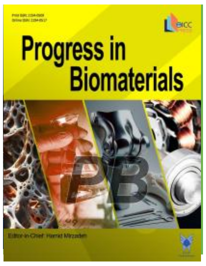

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Analysis and Evaluation of Micro-tensile Bond Strength of Indirect Nanocomposite to Deep Dentin with Various Bonding Agents

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Abstract

Resin composites are frequently used in restorative dentistry, but polymerization shrinkage poses significant challenges. This study aimed to assess the micro-tensile bond strength of indirect composites to deep dentin utilizing various bonding agents under Immediate Dentin Sealing (IDS). Sixty non-carious third molar teeth were selected; their roots were sectioned below the cemento-enamel junction (CEJ) and divided into five groups: four with adhesive systems (Optibond FL, SE bond, G Premio bond, G2 bond) under IDS and one control group using Delayed Dentin Sealing (DDS). After temporary restoration, composite blocks were bonded to each sample. A force of 500N was applied to measure micro-tensile bond strength until fracture, with data analyzed via chi-square tests, ANOVA, and Tukey's post hoc tests. The bond strength values ranked from highest to lowest were Opti bond FL, SE bond, G2 bond, G Premio bond, and the control group. No significant differences were found among Opti bond FL, SE bond, and G2 bond ($P > 0.05$), but these three systems exhibited significantly higher bond strengths than the control group ($P < 0.05$). The bond strength of G Premio bond under IDS was significantly lower than the other adhesives ($P < 0.05$). In conclusion, IDS enhances the micro-tensile bond strength of indirect composite restorations to deep dentin, with Opti bond FL demonstrating the highest bond strength and the control group exhibiting the lowest.

Keywords: Micro-tensile bond strength, Immediate dentin sealing, Delayed dentin sealing, Indirect nanocomposite

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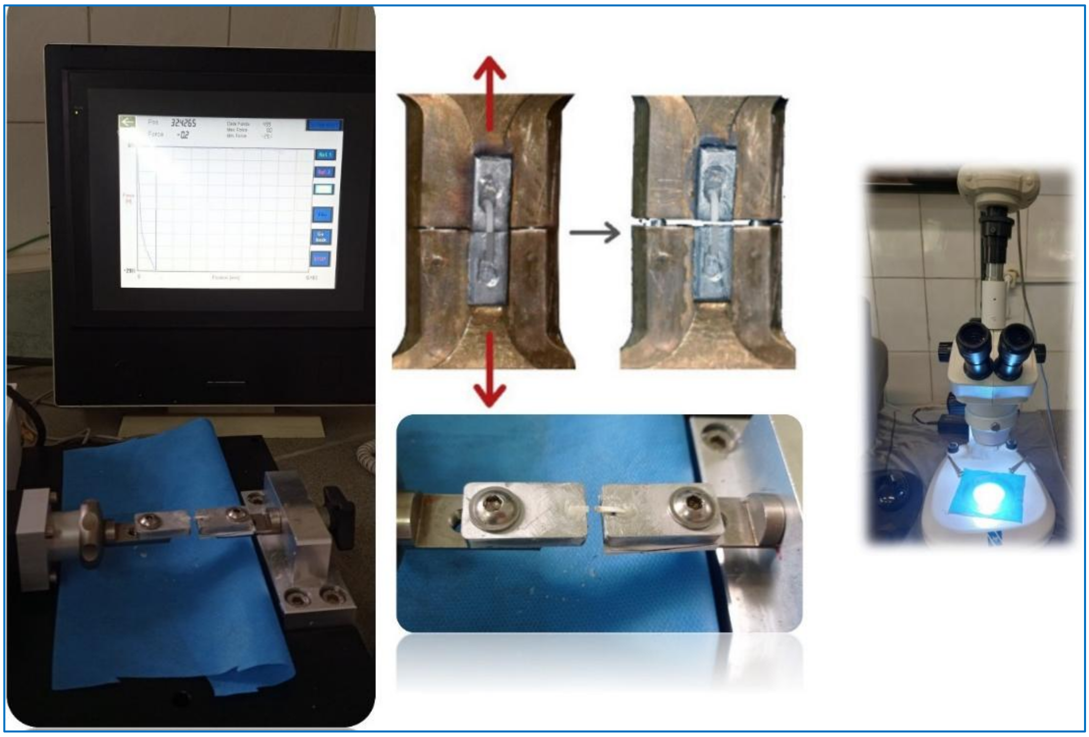
Graphical abstract



1. Introduction

Modern resin composites offer superior wear resistance and color stability compared to older versions. However, polymerization shrinkage during their use must be managed carefully, as it creates stress that can exceed the cohesive and adhesive strengths of the restorative material [1]. Direct resin composites encounter difficulties, particularly in severely damaged teeth or those close to the pulp, due to issues like polymerization shrinkage and suboptimal degrees of conversion [2]. Additional challenges include achieving proper proximal contact, maintaining anatomical form, ensuring wear resistance, and achieving optimal marginal adaptation [3]. In contrast, indirect composite restorations generally provide greater bond strength, improved marginal seals, reduced sensitivity after cementation, and enhanced marginal integrity [4]. Nonetheless, failures of indirect restorations in the oral environment present significant challenges in dentistry, impacting both aesthetics and functionality [5]. The clinical success of these restorations relies on selecting appropriate materials and bonding techniques [4-6]. Various bonding methods are available, with dentin bonding agents (DBA) being the preferred choice for securing composite overlays and crowns to dentin [7]. The Delayed Dentin Sealing (DDS) technique exerts pressure during restoration bonding, which can lead to the collapse of demineralized dentin collagen fibers, ultimately decreasing the bond strength of resin cement to dentin [8,9]. IDS is a newer approach that uses a dentin bonding agent immediately after tooth preparation and prior to impression taking, contrasting with DDS [10,11]. The primary advantages of IDS include protection of the dentin-pulp complex, prevention of dentin sensitivity, and reduction of bacterial infiltration during the temporary restoration phase [3]. IDS can be implemented in two ways: by applying only a dentin bonding agent after tooth preparation, or by using both a bonding agent and a flowable composite [12]. The application of flowable composite prevents interference between the adhesive and impression materials [13]. Additionally, flowable composite enhances bond strength by maintaining the adhesive layer, absorbing internal stresses, and preserving adhesive integrity over time. IDS using a bonding system, combined with a thin layer of flowable composite and allowing adequate time for the formation of the hybrid layer, significantly enhances bond strength [14]. In research by Gailani et al. [15], bond strength varied based on the components of each bonding system and the different methods of IDS and DDS employed.

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Another study by Perugia et al. [16] showed that performing IDS on freshly cut dentin helps protect the pulp from bacterial infiltration and postoperative sensitivity, providing an effective substrate for hybrid layer formation. Pinto et al. [17] found that variations in dentin bonding strategies did not impact the micro-tensile bond strength of indirect resin composites to dentin. Given the necessity for researchers and clinicians to develop new protocols that optimize techniques and adhesive materials—maximizing tooth structure preservation, enhancing patient comfort, and ensuring the longevity of indirectly bonded restorations—this study aims to evaluate the micro-tensile bond strength of indirect composite restorations to deep dentin using various bonding agents under IDS. The aim of this study is to evaluate the micro-tensile bond strength of indirect composite restorations to deep dentin using different bonding agents under IDS. This research is novel in its exploration of how various bonding strategies can enhance the effectiveness of IDS, particularly in challenging cases involving deep dentin. The results are expected to contribute significantly to the field of restorative dentistry by providing clinicians with evidence-based protocols for optimizing adhesive techniques, which may improve patient outcomes through increased bond strength and reduced postoperative sensitivity. This study seeks to advance the understanding of the relationship between bonding materials and methods, aiding in the long-term success of indirectly bonded restorations. Therefore, this study aims to conduct a comparative, controlled evaluation of the micro-tensile bond strength (μTBS) of an indirect nanocomposite restoration to deep dentin. It specifically investigates the efficacy of the Immediate Dentin Sealing (IDS) protocol when performed with four distinct contemporary adhesive systems—representing etch-and-rinse, two-step self-etch, and universal adhesive strategies—compared to a conventional Delayed Dentin Sealing (DDS) control. The novelty of this work lies in its head-to-head comparison of these adhesive classes within a standardized IDS protocol on the clinically challenging substrate of deep dentin, seeking to provide evidence-based guidance for material selection in adhesive dentistry.

2. Materials and Methods

In this experimental laboratory study, a total of 60 extracted, non-carious, and intact third molars were obtained from patients aged 18 to 35 at the dental clinic of Isfahan University of Medical Sciences. Teeth that exhibited fractures during sectioning were excluded from the analysis. All specimens were stored in distilled water with 0.2% thymol for one week to ensure preservation. The roots of each tooth were then sectioned below the cemento-enamel junction (CEJ), and the pulp chambers were thoroughly cleaned using a 2.5% sodium hypochlorite solution (Figure 1 (a-c)). To access deep dentin, the occlusal part of each sample was divided into three equal sections. Using a Cutting Machine (Dentarapid, Krupp Dental, 759DRZ, Hilzingen, Germany) equipped with water irrigation, sections were cut between one-third of the cervical region and the occlusal surface, ensuring they were positioned 0.5 mm away from the pulp chamber. The samples were standardized using 600-grit silicon carbide paper under water, and subsequently, they were mounted in resin wax for stability in further processing. The specimens were categorized into five groups for treatment. Four groups underwent procedures involving different adhesive systems under IDS, while the fifth group served as a control. Specifically, in Group One, Optibond FL, a phosphoric acid solution (Bisco-ETCH 32%, USA) was applied to the dentin for 15 seconds, followed by rinsing and air-drying. A primer was applied, and bonding was subsequently placed, air-dried, and cured using a VALO curing device (Ultradent cordless LED, 1000 mW/cm²) for 20 seconds. This was followed by a Decouple with Time (DWT) treatment for 5 minutes to facilitate the formation of the hybrid layer, after which a Flowable Composite was applied for the resin coating. Group Two utilized SE bond, applying a self-etch primer for 20 seconds, gently air-drying, followed by bonding application, light-curing for 10 seconds, DWT for 5 minutes, and then application of Flowable Composite. In Group Three, G Premio bond was used, with bonding applied, air-dried for 5 seconds, light-cured for 10 seconds, followed by DWT for 5 minutes and the application of Flowable Composite. Group Four involved G2 bond, where primer was applied, air-dried for 5 seconds, and then bonding was placed with uniform air application, light-cured, followed by DWT for 5 minutes, and the final application of Flowable Composite. Group Five, serving as the DDS control, did not receive an adhesive and remained unsealed until the final restoration session. A crucial aspect of the DWT process was allowing a 5-minute period to form the hybrid layer. The Flowable Composite (Dentsply SDR Plus Bulk Fill Flowable, USA) was applied in a thickness limited to below 1.5 mm and cured as specified. To prevent the formation of an inhibition layer, glycerin gel (Cobalt Oxy/bar Glycerin Gel, Iran) was applied for 20 seconds. Each sample was temporarily restored with 3 mm of temporary material (Ena Temp, Micerium, Italy). After one week in water at 37°C, the temporary restoration was removed, and the

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dentin surfaces were cleaned with water irrigation. The surfaces were sandblasted for 10 seconds using an Air Abrasion Master DN-NEO LX (China), treated with phosphoric acid, and finally coated with All Bond Universal (Bisco, USA). The flowable composite was applied in a single increment, with thickness visually controlled to be below 1.5 mm using a calibrated periodontal probe. While the final thickness of this resin coating after subsequent sandblasting was not quantitatively measured, the standardized protocol aimed to minimize inter-sample variability in this parameter. Samples were stored in distilled water for a period of three months. After this storage duration, each sample was sectioned perpendicular to the dentin-adhesive interface into beams with a surface area of 1 mm^2, utilizing a CNC Cutting Section Machine (3 Axes Full Automatic, Nemo Fanavaran Pars, Mashhad, Iran). These beams were then secured in a Micro-tensile Testing Machine (MTD-500 plus, SD Mechatronik, Feldkirchen-Westerham, Germany) using cyanoacrylate adhesive. A tensile force of 500 N was applied at a speed of 0.5 mm/min until the beams fractured. The force values recorded at the moment of fracture, expressed in Newtons (N), were collected through software connected to the testing machine. The bond strength values were subsequently calculated by dividing the applied force by the cross-sectional area of each sample, with results presented in megapascals (MPa) (Figure 3) [18-20]. Fractured surfaces were examined at 40× magnification using a Trinocular Zoom Stereo Microscope (SKP-200, HP, USA) coupled with a Moticam 480 Digital Camera (SP10.0224, Motic Instruments Inc., CA, USA). The fractures were classified into the following categories: 1) Cohesive in dentin (CD), 2) Adhesive between resin cement and dentin (AD), 3) Adhesive between the indirect restoration and resin cement (ADR), 4) Cohesive in composite resin (CR), and 5) Mixed (MI) fracture types [21]. Data normality was evaluated using the Shapiro-Wilk test. For normally distributed data, independent t-tests and analysis of variance (ANOVA) were performed. In cases where normal distribution was not observed, the Mann-Whitney U test and Kruskal-Wallis test were utilized. All statistical analyses were conducted at a significance level of 5% using SPSS software version 26. The substrate of interest was deep dentin, characterized by its higher tubular density and permeability compared to superficial dentin, which presents a greater challenge for achieving durable hybridization and resin infiltration. The adhesive systems were selected to represent fundamental bonding chemistries and clinical application strategies: a three-step etch-and-rinse system (Optibond FL) known for creating a robust, hydrophobic hybrid layer; a two-step self-etch system (Clearfil SE Bond) containing the functional monomer 10-MDP known for chemical bonding to hydroxyapatite; and two 'universal' adhesives (G-Premio Bond and G2 Bond) designed for application in multiple modes, here used in self-etch strategy. The flowable composite (SDR Plus) was chosen for its purported stress-absorbing rheology and higher conversion rate, intended to stabilize the sealed dentin interface. Permanent restorations for all samples were fabricated using universal Nano-hybrid resin composite blocks (Filtek Z 350, shade A1, 3M ESPE, USA), which measured 12 mm in diameter and 4 mm in height. After evenly distributing the resin cement (Duo Link, Bisco, USA) onto the dentin surfaces, the composite blocks were manually positioned with adequate pressure and maintained for the necessary duration to ensure proper adhesion. To prevent the formation of an inhibition layer during curing, glycerin gel was applied. Curing was then conducted from three different angles: the buccal, lingual, and occlusal aspects, ensuring comprehensive polymerization of the composite material (Figure 2).

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Figure 1. (A) Root sectioning below the CEJ. (B) Occlusal reduction to expose deep dentin at a standardized distance of 0.5 mm from the pulp chamber (dotted line). (C) Division of samples into five experimental groups for adhesive treatment

Figure 2. Cementation of resin composite block on the sample

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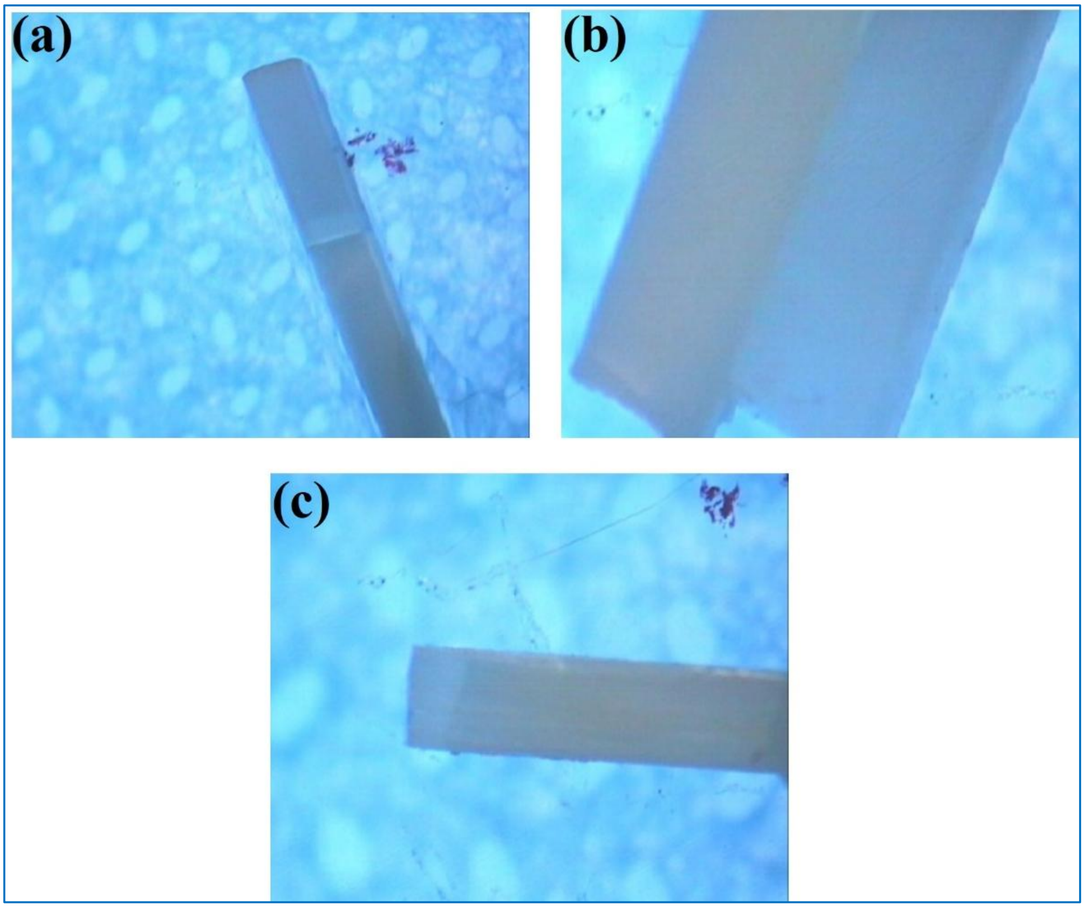

Figure 3. Samples under the microscope

Table 1. Bondings used in the study

Adhesive System	Manufacturer	Contents
Optibond FL	Kerr(USA)	Primer: HEMA, GPDM, PAMM Bonding: TEGDMA, UDMA, GPDM, HEMA, bis GMA
Clearfil SE bond	Kuraray(Japan)	Primer: 10MDP, HEMA, Photo initiator, Water Bonding: 10 MDP, Bis GMA, HEMA, Hydrophilic Di methacrylate, micro filler
G Premio Bond	GC(Japan)	10MDP, 4META, 10Methacryloxydecyl dihydrogen thiophosphate, Methacrylate acid ester, Distilled water, Acetone, Photo initiator, Silica fine Powder
G2 bond	GC(Japan)	4MET, MDP, 10Methacryloxydecyl dihydrogen thiophosphate (HEMA free)

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Table 2. Materials used in the study

Material	Manufacturer	Company
Acid-ETCH 32%,	Bisco	USA
Optibond FL	Kerr	USA
Clerarfil SE Bond	Kuarary	Japan
G Premio Bond	GC	Japan
G2 bond	GC	Japan
Flowable composite	Dentsply SDR Plus Bulk Fill Syringe Refill UNIVERSAL Shade,	USA
Glycerin gel	Cobalt Oxy Bar Glycerin Gel	Iran
Temprary material	ENA Temp micerium	Italy
All bond universal	Bisco	USA
Composite	Filtek Z350,shade A1,3M ESPE	USA
BIS-Silane	Bisco	USA
Resin cement	Duo-link Bisco	USA

Table 3. Equipments used in the study

Equipment	Manufacturer	Company
Cutting Machine	Dentarapid,Krupp Dental,759DRZ,Hilzingen	Germany
Light cure	Ultradent Cordless VALO LED curing light,	USA
Sandblast	Air abrasion master DN-NEO LX	China
CNC Cutting Section machine	3Axes Full Automatic,Nemo FanavaranPars	Iran
Microtensile machine	MTD-5 00plus,SD Mechatronik,Feldkirchen-Westerham	Germany
Strereo Microscope	Trinocular Zoom Strereo Microscope(SMP-200,HP,USA)Supplied with Moticam 480 Digital Camera(SP10.0224,Motic Instuments Inc,CA,USA)	USA

3. Results & Discussion

The application of glycerin gel ensured the creation of a fully polymerized, mechanically stable resin coating surface by eliminating the oxygen inhibition layer. Prior to final cementation, this resin-coated surface was actively conditioned via air abrasion and phosphoric acid etching. This step served a dual purpose: to remove any potential surface contamination from the temporary material and, more critically, to eliminate the thin, potentially weaker oxygen-inhibited layer and create a fresh, micromechanically retentive surface for chemical and mechanical bonding with the subsequently applied resin cement [cite relevant sandblasting/etching studies]. This protocol was designed to ensure that the bond strength measured was representative of the bulk properties of the resin coating and its interface with dentin, rather than a superficial, incompletely polymerized layer. The highest mean micro-tensile bond strength was associated with OptiBond FL, and the lowest mean was related to the control group (Figure 4). According to the analysis of variance, there was a significant difference in the mean micro-tensile bond strength among the samples bonded with different adhesive systems (Table 4). In pairwise comparisons using the Tukey test, the mean micro-tensile bond strength of OptiBond FL was found to be significantly higher than that of G-Premio bond and the control group ($P = 0.001$). Similarly, the mean micro-tensile bond strength of SE bond was significantly greater than that of G-Premio bond and the control group ($P = 0.001$). Furthermore, the mean micro-tensile bond strength of G-Premio bond was significantly lower than that of G2 bond ($P = 0.001$), while the mean micro-tensile bond strength of G2 bond was significantly higher than the control group ($P = 0.001$). No significant differences were observed among the other groups (Table 5). To further understand the failure mechanics, beams from each adhesive group were categorized into 'high-strength' and 'low-strength' subsets based on a median split of their μTBS values. A secondary chi-square analysis revealed no significant correlation ($p > 0.05$)

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between the failure mode (adhesive vs. cohesive/mixed) and the high/low strength categorization within any of the individual adhesive groups. This suggests that for each specific adhesive system under these test conditions, the mode of failure was independent of the magnitude of bond strength at which failure occurred. Figure 5 shows the Mechanical properties evaluation and samples under test, along with microscopic examination of the fractured components. The microtensile bond strengths of OptiBond FL, SE Bond, and G2 Bond (under IDS) were not significantly different from each other, all demonstrating higher values than the control group (DDS). G-Premio Bond displayed lower bond strength, similar to the control group. Additionally, the locations of failure for indirect composites bonded to deep dentin did not differ significantly among the adhesive systems tested. According to the chi-square test, there was no significant difference in the location of fracture based on bonding type (Table 6).The comparatively lower bond strength of G-Premio Bond under the IDS protocol warrants a mechanistic consideration. As a single-bottle, 'universal' adhesive applied in self-etch mode, its performance in the challenging deep dentin environment may be influenced by several factors. Deep dentin's higher water content may hinder the efficient evaporation of the adhesive's solvents (water and acetone), potentially leading to suboptimal polymerization and a more hydrophilic polymer network. While it contains the effective monomer 10-MDP, its performance may be modulated by the presence of other functional monomers like 4-META and the overall adhesive acidity. Furthermore, single-step adhesives must simultaneously fulfill the roles of etching, priming, and bonding, which may compromise the depth and quality of hybridization compared to the more controlled, sequential steps of systems like Optibond FL or SE Bond. This could result in a hybrid layer more susceptible to hydrolytic degradation over time, as suggested by its performance after three months of water storage.

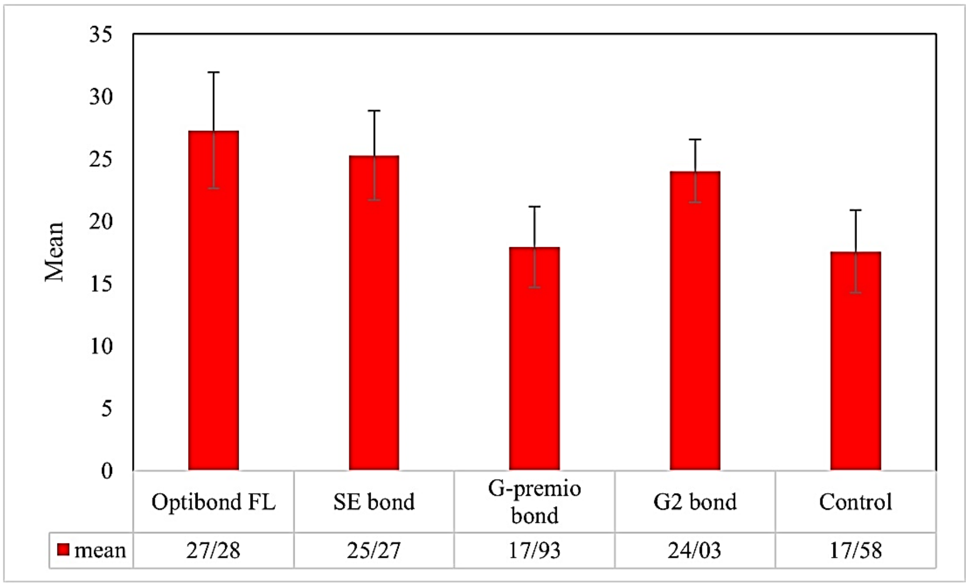

Figure 4. Mean micro-tensile bond strength of samples by bonding type

Table 4. Mean micro-tensile bond strength of samples by bonding type in megapascals (MPa)

Bonding	Number	Minimum	Maximum	Mean	Standard Deviation	P value
Opti bond FL	12	20.20	70.36	28.27	64.4	
SE bond	12	50.20	20.32	27.25	59.3	
G-premio bond	12	80.12	20.22	93.17	24.3	< 0.001
G2 bond	12	90.20	70.28	03.24	512	
Control	12	20.12	20.22	58.17	31.3	

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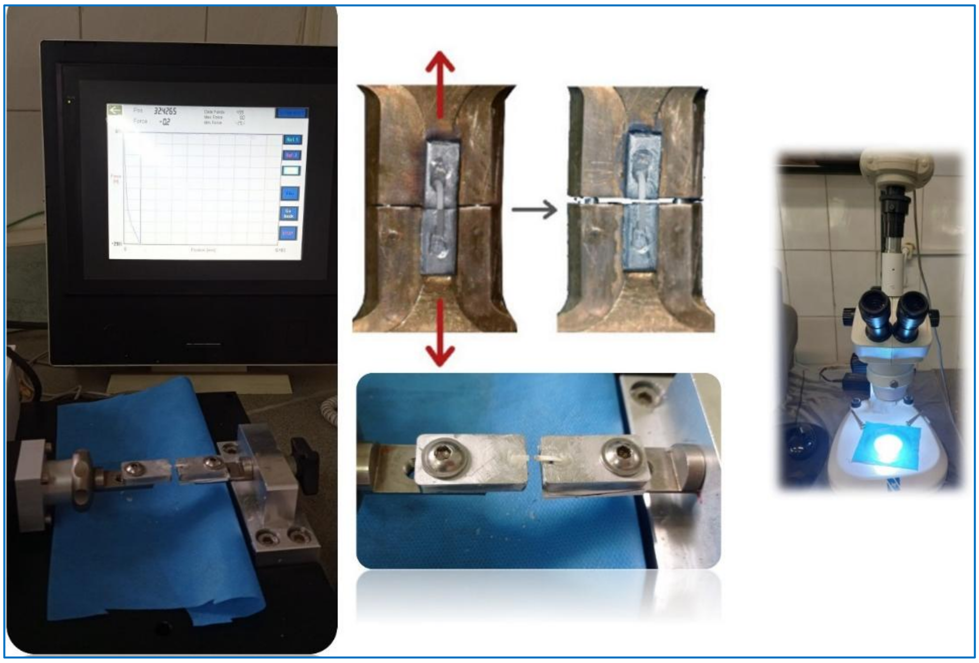

Figure 5. Mechanical properties evaluation and samples under test and microscopic evaluation of the separated parts

Table 5. Multiple comparisons of mean micro-tensile bond strength of samples based on bonding type

Groups		Mean Difference	Standard Error	P value
Opti bond FL	SE bond	2.02	1.440	0.630
	G-premio bond	9.36	1.440	0.000
	G2 bond	3.25	1.440	0.175
	Control	9.70	1.440	0.000
SE bond	G-premio bond	7.34	1.440	0.000
	G2 bond	1.23	1.440	0.911
	Control	7.68	1.440	0.000
G-premio bond	G2 bond	-6.11	1.440	0.001
	Control	0.34	1.440	0.999
G2 bond	Control	6.45	1.440	0.000

Table 6. Frequency and percentage of composite fracture location based on bonding type**

Groups	AD	MI	CR	ADR	CD	P value
Opti bond FL	9 (21.4)	2 (25.0)	1 (25.0)	0 (Zero)	0 (Zero)	0.974
SE bond	7 (16.7)	2 (25.0)	1 (25.0)	2 33.3	0 (Zero)	
G-premio bond	8 (19.0)	2 (25.0)	1 (25.0)	1 (16.7)	0 (Zero)	
G2 bond	9 (21.4)	1 (12.5)	1 (25.0)	1 (16.7)	0 (Zero)	
Control	9 (21.4)	1 (12.5)	0 (Zero)	2 33.3	0 (Zero)	

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In the present study, the micro-tensile bond strengths of OptiBond FL, SE Bond, and G2 Bond (under Immediate Dentin Sealing, IDS) did not significantly differ from one another, and all three adhesive systems demonstrated significantly higher bond strengths compared to the control group (under Delayed Dentin Sealing, DDS). The micro-tensile bond strength of G-Premio Bond under IDS, while significantly lower than the other adhesives, was comparable to that of the control group (DDS). A review by Harden et al. [22], which examined the effects of IDS on bonding indirect restorations across 21 laboratory studies, concluded that the IDS technique enhances bond strength to dentin, regardless of the bonding strategy employed. Furthermore, the use of two-step etch-and-rinse systems or one-step self-etch (SE) systems did not demonstrate any advantages over the DDS technique. This lack of benefit was attributed to insufficient hydrophobicity of the hybrid layer in generations 5 and 7, resulting in increased marginal microleakage and porosity within the hybrid layer. Additionally, the presence of water tree-like structures contributed to interface degradation, ultimately undermining the advantages of the IDS technique over DDS. Improved bond strength was noted primarily when using the three-step etch-and-rinse bonding system (Optibond FL) or when an adhesive system was combined with a layer of flowable composite. The flowable composite layer plays a crucial role in maintaining bonding integrity during cavity cleaning. Additionally, the creation of a thick bonding layer aids in the removal of undercuts and establishes a smooth surface. During sandblasting, this layer helps prevent dentin exposure, absorbs internal stresses, and preserves the integrity of the adhesive interface over time [23]. In a study by Raji et al. [24], Tokuyama Universal Bond (TUB) exhibited the highest bond strength when using the etch-and-rinse technique, while All Bond Universal showed the lowest bond strength in the self-etch approach. The superior bond strength of universal adhesives is attributed to the presence of MDP, which forms a durable bond with hydroxyapatite in a structure known as the Nano layer. However, variations in bond strength between these two approaches were influenced by factors such as water content, solvent type, MDP presence, and dimethacrylate resin composition. Therefore, it can be concluded that enhancements made by manufacturers in universal adhesives can elevate their bond strength to the level of high-performance adhesives. The bond strength values of universal adhesives can vary based on their specific formulation [15]. Additionally, the bond strength is influenced by the components contained within each adhesive, with notable differences observed between the IDS and Delayed Dentin Sealing (DDS) methods. Understanding these components is essential for improving bond strength [22]. In a study by Samartzi et al. [25], it was found that three-step etch-and-rinse systems and two-step self-etch systems demonstrated superior durability and bond strength compared to other adhesive types. This superiority is attributed to their ability to create a hydrophobic layer, which is particularly advantageous for IDS. Similarly, in research conducted by Fabiao et al. [26], both two-steps self-etch adhesive systems (Clearfil SE Bond and Clearfil SE Bond 2) exhibited higher immediate and long-term bond strengths compared to one-step adhesives like G Premio. Notably, the bond strength of these adhesives was not compromised by water storage, corroborating findings from the present study. However, contrary to these results, research by Cevik et al. [27] indicated that the adhesive Nova Compo B Plus, which contains the monomers 4META and 10MDP, achieved superior bond strength. Bond strength values are influenced by both the type of monomer used in the adhesive composition and the depth of the dentin. In the study by Jafarnia et al. [28], G Premio bond exhibited higher bond strength compared to the one-step self-etch adhesive Clearfil S3 bond, which contrasts with the findings of the present study. The effectiveness of adhesive bonding to tooth surfaces relies on factors such as enamel and dentin demineralization and monomer penetration. Moreover, the application technique of adhesives can vary among clinicians, and the formulation of each adhesive is crucial for achieving optimal results. Variations in chemical composition, monomer content, and the types and proportions of fillers in adhesives can significantly affect their performance. In the research conducted by Ferreira-Filho et al. [21], groups that underwent IDS demonstrated higher bond strengths compared to the control group. Notably, both Optibond FL and Xeno V reported a significant decrease in bond strength after three months of water storage, suggesting potential degradation of the adhesive interface. While SE Bond maintained high stability and bond strength after three months, Optibond FL initially presented higher bond strength due to its greater HEMA content (40-20%) compared to Clearfil SE Bond (10-30% HEMA), rendering it more hydrophilic. In the context of indirect restorations, IDS is recognized as an effective method for enhancing bond strength by promptly sealing freshly cut dentin surfaces, which leads to the formation of a superior hybrid layer compared to DDS [16, 28-29]. IDS effectively occludes dentinal tubules, reduces bacterial leakage, and minimizes post-exposure sensitivity, thereby strengthening the bond to the final restoration [23]. Applying immediate sealing following vital tooth preparation contributes to a stronger bond and alleviates sensitivity after cementation [30]. A study by Abo-

Alazm et al. [19] demonstrated that using a universal adhesive in self-etch mode for IDS is an effective strategy for enhancing the bond strength of CAD/CAM resin composite restorations while reducing dentin permeability. Conversely, Pinto et al. [17] found that the micro-tensile bond strength of indirect resin composite to dentin was not significantly affected by various dentin adhesive strategies. The variations in study results can be attributed to differences in the sealing duration, types of adhesive systems used, and the time frame for assessing bond strength. Van den Breemer et al. [20] reported no significant differences in micro-tensile bond strength between various IDS strategies and surface conditioning methods after one week; however, significant differences did emerge during the six-month assessment. In the current study, the evaluation of composite failure locations showed no significant differences among Optibond FL, SE Bond, G Premio Bond, G2 Bond, and the control group. The highest failure rates were observed in the adhesive-dentin interface region (AD), which included samples with adhesive failures regardless of whether the dentin was sealed. Ferreira-Filho's study [21] similarly noted the highest failure rates in the AD region. Van den Breemer [20] found the most significant failures at the dentin-adhesive interface, while Galliani's research [15] reported that most failures occurred at the adhesive interface with the restoration, with the least failures noted in the dentin-adhesive interface. In the study by Ferria (2018), the impact of four adhesives under Immediate Dentin Sealing (IDS) on the bond strength of self-adhesive resin cement to dentin was examined. After a period of 7 days, Clearfil SE Bond and Xp Bond showed no significant differences from the control group; however, all groups that underwent IDS demonstrated superior bond strength compared to the control group. This indicates that both air-etched and wash-etched adhesives exhibit greater demineralization capabilities and enhanced hybrid layer formation compared to the sulfur-etched resin cement used in the control group. The hybrid layer thickness was measured at 0.5 microns for the self-etched adhesive, 5 microns for the wash-etched adhesive, and 200 nm for the 35% self-etched resin cement. Immediate Dentin Sealing is an essential method in restorative dentistry that greatly improves the bond between dental materials and tooth structure, helping to reduce the occurrence of postcementation hypersensitivity, a frequent problem caused by exposed dentinal tubules. To tackle these issues, advancements like PTFE Coating are being researched to enhance the performance of dental restorative resin, as this low-friction material lessens wear and extends the life of restorations [30, 31]. Furthermore, in the field of regenerative dentistry, tissue engineering scaffolds are being recognized for their ability to facilitate dental pulp regeneration by simulating the natural extracellular matrix, encouraging cellular growth and healing. A notable consideration is the inherent biological variability of the deep dentin substrate itself. Although preparation depth was standardized (0.5 mm from pulp), factors such as tubular density, degree of sclerosis, and intertubular dentin morphology naturally vary between teeth. This biological variability is a recognized source of scatter in bond strength data, as reflected in the standard deviations reported in our study, and is a fundamental challenge in *in vitro* dentin bonding research. While our microscopic examination did not reveal an obvious macroscopic correlation between specific fracture site morphologies and bond strength values, this underlying substrate heterogeneity underscores the importance of adequate sample sizes and suggests that clinical outcomes will also be influenced by patient-specific dentinal characteristics.

Limitations and Future Research

This study shows the hydrolytic stability of different IDS adhesive combinations over a three-month period. However, certain limitations must be acknowledged. The aging protocol utilized static water storage, which primarily tests hydrolytic degradation. Clinically, restorations are subjected to thermomechanical fatigue from temperature fluctuations and masticatory loads. The absence of thermocycling in this model is a limitation, as it may influence the comparative ranking of adhesives and the prevalence of failure modes. Future studies should incorporate dynamic aging models, including thermocycling and mechanical loading, to more closely simulate the oral environment. Furthermore, while the resin coating thickness was visually controlled, future work could benefit from its precise measurement post-conditioning to definitively rule out its influence. Lastly, extending the water storage period beyond three months would provide data on longer-term durability.

4. Conclusion

In conclusion, this study underscores the importance of IDS in enhancing the micro-tensile bond strength of indirect composite restorations to deep dentin. Among the various adhesive systems evaluated, Optibond FL, SE Bond, and G2 Bond demonstrated significantly superior bond strengths compared to the control group using DDS. While G Premio Bond showed lower bond strength under IDS, it exhibited similarities to the control group, highlighting potential limitations in its effectiveness. The adhesive performance was found to be heavily influenced by the type of monomers, the configuration of the adhesive system, and the dental preparation techniques employed. Observations regarding failure locations indicated that the adhesive-dentin interface (AD) was particularly vulnerable, aligning with findings from prior literature. In conclusion, this study confirms that Immediate Dentin Sealing (IDS) significantly enhances the bond strength of indirect composite restorations to deep dentin compared to Delayed Dentin Sealing (DDS). Among the adhesives tested, the three-step etch-and-rinse system (Optibond FL) and the two-step self-etch system (Clearfil SE Bond) provided the highest and most comparable bond strengths under the IDS protocol. The single-step universal adhesive (G-Premio Bond) showed significantly lower performance in this specific deep-dentin IDS model. These findings suggest that for indirect restorations where maximum bond durability is critical, clinicians may achieve more predictable outcomes by employing a multi-step adhesive system (either etch-and-rinse or two-step self-etch) for the IDS procedure, despite the slightly increased clinical time, rather than relying solely on a simplified universal adhesive in self-etch mode.

Data Availability

The data supporting the findings of this study are available upon reasonable request from the corresponding author.

Conflict of Interests

The authors declare that there are no conflicts of interest regarding the publication of this article.

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Authors contributions
All authors contributed equally to the conception, design, execution, and writing of this work. All authors read and approved the final manuscript.

Availability of data and materials
The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Conflict of interests
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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