumicing before bonding procedures.[3]

For SDF -treated teeth requiring restoration, consider removing a thin superficial layer (approximately 0.1mm) of dentin to eliminate silver precipitates.[11]

Fluoride agent selection

Clinicians should prefer neutral NaF formulations (2% gel) over APF when patients need adhesive procedures.[1,2] Use of low-concentration fluoride (<1000 ppm) for patients requiring frequent restorations, especially with dentin bonding.[5] For caries arrest with SDF, consider lower-concentration (3.8%) or SDF+KI combinations when bonding is planned.[11]

Adhesive system selection

It is preferable to use etch-and-rinse adhesives rather than self-etch methods for bonding to fluoride-treated dentin due to their reliability.[5] Use universal adhesives in etch-and-rinse mode on fluoride-treated surfaces for flexibility and strong performance.[3,5] After fluoride exposure, consider using adhesion promoters when applying self-etch systems to improve bond strength.[59]

Special considerations for orthodontic bonding

Orthodontic bracket bonding requires a strong yet controllable bond strength to withstand forces and allow debonding at the end of treatment. Yang *et al*. (2021) recommend a 21-day delay between fluoride application and bracket placement.[6] This recommendation balances the need for caries prevention during orthodontic treatment with the need to ensure adequate bond strength for bracket retention. Neutral fluoride formulations and SnF_2 are preferred in orthodontic patients.

Strategies for compromised substrates

Primary teeth might react to fluoride differently than permanent teeth because of their structural differences.[2]

Neutral NaF seems safe for bonding to primary enamel; however, the varnish should be removed before placing the sealant.[4] When planning pediatric treatment, consider the timing of fluoride varnish applications relative to planned restorative procedures. In high-caries-risk patients, balance intensive fluoride therapy with restorative needs, alternating between neutral and acidulated fluoride based on upcoming treatment requirements.

Use post-etching fluoride applications that maintain bonding strength and provide fluoride benefits.[12] Fluoridated bleaching agents might better preserve bond strength than non-fluoridated agents.[60] Using topical fluoride with CO_2 laser treatment can improve the microhardness and bond strength of eroded enamel.[61]

LIMITATIONS OF PRESENT EVIDENCE AND FUTURE DIRECTIONS

- Methodological diversity: The studies included in this review showed differences in the measurement method of bond strength, samples studied, failure modes, and aging protocol.
- Limitations of *in vitro* studies: The present review mainly comprised of *in vitro* studies, which do not fully reflect the oral environment.
- Limited data available on long-term clinical outcomes: The shortage of published clinical trials evaluating adhesive systems following topical fluoride application.
- Gaps in substrate and population: Limited data exist on primary teeth, and no research has examined deciduous dentin bonding after fluoride treatment.
- New fluoride formulations: Fluoride-releasing adhesives, bioactive materials, and nanoparticle formulations have not been well reported for their effect on adhesive bonding.
- Mechanistic understanding: Molecular interactions among fluoride compounds, adhesive monomers, and tooth substrates remain unclear.

FUTURE RESEARCH PRIORITIES

Future studies should include multicenter RCTs assessing the longevity of the restoration subject to different fluoride application protocols. There must be a standard format for studying bond strength of newer adhesive materials for *in vitro* studies. Research should focus on novel fluoride formulations compatible with adhesives. Further investigation should be undertaken to assess the adhesive outcomes in the child and elderly population.

CONCLUSION

Topical fluoride and composite bonding can be incorporated into clinical practice through the careful selection of suitable agents and the proper timing of their application. The recommended adhesive protocol should be strictly followed. Clinicians must place the highly proven benefits of fluoride in preventing caries against the need for reliable adhesion in restorative and orthodontic work to deliver good patient outcomes.

DATA AVAILABILITY

Not applicable

GRANT INFORMATION

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