



Review

Functional Adhesives for a Restorative Future

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Abstract

Cementation of indirect restorations has undergone a profound change over the past century, evolving from a philosophy of purely mechanical cementation to sophisticated biomaterials science based on adhesion. The aim of this narrative review is to provide essential context for understanding contemporary clinical decision-making. A key aspect is the structural and compositional characteristics of enamel and dentin as bonding substrates, underlining why enamel remains the gold standard, while dentin continues to present significant challenges. The synthesis is based on evidence of adhesive strategies for the four main classes of contemporary restorative materials, such as glass-ceramics (lithium disilicate and leucite), polycrystalline zirconia, resin-matrix ceramics (hybrid ceramics), and indirect composites. Each material was detailed in terms of surface penetration (e.g., hydrofluoric acid etching and air abrasion), chemical coupling (e.g., silanization and MDP-based primers), and appropriate resin cement selection (light-cured, dual-cured, or self-adhesive). A step-by-step clinical protocol is synthesized based on current evidence, integrating critical techniques such as immediate dentin sealing and optimized polymerization. This review concludes that while adhesive resin cements provide predictable long-term results, significant challenges remain, guiding future clinical research and innovation.

Keywords: adhesive cementation; resin cements; lithium disilicate; zirconia; hybrid ceramics; dentin bonding; enamel etching; universal adhesives

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1. Introduction

The history of cementation in indirect restorative dentistry reflects a significant shift in how clinicians and scientists view the tooth–restoration interface. What originated as a purely mechanical process, where cements served merely to occupy space between two rigid, retentively prepared surfaces, has transformed into a biomaterial-driven field focused on adhesion, interface durability, and minimally invasive principles. This transition from passive luting to active bonding provides the essential historical and

scientific context for understanding the rationale behind contemporary cementation procedures.

For most of the 20th century, the success of a crown or bridge depended almost entirely on the geometry of the tooth preparation. The luting agent was a passive filler, and retention was a function of taper, height, and surface area. However, the advent of acid etching, the development of dentin-bonding hybrid layers, and the introduction of high-performance ceramic and resin-based restorative materials have rendered this mechanical philosophy obsolete. Today, cementation is a highly specialized, substrate-specific, and material-specific process. It is no longer a single technique, but a range of tailored strategies designed to create a durable, biomimetic interface that can reinforce brittle restorations, preserve tooth structure, and improve long-term survival.

From a functional materials perspective, modern luting agents are no longer passive space-fillers but active components that must exhibit a complex combination of properties, such as adequate mechanical strength, appropriate modulus of elasticity, hydrolytic stability, chemical adhesion to dissimilar substrates, biocompatibility, and bioactive functionality [1,2]. The interface they create functions as a multi-layered structure that must withstand cyclic mechanical loading, thermal fluctuations, and enzymatic degradation over decades of service.

This narrative review has three primary objectives, which are justified by the current state of clinical and scientific evidence. Despite the availability of modern adhesives, many clinical practices are still influenced by habits formed during the “mechanical era.” A clear understanding of why traditional cements (e.g., zinc phosphate and glass ionomer) fail where modern resin cements succeed is necessary to justify the adoption of more complex, technique-sensitive adhesive protocols [2,3]. We therefore hypothesize that the evolution from mechanical to adhesive cementation is directly correlated with improved clinical outcomes for tooth-supported prostheses, but only when substrate-specific principles are followed.

The market is flooded with diverse restorative materials (e.g., lithium disilicate, zirconia, and hybrid ceramics) and a bewildering array of adhesives and cements. A major source of clinical failure is the mismatch between a restorative material’s surface chemistry and the chosen adhesive protocol (e.g., attempting to etch zirconia with hydrofluoric acid). This review tests the hypothesis that each class of restorative material requires a unique, non-interchangeable combination of micromechanical (e.g., air abrasion, acid etching) and chemical (e.g., silane, MDP) surface pretreatment to achieve a durable bond.

Despite significant advances, problems such as durable dentin bonding, reliable zirconia adhesion, and complete polymerization under thick restorations remain unresolved. By systematically reviewing the limitations of current materials and techniques, this review aims to justify and direct future research toward bioactive, self-healing, and digitally integrated cementation systems [4,5].

2. Methodology

This narrative review was conducted to provide a comprehensive overview of functional materials used for adhesive cementation in indirect restorative dentistry. A systematic literature search was performed in PubMed, Scopus, and Web of Science databases for articles published between January 2015 and March 2026. The following search terms were used in various combinations: “dental cement,” “resin cement,” “adhesive cementation,” “cementing agent,” “bond strength,” “zirconium bond,” “lithium disilicate,” “universal adhesive,” “10-MDP,” “dentin bond,” and “bioactive cement.” Inclusion criteria included peer-reviewed articles in English, in vitro studies reporting mechanical or physicochemical properties, clinical trials, systematic reviews, and meta-analyses. Reference lists of included articles were hand-searched to identify

additional relevant publications. Given the narrative nature of this analysis, a quantitative meta-analysis was not performed. To address potential selection bias and heterogeneity, where there was conflicting evidence, we prioritized results from systematic reviews and meta-analyses. When these were not available, we reported a range of results from high-quality in vitro studies. A PRISMA flow chart of the search and selection process is shown in Supplementary Materials File S1.

3. The Historical Evolution of Cementation: From Mechanical Luting to Adhesive Dentistry

To appreciate the sophistication of contemporary cementation, one must first understand the limitations of the past. This evolution is best understood as three distinct eras, summarized in Table 1.

Table 1. Historical Eras of Cementation.

Era	Philosophy	Materials	Primary Retention Mechanism	Limitations
Old Luting Era (1900s–1970s) [2,3,6]	Mechanical—Cement as a passive space-filler	Zinc phosphate, Zinc Polycarboxylate, Glass ionomer cements	Macro-mechanical (preparation geometry: taper, height, surface area).	No adhesion, high solubility, low strength, marginal degradation, required aggressive tooth preparation
Transitory Resin Cement Era (1980s–2000s) [7–9]	Micromechanical—First true bonding	Early Bis-GMA resin cements, Dual-cure cements, Early etch-and-rinse adhesives.	Micromechanical via resin tag formation in etched enamel; primitive hybrid layer in dentin.	Technique sensitivity, polymerization challenges under thick ceramics, hydrolytic degradation of hydrophilic adhesives
Modern Adhesive Era (2000s–Present) [4,5,10,11]	Biomimetic & Chemical—Durable, integrated interface	Universal adhesives (10-MDP), Self-etch systems, Bioactive cements	Combined micromechanical + stable chemical bonding (e.g., MDP-Ca/MDP-Zr salts)	Complexity of dentin bonding, zirconia adhesion still technique-sensitive, long-term degradation of some interfaces

3.1. The Old Luting Era: A Mechanical Philosophy

For most of the 20th century, the cementation process was predominantly understood as a mechanical phenomenon. The cementing agent was merely a passive filling material, and the long-term viability of the prosthetic restoration depended almost entirely on the geometry of the preparation, such as taper, height, and surface area [2,3] (Table 2).

Table 2. Historical Evolution of Luting Cements.

Cement Type	Year Introduced	Clinical Significance	Advantages	Key Limitations
Zinc Phosphate	Late 1800s	Mainstay for decades; longest clinical history	Acceptable clinical performance; low cost	No adhesion to tooth structure; high solubility; low tensile strength; requires aggressive preparation designs
Polycarboxylate	1960s	First chemically adhesive cement	Chemical bonding via calcium ion chelation	High viscosity; difficult handling; limited clinical adoption
Glass Ionomer Cement (GIC)	1970s	Milestone in adhesive dentistry	Chemical bonding to tooth; cumulative	Moisture sensitivity; low fracture toughness (0.5–1.5

			release (23.67 ppm); MPa·m ^{1/2}); solubility; limited favorable CTE (10–14 ppm/°C) close to tooth structure	to low-stress areas
Resin-Modified GIC (RMGIC)	1990s	Addressed GIC moisture sensitivity and initial strength	Improved mechanical properties; reduced moisture sensitivity; fluoride release	Inferior adhesive performance vs. resin cements; higher failure rates

The old era was defined by the limitations of a purely mechanical philosophy, creating the need for a new generation of cementing agents capable of bonding and strengthening [6,12–19].

3.2. The Transitory Era: The Rise of Resin Cements

The introduction of resin cements in the 1980s marked a pivotal shift. Formulated with Bis-GMA and other dimethacrylates, they offered superior mechanical strength (flexural strength 80–150 MPa), low solubility (<0.05% after 24 h), and the potential for micro-mechanical bonding. This allowed for more conservative preparations [3,20].

A critical development was the dual-cure resin cement, designed to polymerize in areas where light penetration is poor (e.g., under thick or opaque crowns). However, research consistently shows that light activation remains critical for optimal conversion. Insufficient light exposure compromises the degree of conversion (reducing from >70% with adequate light to <50% without) and long-term stability [8,21,22]. This era laid the scientific foundation for modern adhesive strategies.

3.3. The Modern Adhesive Era: The Engineering of an Interface

The evolution to contemporary bonding represents a fundamental shift from mechanical retention to the design of a resilient, biomimetic interface. Buonocore's groundbreaking discovery in 1955 that etching with phosphoric acid creates a micro-retentive surface in enamel marked the beginning of this period. People around the world agree that this is when adhesive dentistry began [10,23].

Nakabayashi's hybrid layer concept was a major step forward for dentin. It is the micromechanical interlocking zone that forms when resin infiltrates demineralized dentin. Early etch-and-rinse systems were susceptible to technical problems and were likely to leak at the nanoscale and degrade in water [7,14].

Development continued through several generations of adhesives, culminating in universal adhesives. Functional monomers such as 10-MDP (10-methacryloyloxydecyl dihydrogen phosphate) are a major reason why they work so well. They produce stable MDP-Ca salts with hydroxyapatite that do not decompose in water [5,11]. The bond strength of 10-MDP-based systems is typically between 20 and 40 MPa for dentin and between 15 and 30 MPa for zirconia. This represents a significant improvement over the previous generation [24,25].

The most important change in thinking during this period is the realization that adhesion is substrate-dependent, as shown in Figure 1.

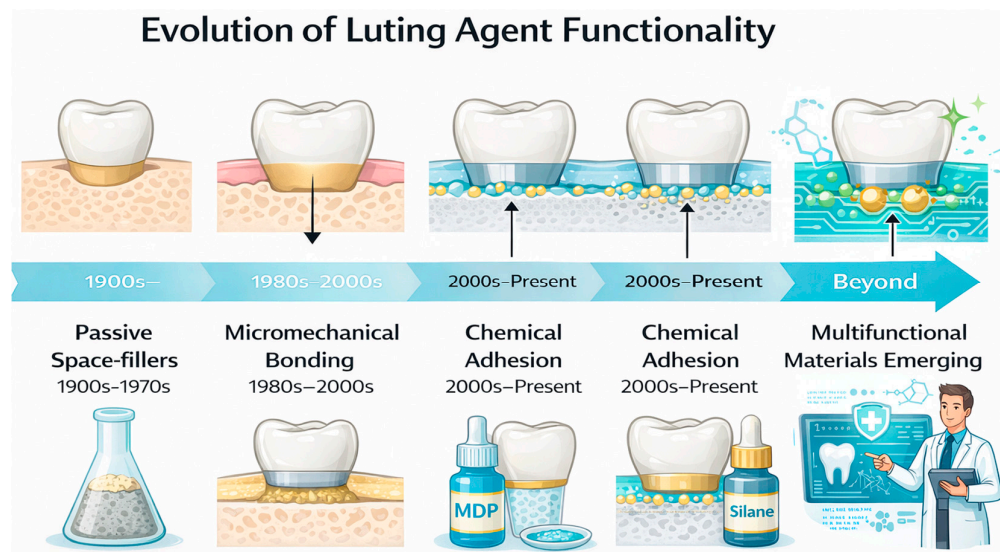


Figure 1. Evolution of luting agent functionality. Timeline from passive space-fillers (1900s–1970s) to micromechanical bonding (1980s–2000s) to chemical adhesion (2000s–present) to emerging multifunctional materials (bioactive, self-healing, digitally integrated).

4. The Biological Substrates

The success of any adhesive cementation procedure depends on a thorough understanding of the dental substrate. Enamel and dentin are fundamentally different in terms of structure, composition, and adhesion.

4.1. Enamel as a Substrate

Enamel remains the most predictable and durable substrate for adhesive dentistry due to its highly mineralized, acellular structure. Histologically, it is composed of approximately 92–95% vol. hydroxyapatite, providing a stable surface for resin infiltration. The foundation of modern cementation is the Buonocore acid etching technique, which produces a microporous surface that facilitates durable hybridization, with reported bond strengths of 25–40 MPa [4,26].

However, adhesion to aprismatic enamel, commonly found on unpolished surfaces or in cervical regions, is less predictable, with bond strengths reduced by up to 50%. Selective etching of enamel prior to application of self-etching adhesive has been repeatedly shown to overcome this limitation and improve fracture resistance [27]. Regarding surface degradation, although erosion significantly impairs dentin adhesion, bond strength to eroded enamel is not consistently reduced (typically within 10–20% of healthy enamel), although prolonged erosion may compromise dental resin formation [28]. Ultimately, enamel preservation is a determinant of restoration longevity, and maximizing enamel contact through selective etching remains an essential strategy [29].

4.2. Dentin as a Substrate

Dentin is a significantly more difficult material to bond to, as it is composed of approximately 45% minerals, 33% organic matrix (mostly type I collagen) and 22% water. It also has a dynamic, hydrated tubular structure. This environment makes resin infiltration difficult and makes dentin adhesion less predictable. Bond strength is typically between 15 and 30 MPa, while bond strength for enamel is between 25 and 40 MPa [4,26,30].

The complication is further compounded under pathological circumstances. Erosion reduces dentin bond strength by 30–60%, resulting in a demineralized, collagen-rich superficial layer that is prone to collapse and inhibits the proper formation of a hybrid layer

[28,31]. It is also well known that dentin can degrade over time when exposed to water. After 6 to 12 months of storage in water, bond strength can decrease by 20 to 50% as the collagen fibrils and resin components of the hybrid layer degrade [4,32]. To reduce these weaknesses, the immediate dentin sealing (IDS) method has become an important option. Applying the adhesive immediately after tooth preparation creates a stable hybrid layer before impression taking. This makes the bond last longer, keeping the hybrid layer intact and reducing sensitivity after surgery [33–35]. A systematic review confirms that IDS increases bond strength and decreases marginal detachment compared with delayed sealing methods [36]. Regarding clinical implementation, when using IDS cements, the choice of provisional cement is critical; cements containing eugenol should be avoided as they inhibit adhesive polymerization. If a provisional cement containing eugenol was used, the IDS layer should be cleaned with 50 μm aluminum oxide and re-etched before final cementation. For provisional cements without eugenol, light cleaning with pumice is usually sufficient [20].

Sclerotic dentin presents a unique clinical problem, frequently seen in non-carious cervical lesions. This hyper-mineralized dentin with blocked tubules is very difficult to etch, and the bond strength is 40–60% lower than that of normal dentin. Sclerotic lesions frequently have a hyper-mineralized superficial layer that inhibits sufficient acid penetration and resin infiltration, thus requiring additional surface pretreatment methods [37]. In conclusion, dentin sealing is still the weakest part of adhesive dentistry to achieve predictable, long-term clinical results, careful techniques and methods, such as IDS [38,39] (Figure 2).

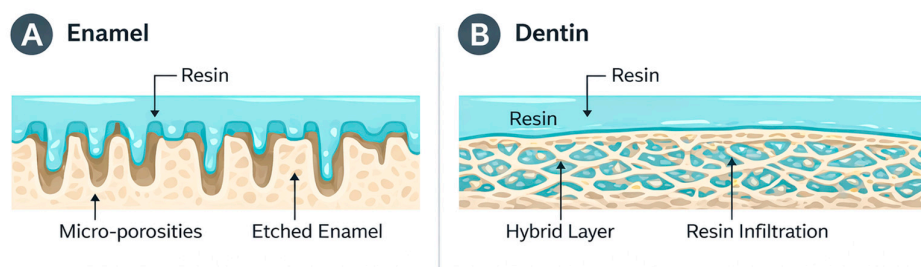


Figure 2. Schematic illustration of the contemporary adhesive interface. (A) Enamel: Resin tags penetrating etched enamel prisms. (B) Dentin: Hybrid layer with resin infiltration into demineralized collagen network.

5. Physicochemical Properties of Functional Luting Agents

The performance of a cementing agent is governed by its physicochemical properties, which determine its handling characteristics, polymerization behavior, mechanical integrity, and long-term stability. The physicochemical properties of functional luting agents, particularly their adhesion to tooth substrates, can be influenced by surface treatments, while the application of preheated resin composites as luting agents offers potential improvements in their handling and mechanical characteristics [40–42]. Table 3 summarizes the key properties of contemporary classes of cementing materials (Table 3).

Table 3. Comparative Physicochemical Properties of Luting Agents.

Property	Conventional GIC	RMGIC	Self-Adhesive Resin Cement	Adhesive Resin Cement
Flexural Strength (MPa) [16,20,43,44]	20–50	50–80	80–120	100–150
Elastic Modulus (GPa)	2–6	4–8	5–10	8–15

[43–45]				
Degree of Conversion (%) [21,22,46–49]	N/A (acid–base reaction only)	40–60	55–75	65–85
Water Sorption ($\mu\text{g}/\text{mm}^3$) [50,51]	50–150	40–170	20–40	15–35
Solubility ($\mu\text{g}/\text{mm}^3$) [51,52]	5–20	2–8	0.5–2.0	0.1–1.0
Cumulative Release (ppm) [53–55]	23.67	20.37	Not specified	Not specified
Bond Strength to Dentin (MPa) [24,25,38,56–59]	2–5	5–10	10–20	20–40
Bond Strength to Zirconia (MPa) [27,60,61]	0–2	1–3	5–15	15–30

5.1. Polymerization Kinetics and Degree of Conversion

The degree of conversion (DC) is an important factor influencing mechanical characteristics, dimensional stability, and biocompatibility. Under ideal circumstances, dual-cure resin cements exhibit DC values between 55 and 75%. However, these values can diminish to below 50% when light activation is inadequate [22,46,62]. This decrease is of clinical importance, as insufficient DC is associated with elevated monomer release, thereby raising concerns regarding pulp irritation and the long-term success of restorations [39,50]. Preheated composites, utilized as luting agents, attain DC values ranging from 60–80% due to enhanced monomer mobility at elevated temperatures (typically 55–68 °C) [47,63]. Furthermore, preheating diminishes film thickness and improves adaptation to the tooth structure, thereby augmenting bond durability [64–66]. The existence of oxygen-inhibited layers at the restoration–cement interface can reduce surface DC by 10–20%, thereby compromising marginal integrity [64]. This incompletely polymerized layer not only weakens the adhesive interface but also serves as a preferred site for biofilm accumulation and microleakage, thus highlighting the significance of adequate light exposure through the restorative material [65–67].

This vulnerability to inadequate light activation is particularly critical when cementing highly translucent zirconia or lithium disilicate restorations, as the crystal structure of the ceramic can attenuate up to 30–40% of the incident light, effectively reducing the curing efficiency at the cement interface [51,54,68]. In addition, the chemical initiator system in dual-cure cements (tertiary amines associated with benzoyl peroxide) is sensitive to acidic monomers commonly present in self-adhesive formulations, which can lead to premature decomposition and reduced contribution to dark cure when light penetration is compromised [2,37,48]. Although 68 °C is at the upper limit of recommended commercial or research-based preheating, many studies find that preheating to 54–68 °C reduces viscosity, increases flowability, and improves degree of conversion (DC) [69–71].

In addition, prolonged heating cycles have been shown to degrade the activity of the camphor quinone photo-initiator, requiring strict adherence to the manufacturer’s specified preheating protocols [72].

5.2. Physical Properties

The ability of cement to withstand masticatory forces and distribute stress across the contact is measured by its flexural strength and modulus of elasticity. Compared with conventional cements, adhesive resin cements (100–150 MPa) and heated composites (120–180 MPa) have better mechanical properties [20,35]. However, if the modulus is too

high (more than 18 GPa), it can put too much pressure on the contact, which could cause delamination [73]. The best values of modulus are considered to be between 10 and 15 GPa, which are close to the values for dentin (12–18 GPa) and enamel (40–80 GPa), while still allowing for stress absorption [49].

5.3. Absorption and Water Solubility

Absorption and water solubility are important factors affecting long-term hydrolytic stability. Resin-based adhesive cements have the lowest water absorption (15–35 $\mu\text{g}/\text{mm}^3$) and solubility (0.1–1.0 $\mu\text{g}/\text{mm}^3$). GIC and RMGIC cements, on the other hand, have much higher values [12,49]. Some universal adhesives are hydrophilic, meaning they can absorb more water over time. This could lead to the breakdown of the hybrid layer by hydrolysis [11]. Functional monomers, such as 10-MDP, improve hydrolytic stability by creating stable ionic bonds with hydroxyapatite, which prevents water penetration [74].

6. Mechanisms of Bond Degradation and Interface Durability

To design useful materials that last longer, it is important to understand how adhesive surfaces degrade over time (Figure 3).

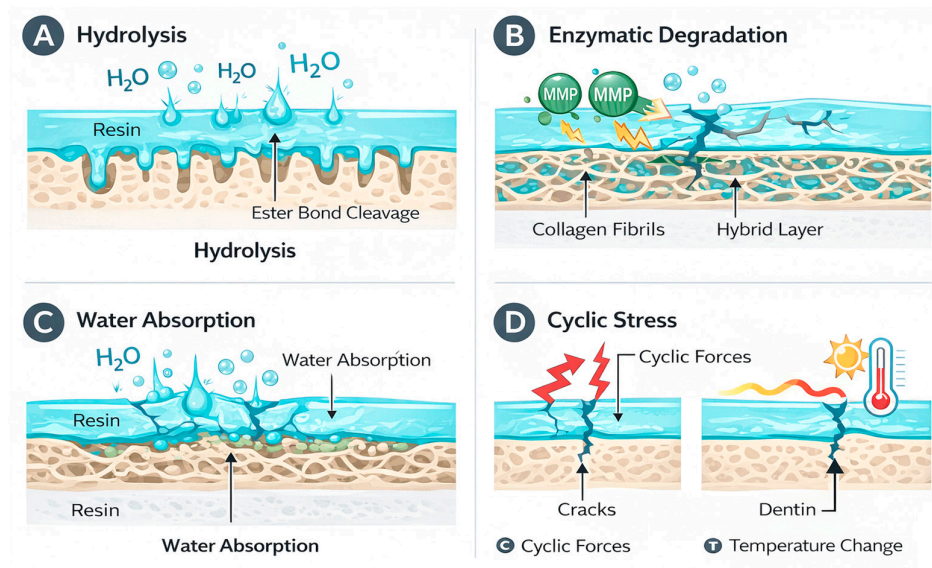


Figure 3. Mechanisms of adhesive interface degradation. (A) Hydrolytic cleavage of ester bonds in methacrylate polymers. (B) Enzymatic degradation of collagen fibrils by MMPs. (C) Water absorption leading to plasticization and swelling. (D) Cyclic thermal and mechanical stress causing interfacial crack propagation.

This degradation is a multifactorial process driven by chemical, enzymatic, and mechanical challenges in the dynamic oral environment.

Hydrolytic degradation: Water is the main agent of chemical degradation. Hydrolysis cleaves ester bonds in the methacrylate resin matrix and degrades the exposed collagen fibrils of the hybrid layer. At the same time, water absorption plasticizes the polymer network, decreasing its mechanical properties by 20–40% after 6–12 months of water storage [11,49]. The inclusion of hydrophilic monomers, such as HEMA (hydroxyethyl methacrylate), exacerbates this problem by increasing water sorption.

Enzymatic degradation: Acid etching conditions activate endogenous dentin matrix metalloproteinases (MMPs) and cysteine cathepsins. These enzymes slowly proteolyze the exposed collagen fibrils in the hybrid layer, causing a 30–50% reduction in bond

strength over a period of 12–24 months. Application of MMP inhibitors, such as chlorhexidine and benzalkonium chloride, has been shown to effectively attenuate this enzymatic degradation [4].

Thermal and mechanical fatigue: Cyclic thermal variations (5–55 °C, typically 5000 to 10,000 cycles) induce differential expansion between the restorative material, cement, and tooth substrate. This mismatch generates interfacial stresses that weaken the bond by 15–35%. Mechanical fatigue (cyclic loading at 50–200 N for 10^5 – 10^6 cycles) further contributes to interfacial cracking, a critical failure mode in bonded brittle ceramics [75,76].

Galvanic corrosion: Although less relevant for all-ceramic restorations, galvanic currents can form between dissimilar metal restorations or between titanium implants/posts and adjacent structures. These electrochemical couples can accelerate adhesive degradation at the cement–tooth interface [2].

Synergistic degradation: It is worth noting that these degradation mechanisms do not operate in isolation. Hydrolytic swelling can enlarge micro-lacunae, facilitating bacterial infiltration and enzymatic activity. Similarly, mechanical fatigue can expose fresh hydrolytic sites, accelerating chemical degradation [32]. This synergy highlights that complete bond breakage is often the cumulative result of multiple interacting degradation pathways [4,10,32].

Contemporary issue: Current research is increasingly focusing on the complex, site-specific dynamics of degradation in vivo. In contrast to simplified laboratory aging, the oral environment presents a dynamic cocktail of salivary enzymes, cyclical pH fluctuations from dietary acids and bacterial plaque, and a polymicrobial biofilm [2,14]. This biofilm not only produces acids but also secretes bacterial enzymes that can directly degrade adhesive components, a factor often underestimated in vitro. In addition, long-term clinical performance is critically influenced by the quality of the hybrid layer; incomplete resin infiltration leaves a gaping collagen zone vulnerable to both host-derived proteases (MMPs) and bacterial ones. Therefore, contemporary strategies are moving towards “bioactive” adhesives that not only resist degradation but also actively buffer pH, release therapeutic ions (e.g., calcium, phosphate), or incorporate antibacterial monomers to disrupt biofilm formation at the interface, representing the next frontier in improving clinical durability [4,11,32].

7. Material-Specific Adhesive Strategies

7.1. Glass-Ceramics (*Lithium Disilicate & Leucite*)

Glass-ceramics require a two-step bonding protocol. The first step consists of etching with hydrofluoric acid (HF) for micromechanical interlocking, followed by the application of silane for chemical coupling [77]. Etching parameters are critical, namely, insufficient etching compromises bond strength, while excessive etching degrades the flexural strength of the ceramic [77]. Resin cements containing MDP monomers demonstrate superior chemical interaction with silanized glass surfaces compared to self-adhesive alternatives [78].

The cementing agent significantly influences the final shade, especially for thin laminates (0.3–0.5 mm), where the cement layer exerts the greatest color impact [79,80]. Trial pastes help to evaluate shade, but do not perfectly reproduce the final appearance of the resin cement. Preheated composite resins offer a viable alternative, demonstrating equivalent or improved color stability while maintaining adequate mechanical properties [81,82].

The mode of polymerization directly affects bond strength, with dual-curing systems providing a more reliable bond to lithium disilicate than single-cured formulations, particularly for thicker or highly translucent restorations with low light transmission [83].

Resin cements and flowable composites improve ceramic performance by infiltrating surface microdefects and transferring occlusal stresses, increasing fracture resistance, which is particularly important for minimally invasive preparations with reduced ceramic thickness [84]. Dual-cure resin cements provide superior marginal sealing, reducing microleakage and postoperative sensitivity compared to conventional cements [85]. (Table 4).

Table 4. Recommended Adhesive Protocol for Glass-Ceramics.

Step	Procedure	Principal Support
Surface Pretreatment [60,86,87]	1. Etch with 4–9% hydrofluoric acid (HF) for 20–60 s. 2. Rinse thoroughly. 3. Apply silane coupling agent.	HF creates micro-retentive surface with etch depth of 10–50 µm and increases surface area by 10–20. Silane forms siloxane bonds (Si–O–Si) with ceramic and copolymerizes with resin matrix, yielding bond strengths of 25–40 MPa.
Tooth Management [26]	Selective enamel etching + immediate dentin sealing (IDS) as needed data	Maximizes enamel bond and reduces post-operative sensitivity.
Luting Agent [8,88]	Light-cure cement for thin veneers (<1.5 mm). Dual-cure cement for thicker crowns/onlays.	Light-cure offers better color stability ($\Delta E < 1.5$ after aging). Dual-cure ensures polymerization under thick ceramics, with DC of 60–75%.
Clinical Outcome [23,75,89]	Excellent survival rates (95–98% at 5–10 years), reinforced structure.	-

7.2. Zirconia (Polycrystalline)

Zirconia is a polycrystalline ceramic and has no glass phase and is resistant to hydrofluoric acid etching. Achieving durable adhesion requires both micromechanical retention through surface modification and chemical bonding between the resin cement and the zirconium substrate [90,91].

Zirconia is available in several generations with distinct properties. Conventional 3Y-TZP has high flexural strength (~1200 MPa) but limited translucency and is prone to phase transformation under excessive abrasion pressure (>0.3 MPa) or particle sizes >110 µm [61,91]. 4Y-TZP has intermediate strength (~1000 MPa), while 5Y-TZP has maximum translucency but at the expense of strength (~700 MPa) and is less prone to phase transformation, though more vulnerable to surface chipping [61,91]. Abrasion of airborne particles with Al₂O₃ (50–110 µm) is the gold standard for creating micromechanical retention, increasing surface energy and wetting [92,93]. However, parameters must be adapted for the generation of zirconia: 4Y- and 5Y-TZP need lower pressure (0.2 MPa) and smaller particles (30–50 µm) to prevent surface damage [61,77]. Saliva contamination should be removed before abrasion, since residual organic material compromises bond formation. Micromechanical retention is insufficient.

Resin cements containing the monomer 10-MDP are essential, as the phosphate group builds stable ionic bonds with zirconium oxides [94]. This chemical interaction significantly enhances bond strength and hydrolytic stability [95]. Universal adhesives with MDP are effective, although some studies have shown that MDP-based cements can achieve comparable bonds without an additional adhesive layer [96,97]. Chemical etching solutions with hydrofluoric acid selectively etch the zirconia grain boundaries, achieving bond strengths equal to or exceeding those of air abrasion without the risk of phase transformation [98,99]. Additionally, the application of a silica-based ceramic layer on the inlay surface allows for conventional silanization, expanding adhesive options [2,100,101]. (Table 5).

Table 5. Recommended Adhesive Protocol for Zirconia (Polycrystalline).

Step	Procedure	Principal Support
Surface Pretreatment [5,102]	1. Airborne-particle abrasion with 50 μm Al_2O_3 at 0.2–0.3 MPa. 2. Clean ultrasonically. 3. Apply MDP-containing primer or universal adhesive.	Air abrasion creates micromechanical retention with surface roughness (Ra) of 0.5–1.5 μm ; 10-MDP forms stable MDP-ZrO ₂ salts with bond strengths of 15–30 MPa.
Luting Agent [61,103,104]	Adhesive resin cement containing MDP. Avoid self-adhesive cements alone.	MDP-containing cements outperform non-MDP systems by 30–50% in bond strength.
Critical Note [54,105–107]	Saliva contamination severely inhibits bonding (50–80% reduction). Reabrade or use alkaline cleaners if contaminated.	Contamination compromises the chemical interaction between MDP and zirconia, necessitating immediate re-treatment.

7.3. Resin-Matrix Ceramics/Hybrid Ceramics (e.g., PICN)

Resin matrix ceramics, including polymer-infiltrated ceramic network (PICN) materials, possess an organic–inorganic composition that requires a fundamentally different bonding approach compared to glass-ceramics. Hydrofluoric acid etching is not effective due to the limited ceramic phase and the polymer matrix's resistance to uniform acid dissolution [108–110]. Surface treatment is based on particle abrasion in air with 50 μm aluminum oxide, which results in a 40–60% increase in bond strength compared to untreated surfaces by creating a microroughness that facilitates resin infiltration [109]. This mechanical activation is critical for the establishment of durable micromechanical retention. The role of silane is less definite for resin matrix ceramics due to the limited ceramic content, which diminishes the silanol groups available for condensation reactions [109,111,112].

Contemporary universal adhesives containing 10-MDP have emerged as the preferred chemical coupling strategy, achieving bond strengths of 20–35 MPa. MDP has a double affinity for the exposed ceramic phases and can copolymerize with the polymer matrix, thus eliminating the need for a separate silanization step [112,113]. The highest and most predictable bond strengths of adhesive resin cements are achieved in combination with pretreatment and universal adhesive.

Self-adhesive resin cements show significantly lower bond strengths (10–20 MPa) when used without an additional adhesive system because they lack the acidic monomers to condition the resin-rich surface [114,115]. High-viscosity preheated composites have also been proposed by taking advantage of the improved penetration of monomers into the abraded surface [110].

A successful cementation follows a sequential approach, namely air abrasion with 50 μm Al_2O_3 for micromechanical retention, a universal adhesive (containing 10-MDP) for chemical bonding, and resin-based adhesive cement or a preheated composite for cementation. Omitting sandblasting or using self-adhesive cements without pretreatment leads to a clinically relevant reduction in bond strength, especially under thermal and mechanical loading [111,116] (Table 6).

Table 6. Recommended Adhesive Protocol for Resin-Matrix Ceramics.

Step	Procedure	Principal Support
Surface Pretreatment [5,102]	1. Airborne-particle abrasion (sandblasting) with 50 μm Al_2O_3 . 2. Avoid HF etching (ineffective).	Sandblasting improves micromechanical retention, increasing bond strength by 40–60% compared to untreated surfaces.

Chemical Coupling [110–112]	Adhesive resin cement containing MDP. Avoid self-adhesive cements alone.	Bond strengths of 20–35 MPa are achievable with universal adhesive.
Luting Agent [113–116]	Saliva contamination severely inhibits bonding (50–80% reduction). Alkaline cleaners if contaminated.	Self-adhesive cements show lower bond strengths (10–20 MPa) without pretreatment.

7.4. Indirect Composite Restorations

The durability of indirect composite restorations relies on a dual-bonding approach to both the resin matrix and exposed filler particles, a concept that deviates significantly from ceramic bonding.

The most proven technique involves abrasion with 50 µm suspended aluminum oxide particles, which removes contaminants and creates a micro-retentive topography, increasing bond strength by 50–100% over untreated surfaces [109]. Lack of sufficient roughness compromises interfacial cohesion.

Upon post-mechanical activation, application of silane or a universal adhesive leads to covalent bonds with the exposed glass fillers [117]. This chemical coupling improves immediate bond strength and provides essential hydrolytic stability against intraoral water absorption and interfacial degradation.

Preheated composites have higher flexural strengths of 120–180 MPa and filler contents of 70–85% by weight compared to conventional resin cements [35,118] and are associated with improved mechanical performance and wear resistance. However, they have 2–3 times greater bacterial adhesion and therefore careful marginal finishing and increased vigilance against biodegradation are required [118]. Material selection should be individualized according to the site of the restoration, aesthetic requirements, and the patient's caries risk, balancing mechanical benefits with increased biofilm susceptibility [118] (Table 7).

Table 7. Recommended Adhesive Protocol for Indirect Composites.

Step	Procedure	Principal Support
Surface Pretreatment [109]	Airborne-particle abrasion with 50 µm Al ₂ O ₃ .	Increases bond strength by 50–100% compared to untreated surfaces.
Chemical Coupling [117]	Silane or universal adhesive.	Improves compatibility with resin cement; silane provides chemical coupling to glass filler particles.
Luting Agent [35,118]	Preheated composite (superior mechanical properties) or conventional resin cement.	Preheated composites offer high filler content (70–85 wt%) and strength (120–180 MPa). However, monitor for increased biodegradation (bacterial adhesion 2–3 or higher).

8. Discussion

Active functionality beyond passive adhesion is what defines the next generation of cementing agents. Bioactive materials are engineered to interact positively with the biological environment, encouraging remineralization, suppressing bacterial growth, and possibly promoting tissue regeneration [1,119]. To offer clinically useful advice, these emerging technologies need to be clearly differentiated by their commercial availability, translational barriers, and comparative performance against current standards. Among the commercially available choices, ion-releasing cements, such as Activa Bioactive (Pulpdent) and Ceramir (Doxa), release calcium, phosphate, and fluoride ions to inhibit secondary caries. However, their mechanical properties are still inferior to resin-based systems and long-term clinical data are scarce. Bioactivity is evident in calcium silicate

cements such as Biodentine, but their low flexural strength (30–50 MPa) limits their use in light-duty fillings [1,120,121].

Several experimental bioactive systems remain in the preclinical stage. Hydroxyapatite nanoparticles incorporated into magnetic glucuronate cements (GICs) improve compressive strength by 20–30% [17,119], while bioactive resin cements aim to combine mechanical strength (80–120 MPa) with sustained ion release (2–5 $\mu\text{g}/\text{cm}^2$ fluoride/24 h) [122]. However, no truly bioactive resin cement with both high strength (>100 MPa) and sustained ion release is commercially available. Challenges include stable ion release over time without loss of mechanical properties, regulatory issues for bioactivity claims and higher costs of the material. Antibacterial monomers, such as quaternary ammonium methacrylates, provide a dual therapeutic effect by preventing biofilm formation without loss of mechanical properties [122]. However, all data are still laboratory-based, with no available commercial luting cement using this technology. Self-healing materials are based on microcapsules (50–200 μm , 5–15 wt%) filled with TEGDMA that break upon crack formation, polymerizing to seal the defect. Laboratory studies demonstrate a 50–80% recovery of original mechanical properties [123–125]. However, no commercially available product exists, and all data remain preclinical due to barriers including capsule–matrix compatibility, healing efficiency under cyclic loading, and lack of regulatory pathways.

While these materials offer bioactive benefits, they cannot match the mechanical performance of modern resin cements and are best for low-stress situations where bioactivity outweighs strength. Surface functionalization technologies provide direct clinical advantages. UV-mediated photofunctionalization (360–400 nm, 5–15 min) increases the surface energy of zirconia by 50–100%, improving bond strength by 20–40% through photocatalytic decomposition of surface hydrocarbons [126–128]. This technology is commercially available, easy to implement, and adds minimal clinical time.

Digital workflow integration has been extended by the introduction of preheated composite delivery systems (55–68 °C) to reduce viscosity by 50–80% and improve the fit [129,130], as well as automated mixing to ensure constant proportions and 3D-printed prostheses that need customized cementation protocols for the new materials [131–133]. These technologies are commercially available and clinically mature, offering immediate advantages without any fundamental changes in established adhesive principles. Evidence on clinical performance indicates that resin-based adhesive cements remain the gold standard, offering 5-year survival rates of 94–98% for lithium disilicate, 92–96% for zirconia crowns with MDP-containing cements (as compared to 85–90% without cements), and 90–95% for indirect composites [134–140]. The most common failure modes include delamination (30–50% of failures, mainly at the dentin–cement interface), ceramic/composite fracture, secondary caries (more common with non-adhesive cements), and postoperative sensitivity (more common with etch-and-rinse systems) [2,28,135,141].

Although adhesive cements cost 3–5 times more than conventional alternatives, they become cost-effective when restoration survival exceeds 5–7 years. However, the sensitivity of the technique and the additional clinical time remain barriers to widespread adoption [142,143].

Specific substrate surface management is essential for optimal results. For zirconia, air abrasion remains the gold standard, increasing bond strength by 50–100%, although contamination severely compromises the bond [108,144–147]. For lithium disilicate, hydrofluoric acid etching combined with silane application provides the most predictable bond through micromechanical interlocking and covalent bonding with siloxane [148,149]. For dentin, IDS preserves the substrate, reduces postoperative sensitivity, and improves marginal integrity. Composite-reinforced flowable IDS further increases bond strength [34,36,150–152].

In terms of luting agent selection, resin-based adhesive cements remain the gold standard for nonretentive preparations under high stress due to their better retentiveness and ceramic hardening. Self-adhesive cements provide a clinically comfortable solution but present a higher failure rate when the etching of enamel is not performed and are therefore mostly used in posterior molars with macromechanical retention or in cases where isolation is difficult [153,154]. Preheated composites with high viscosity have better mechanical properties but require the use of additional equipment and demonstrate 2–3 times more bacterial adhesion [119,155–157]. Self-adhesive cements present acceptable but suboptimal performance (85–90% survival at 5 years), while preheated composites present a better mechanical profile but an increased risk of biofilm formation.

The dynamics of polymerization also affect the results. The polymerization mode is essential for the polymerization of resin-based luting cements, with light-curing systems exhibiting better wear resistance than dual-curing systems. The COMBO technique offers a simplified approach to cementation, using a high-viscosity bulk-fill composite that achieves adequate polymerization due to its optimal light transmission and reduced thickness [158–161]. The step-set technique, which includes partial polymerization before final cementation, reduces marginal discrepancies, especially in translucent restorations, while selective adhesive cementation decreases interfacial stress without affecting bond strength [162–164]. Strict moisture control is required regardless of the polymerization technique [165].

New considerations arise with digital workflows and CAD/CAM materials, and fiber-reinforced composites require careful selection of surface pretreatment [166,167]. The resin-coating technique is a thin layer of unfilled resin applied to the prepared tooth, which protects the dentin surface and aids cementation for CAD/CAM materials [33].

Novel bioactive formulations with calcium phosphate nanoparticles and quaternary ammonium methacrylates are shifting the cementation interface from a passive mechanical connection to an active protective zone. However, long-term clinical studies are needed as current evidence is largely based on laboratory studies [168,169]. In summary, the current body of evidence supports a shift to customized, substrate-specific adhesive cementation methodologies including mechanical surface preparation, chemical bonding agents and judicious material choices. The previously dominant “one-size-fits-all” approach is giving way to sophisticated strategies considering the specific restorative material, dental substrate, preparation design and functional requirements. Resin adhesive cements remain the gold standard for predictable long-term outcomes. Self-adhesive cements are convenient but at the expense of performance. Bioactive materials have promising adjunctive benefits but are largely preclinical, with the exception of ion-releasing GICs. Digital tools offer immediate clinical benefit and are the most mature emerging technology. Future investigations should focus on long-term clinical studies directly comparing emerging techniques, particularly as bioactive materials and digital workflows are increasingly integrated into routine prosthetic procedures.

9. Limitations of This Review

As a narrative review, this work has some limitations, including the potential for selection bias and the lack of systematic, quantitative meta-analysis. The existing literature is highly variable with respect to study design, testing methods, and follow-up periods. Furthermore, many newer materials (e.g., bioactive cements) are supported mainly by *in vitro* research, and their long-term clinical performance remains uncertain. The bond strength, survival rates, and conversion rates cited are presented without a formal critical assessment of study quality. *In vitro* bond strength studies often overestimate clinical performance due to idealized conditions and methodological heterogeneity (e.g., storage time, thermal cycling protocols, loading conditions) that limit direct comparisons between

studies. We preferred the results of systematic reviews and meta-analyses when they were available; otherwise, data from a single study should be considered preliminary. Finally, adhesive dentistry is a field that is rapidly evolving, and not all recent developments may be fully represented here.

10. Future Directions

The future of adhesive dentistry lies in translating mechanistic understanding into durable, clinically tolerant materials. First, degradation-resistant chemicals should be prioritized. Long-term studies should validate MMP inhibitors (e.g., chlorhexidine 2%), while novel monomers (vinylcyclopropanes) and crosslinkers (proanthocyanidins) should target a 40% increase in collagen stability, with $\leq 10\%$ strength loss after aging. Second, technical insensitivity requires universal primers that provide ≥ 25 MPa bond strength even in humid conditions, reducing operator variability from 30% to $\leq 15\%$. Third, depth-independent polymerization requires redox/thermal initiators that achieve $\geq 65\%$ conversion through 6 mm of opaque ceramic, with dual-cure cements that offer practical working times and an ultimate modulus ≥ 8 GPa. Fourth, bioactive multifunctionality should combine ion-releasing fillers (bioglass or calcium phosphates) with antibacterial monomers (quaternary ammonium compounds) to simultaneously combat degradation and infection without sacrificing mechanical integrity. Fifth, self-repairing systems should demonstrate $\geq 70\%$ bond strength recovery over multiple cycles and limit fatigue-induced losses to $\leq 20\%$ versus 50% for the control group.

11. Conclusions

The progression of cementation techniques in indirect restorative dentistry, from mechanical methods to functional adhesive interfaces, reflects significant developments in materials science and the understanding of tooth–restoration interactions. Modern functional cements are subject to stringent criteria, including sufficient mechanical strength, hydrolysis resistance, chemical adhesion to various substrates, biocompatibility, and, more recently, bioactive properties.

The incorporation of sophisticated functional materials alongside clinically validated protocols presents an opportunity to develop durable biomimetic restorations, thereby preserving tooth tissue and improving patient outcomes over time. Sustained interdisciplinary collaboration between materials specialists, engineers, and dental professionals will be important for the successful implementation of these innovations in standard clinical settings.

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Abbreviations

The following abbreviations are used in this manuscript:

IDS	Immediate dentin sealing
DC	Degree of conversion
HEMA	Hydroxyethyl methacrylate
GICs	Glass ionomer cements
RMGICs	Resin-modified glass ionomer cements
MMPs	Matrix metalloproteinases
HF	Hydrofluoric acid
Al ₂ O ₃	Aluminum oxide
PICN	Polymer-infiltrated ceramic network
TEGDMA	Triethylene glycol dimethacrylate

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