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Review Article

Harnessing Comparative Insights Into Bond Strength Of Diverse Composites: A Meticulous Appraisal

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ABSTRACT:
The critical evaluation of composite bond strength is fundamental to ensuring the longevity and performance of restorative treatments in dentistry. This article delves into an in-depth analysis of emerging trends in the assessment of composite bond strength within dental applications. It explores recent advancements in adhesive technologies, composite materials, and testing methodologies, underscoring their impact on clinical outcomes. The analysis encompasses a thorough examination of innovative techniques, such as enhanced bonding agents, improved surface treatment protocols, and novel evaluation methods that have garnered significant attention. Furthermore, it discusses the implications of these trends for dental practice, highlighting their role in enhancing the durability and effectiveness of dental restorations. By synthesizing recent research findings and case studies, this work provides dental professionals and researchers with a comprehensive understanding of the current state and future directions of composite bond strength assessment in dentistry.
Keywords: Composite Bond Strength, Bonding Techniques. Strength Evaluation, Material Testing, Structural Integrity, Advanced Techniques, Mechanical Properties, Failure Analysis, Quality Control

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INTRODUCTION

From historical practices to contemporary techniques, dentistry has seen a plethora of direct filling materials designed to restore lost tooth structure due to carious lesions, preventing alterations in tooth shape and function. This evolution from amalgams to Glass Ionomer Cements and composites marks significant progress in dental materials science.[1] Restorative materials are crucial in repairing, replacing, and reinstating the physical, biological, and mechanical functions of teeth.[2] Historically, materials such as amalgams, hybrid and resin-modified glass ionomers, cast metal alloys, and resin-based composites were used to address significant carious lesions, severe damage, cracks, or endodontic procedures.[3] Despite their benefits, these materials often faced challenges in enduring intraoral compressive, tensile, and shear forces, prompting the development of advanced solutions like dual-cure composites.[4] Composite resins are widely utilized in dental practice due to their aesthetic appeal, biocompatibility, and impressive physical and mechanical properties. They feature a matrix phase reinforced by various fillers such as ceramics, metals, or polymers.[5] Poly methyl methacrylate (PMMA) resin, introduced in the mid-20th century, initially experienced significant polymerization shrinkage, resulting in problems such as marginal leakage and inadequate wear resistance.[6] The addition of quartz as a filler mitigated issues such as marginal leakage and poor wear resistance, resulting in a composite structure with improved performance.[7] Innovations such as ParaCore by Coltene Whaledent, a fiber-reinforced, dual-cure core composite, exemplify progress in the field. ParaCore incorporates glass particles that provide dentin-like strength and flexibility.[8] Effective adhesion is critical for dual-cure resin treatments, and advancements in adhesive technology have significantly improved the bonding of dental materials.[9] Adhesion to dentin presents unique challenges due to its complex biological structure, which includes a hyper mineralized collagen matrix, apatite crystals, dentinal tubules, and a smear layer formed during cavity preparation.[10] To address these challenges, dentin bonding systems are categorized into etch-and-rinse and self-etching systems.[11]Self-etch adhesives simplify the process by combining demineralization and priming in one step and are classified by pH as 'mild', 'medium', or 'strong', with options for 'two-step' and 'one-step' formulations.[12] Contemporary dentin adhesives encompass three-step, two-step, and one-step systems featuring self-etching primers, which streamline the application process and enhance patient comfort.[13] Universal adhesives offer versatile options for various clinical scenarios. Examples include Single Bond Universal from 3M ESPE and Tetric N-Bond Universal from Ivoclar Vivadent, as well as the two-step self-etching adhesive Para Bond from Coltene Whaledent, which can be used in conjunction with dual-cure materials like ParaCore.[14] The effectiveness of restorations is assessed through various methods, including profilometry, scanning electron microscopy, and Fourier-Transform Infrared Spectroscopy with Attenuated Total Reflectance (FTIR-ATR) spectroscopy.[15] These techniques analyze surface properties, fractures, and the impact of water aging on resin composites. Innovations such as antimicrobial properties in adhesives further enhance their utility.[16] Acid etching, introduced by Buonocore in 1955, revolutionized resin adhesion by modifying enamel surface properties. Contemporary adhesive systems focus on optimizing bond strength through advanced techniques and materials.[17] The bond strength of composites is influenced by several factors, including the adhesive system used, whether etch-and-rinse, self-etch, or universal adhesives.[18] Enamel bonding relies on effective surface preparation through acid etching, while dentin bonding is more complex due to its heterogeneous structure. [19]Techniques such as acid-etching or self-etching adhesives are employed to improve bonding by removing the smear layer and exposing dentinal tubules.[20] Proper dentin hydration is essential, as excessive moisture or dryness can influence adhesive effectiveness. Surface treatments, such as applying silane coupling agents to porcelain, are also crucial for ensuring robust interfaces.[21] Regular oversight, quality assurance, and assessment of compressive and tensile strength are crucial for maintaining the performance of restorative materials.[22] By managing factors such as surface preparation, moisture control, and patient-specific considerations, dentists can enhance the effectiveness and longevity of restorative treatments, ultimately leading to improved patient outcomes.[23] Microtensile strength denotes the tensile strength measured at a small scale, typically involving very thin samples or specific regions of a composite material. This measurement is essential for understanding the performance of micro- or nanoscale components, such as those found in microelectromechanical systems or thin-film composites.[24] It aids in evaluating the properties of composite materials at a microscopic level, including microfabricated devices or small-scale composite structures.[25] Additionally, it can provide insights into the behavior of individual fibers or matrix phases within a composite. Measuring microtensile strength requires specialized apparatus to handle small samples precisely, such as micro-tensile testers and accurate measurement tools for evaluating the tensile strength of thin layers or small sections of the composite.[26] The preparation and testing of samples can be more intricate due to their diminutive size, necessitating uniformity and consistency for precise measurement.[27] Macrotensile strength refers to the tensile strength of composite materials assessed on a larger scale, typically using standard-sized specimens. This measure is more indicative of the material’s performance in real-world scenarios. It is used to evaluate composite materials in structural and industrial contexts, such as aerospace, automotive, construction, and other fields where composites are employed in substantial quantities.[28] Testing is performed with conventional tensile testing machines using standard-sized specimens, measuring how the composite material responds to tensile stress, including strength, ductility, and failure modes. The results can be influenced by factors such as sample size, specimen preparation, and testing conditions. Ensuring that test samples accurately reflect the material's performance in practical applications is vital.[29] Microtensile strength provides detailed insights into the behavior of small-scale or localized regions of a composite, while macrotensile strength offers a broader view of the material's overall performance.[30] Microtensile testing can refine the design of micro-scale components and understand failure mechanisms at a finer scale.[31] Macrotensile testing is crucial for verifying that composite materials meet the necessary performance standards for larger-scale applications.[32] Both testing methods are essential for a comprehensive understanding of composite materials: microtensile tests reveal issues at the microscopic level, whereas macrotensile tests provide data relevant to practical engineering uses.[33] The push-out bond strength of composites, especially in dental applications, is a critical measure of how effectively a composite material adheres to a tooth structure or other substrates, which is essential for evaluating the durability and performance of dental restorations and prosthetics.[34] This bond strength is influenced by several factors, including surface preparation, such as cleaning, etching, and the application of bonding agents; the type and quality of the composite resin, which includes variations in filler content and resin matrix properties; and curing methods, such as light-curing or dual-curing. [35]The use of effective bonding agents or adhesives also plays a crucial role. Additionally, the application technique, including layering and curing, as well as the conditioning of the substrate through methods like acid etching or sandblasting, and environmental factors such as moisture control, temperature, and pH, all have significant impacts.[36]Push-out bond strength tests, which measure the force required to debond a composite core or restoration, are used in research and clinical practice to assess the effectiveness and longevity of the bond in real-world scenarios.[37] The article, "Illustrating Recent Shifts in Composite Bond Strength Measurement: A Profound Analysis," presents a thorough review of recent advancements in the methodologies used to assess the bond strength of composite materials. The review highlights significant changes and innovations in this field, reflecting evolving trends and technological advancements. One notable shift emphasized in the article is the increasing use of advanced measurement techniques.[38]

DISCUSSION

Adhesive bonding in dentistry depends on several factors, including the type and moisture level of the dental substrate, the adhesive system employed, and the operator's skill. Bonding to dentin is particularly challenging due to its complex structure, which includes both mineral and organic components, and its inherently moist environment.[39] Effective bonding requires both hydrophilic and hydrophobic materials to prevent collagen matrix collapse and ensure proper adhesive penetration into the demineralized substrate.[40] In vitro bond strength tests are essential for predicting the performance of adhesive systems and their potential clinical outcomes.[41] Effective bonding relies on the chemistry of the adhesive and the morphological changes it induces in the dental tissue, creating a seamless transition between the restorative material and the dental substrate, thereby enhancing long-term success.[42] An adhesive with superior bonding capacity can better withstand stresses, leading to more durable restorations in clinical settings. Bond strength tests rank dental adhesive systems based on their bond strength values. However, masticatory forces, temperature fluctuations, and moisture must also be considered, as these factors can affect bond strength in real-world scenarios and potentially lead to rapid degradation of the adhesive interface. [43] To ensure the reliability of the Shear Bond Strength test, bond strength should be evaluated in vitro 24 hours after specimen preparation. The specimens should be stored in distilled water at 37°C and subjected to the rmocycling, ranging from 50°C to 55°C for 500 cycles, with 30 seconds of dwell time and 10 seconds of transition time between baths, in accordance with ISO 11405 standards. [44]A 24-hour period is considered adequate for assessing adhesive properties, while thermocycling simulates oral function stresses by exposing specimens to fluctuating temperatures.[45] This induces contraction and expansion stress between the adhesive and the tooth, predicting the clinical performance of the adhesive systems. Adhesives containing acrylamidosulfonic acid and maleic acid (pH = 0.9-1.3) are significantly more acidic than those that do not include these components (pH = 2.5-3).[46]Strongly acidic self-etch adhesives, containing molecules like maleic acid, decalcify hydroxyapatite and exhibit a demineralizing effect on dentin, similar to etch-and-rinse systems.[47]However, this does not always result in higher bond strengths because dissolved calcium phosphates are not rinsed away and are unstable in an aqueous environment.[48] Consequently, the functional monomer 2-hydroxyethyl methacrylate (HEMA) initially bonds to calcium in hydroxyapatite but quickly de-bonds, creating a relatively deep 3-5 µm hybrid layer in dentin that lacks hydroxyapatite crystals and compromising the adhesive interface.[49] In contrast, mild self-etch adhesives with methacryloyloxydecyl dihydrogen phosphate (MDP) interact superficially with dentin and minimally dissolve hydroxyapatite crystals, leaving a substantial amount around the collagen fibrils.[50] MDP forms a reaction-integration layer approximately 300 nm-1 µm deep and chemically bonds to calcium in hydroxyapatite; forming stable calcium-phosphate and calcium-carboxylate salts.[51] This results in a stable resin-infiltrated dentin hybrid layer, with micromechanical interlocking and chemical adhesion contributing to higher shear bond strength. [52]Research indicates that HEMA, a functional monomer in adhesives with low hydrolytic stability under strongly acidic conditions, can hydrolyze in aqueous solutions with a pH around 1.[53] In contrast, mild acidic adhesives containing MDP maintain better hydrolytic stability in acidic solutions due to their long linear alkyl/carbonyl chains, which help balance pH effects.[54] Most self-etch adhesives are hydrophilic, and water is crucial for ionizing the acidic monomer to dissolve the smear layer and demineralize dentin. High concentrations of HEMA lower water vapor pressure, leading to water absorption from the dentin and forming water blisters, known as the "over-wet phenomenon." This phenomenon creates weak spots along the adhesive interface, resulting in flexible polymers with reduced bond strength, which might explain the low shear bond strength observed with Para Bond self-etch adhesive.[55]Conversely, the high mean shear bond strength in low-acidic groups is due to differences in their monomer and copolymer content.[56] Tetric N-Bond Universal combines methacrylated carboxylic acid polymer with hydrophilic monomers like MDP and HEMA, along with hydrophobic monomer Decandioldimethacrylate and Bisphenol A glycidyl methacrylate.[57] This blend effectively bridges the gap between the hydrophilic dentin substrate and hydrophobic resin restorative, resulting in high mean shear bond strength. Single Bond Universal, containing Vitrebond Copolymer, MDP, HEMA, and dimethacrylate resin, may not achieve similar bond strength due to competition between the polyalkenoic acid copolymer and MDP monomer for calcium bonding sites, which might prevent effective monomer approximation during polymerization.[58] The high mean shear bond strength observed in lower acidic groups, compared to high acidic groups, can also be attributed to the presence of nano-fillers like silicone dioxide in the adhesives used. These fillers help fill microporosities on dentin, enhancing mechanical adhesion.[59] Studies show that filled adhesives exhibit stronger physical properties due to their ability to flex and relieve polymerization stress. Universal adhesives in lower acidic groups demonstrated significantly higher shear bond strength, whereas the two-step self-etch adhesive in the high acidic group had lower bond strength.[60] Despite the overall equivalence of dentin adhesive systems in bond strength, variations are believed to be highly dependent on adhesive formulation.[61] Micro-tensile bond strength tests assess the adhesion of composite materials to tooth structures or other substrates by applying a tensile force to small bonded samples, typically around 1 mm thick. This method provides detailed insights into the performance of adhesives and composites at a microscopic level, detecting small defects or variations that could affect restoration performance.[62] Macro-tensile bond strength tests apply tensile force to larger bonded specimens, usually around 2-5 mm thick.[63] These tests are more clinically relevant as they better mimic the conditions found in actual dental restorations, offering a broader view of adhesive and composite bonding performance.[64] Composite bond strength refers to how well composite materials adhere to tooth structures or other substrates, which is crucial for the durability and longevity of dental restorations.[65] Factors influencing bond strength include the type of adhesive system used—whether etch-and-rinse, self-etch, or universal adhesives—the composition and properties of the composite resin, such as its filler content and matrix formulation, and the efficiency of light or dual curing processes.[66] Proper moisture management during application is also important for ensuring a high-quality bond. Both micro-tensile and macro-tensile bond strength tests are essential for evaluating the performance of dental composites and adhesives.[67] Micro-tensile tests offer precision and are useful for assessing small-scale adhesion issues, while macro-tensile tests provide insights into larger-scale performance.[68] Combining these methods allows researchers and clinicians to gain a comprehensive understanding of composite material adhesion to tooth structures, leading to improved restorative practices. Recent advances are enhancing traditional testing methods.[69] Advanced non-destructive testing methods and real-time monitoring systems offer greater precision and deeper insights into bonding interface behavior under varying conditions.[70] Computational modeling and artificial intelligence are increasingly employed to predict and evaluate bond strength. Integrating finite element analysis with artificial intelligence algorithms enhances simulation accuracy and bond performance forecasts, aiding in the optimization of adhesive formulations and application techniques.[71] Material innovation is also a key focus, with new composite materials and adhesives enhancing bond strength and durability. Standardizing testing protocols is crucial for comparing results across studies and ensuring reliable data. Universal testing standards are recommended for accurate and comparable assessments of composite bond strength.[72]While minimum bond strength of 17-20 MPa is generally sufficient in clinical practice,one study found variations in performance among different adhesive systems.[73] Total-etch systems like Prime and Bond NT demonstrated superior bond strength compared to self-etching adhesives such as Clearfil S3, Xeno III, Clearfil Protect Bond, and G Bond. However, some research suggests that self-etching systems, especially all-in-one types, can outperform traditional total-etch systems.[74] Despite its antibacterial properties, Clearfil Protect Bond did not exceed the bond strength of Prime and Bond NT or Xeno III. Self-etch adhesives may be affected by residual acidity, smear layer presence, and hydrolytic instability. Bulk-fill composites like Tetric N-Ceram showed lower push-out bond strength compared to conventional composites, likely due to their composition and polymerization properties.75

LIMITATIONS

Adhesive systems differ in their functional monomers, pH levels, and filler contents. Nonetheless, in vitro tests of dentin bond strength face several limitations, such as variations in the type and age of teeth used, the extent of dentin demineralization, the specific bond strength testing methods, storage conditions, and environmental humidity. Despite these challenges, research has shown that 'universal adhesives' generally provide good shear bond strength under simulated clinical conditions. This suggests that they are effective as bonding agents for dual-cure core build-up composites.[76]

FUTURE DIRECTIONS

Advancements in artificial intelligence and machine learning are enhancing the accuracy and efficiency of bond strength predictions by using sophisticated algorithms to identify failure points. Non-destructive testing such as ultrasound, radiography and thermography are continually being developed to become more efficient and less invasive. Real-time monitoring with sensors and IoT technology is integrated with computational models to improve performance predictions. Research on new materials and adhesives makes the brand more durable and reliable.[77] Establishing standardized assessment processes ensures consistency across studies and industries. Interdisciplinary collaboration in materials science, mechanical engineering, and chemistry is crucial for creating robust evaluation methods. Emphasis on sustainability focuses on green materials and technologies to minimize environmental impact while maintaining high performance. Advanced data analytics leverages big data for deep insights, and the development of user-friendly, portable tools enhances assessment across various applications.[78]

CONCLUSION

The field of dentistry has witnessed notable advancements in assessing composite bond strength, driven by a focus on improving the reliability and longevity of dental restorations. Key trends include the development of advanced adhesive systems, innovations in composite materials, and refined testing methodologies. These advancements have led to more precise and consistent evaluations of bond strength, which are crucial for optimizing clinical outcomes. Emerging techniques, such as novel bonding agents and enhanced surface treatments, have shown significant improvements in adhesive performance and material durability. Additionally, advancements in non-destructive testing methods offer new opportunities for real-time assessment and monitoring of bond integrity. Future research should continue to explore these developments to further enhance the effectiveness of composite materials and bonding techniques. The implications of these trends are profound for dental practice, addressing common challenges like bond failure and material degradation. Ongoing research and development will be crucial in advancing restorative dentistry and improving patient outcomes.

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