Resin-ceramic bonding: a review of the literature

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Current ceramic materials offer preferred optical properties for highly esthetic restorations. The inherent brittleness of some ceramic materials, specific treatment modalities, and certain clinical situations require resin bonding of the completed ceramic restoration to the supporting tooth structures for long-term clinical success. This article presents a literature review on the resin bond to dental ceramics. A PubMed database search was conducted for in vitro studies pertaining to the resin bond to ceramic materials. The search was limited to peer-reviewed articles published in English between 1966 and 2001. Although the resin bond to silica-based ceramics is well researched and documented, few in vitro studies on the resin bond to high-strength ceramic materials were identified. Available data suggest that resin bonding to these materials is less predictable and requires substantially different bonding methods than to silica-based ceramics. Further in vitro studies, as well as controlled clinical trials, are needed. (J Prosthet Dent 2003;89:268-74.)

An increasing number of all-ceramic materials and systems are currently available for clinical use. Multiple clinical studies document excellent long-term success of resin-bonded restorations, such as porcelain laminate veneers,[1-5] ceramic inlays and onlays,[6-15] resin-bonded fixed partial dentures,[16-19] and all-ceramic crowns.[6,20-22] A strong, durable resin bond provides high retention,[23] improves marginal adaptation and prevents microleakage,[24] and increases fracture resistance of the restored tooth and the restoration.[25,26]

Adhesive bonding techniques and modern all-ceramic systems offer a wide range of highly esthetic treatment options.[5,6,19,27,28] Bonding to traditional silica-based ceramics is a predictable procedure yielding durable results when certain guidelines are followed.[24-26,29-94] However, the composition and physical properties of high-strength ceramic materials, such as aluminum oxide-based (Al_2O_3)[95-99] and zirconium oxide-based (ZrO_2) ceramics,[100] differ substantially from silica-based ceramics[96,101,102] and require alternative bonding techniques to achieve a strong, long-term, durable resin bond. Controlled clinical trials are ideal to test specific treatment modalities and their long-term durability. However, in vitro investigations are indispensable to identify superior materials before their clinical evaluation, especially for comparative studies of bonding agents and cements.

This literature review evaluated and compared in vitro studies on the resin bond to dental ceramics. A search of PubMed databases was conducted and limited to peer-reviewed articles in English that were published between the years 1966 and 2001. Reference lists of culled articles were screened for additional publications. Of the retrieved articles, a total of 68 articles were selected on the resin bond to silica-based ceramics,[24-26,29-94] 8 on the bond to aluminum-oxide ceramics,[103-110] and 3 on the bond to zirconium-oxide ceramics.[111-113] Additional references were included to accompany statements of facts.[1-23,27,28,95-102,114-133]

SILICA-BASED CERAMICS

Silica-based ceramics, such as feldspathic porcelain and glass ceramic, are frequently used to veneer metal frameworks (commonly referred to as *metal ceramic restorations* or *PFMs*)[114] or high-strength ceramic copings for all-ceramic restorations.[97] Their excellent esthetic properties make them the material of choice for ceramic laminate veneers[115] and inlays/onlays.[6] In spite of the inherent brittleness and limited flexural strength of silica-based ceramics, final adhesive cementation with composite increases the fracture resistance of the ceramic restoration and the abutment tooth.[25,26] Leucite-reinforced feldspathic porcelain (for example: IPS Empress; Ivoclar-Vivadent, Schaan, Liechtenstein) achieves significantly higher fracture strength and provides the restorative team with the ability to fabricate full-coverage all-ceramic restorations for both anterior and posterior teeth if resin bonding techniques are properly applied.[6] A lithium-disilicate glass-ceramic core veneered with a sintered glass-ceramic (for example: IPS Empress 2; Ivoclar-Vivadent) offers further strength that allows for the fabrication of short-span fixed partial dentures (FPDs).[116]

Intraoral porcelain-repair systems for chipped or fractured veneering ceramic also rely on strong resin bonds and adequate surface treatment.[29] These systems may

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increase the longevity of a failing restoration and may be a provisional, cost-effective alternative to immediate replacement.[29]

Surface treatment

A strong resin bond relies on micromechanical interlocking and chemical bonding to the ceramic surface, which requires roughening and cleaning for adequate surface activation.[30-37] Common treatment options are grinding,[30] abrasion with diamond rotary instruments,[31,32] airborne particle abrasion with aluminum oxide,[48,49] acid etching,[33] and combinations of any of these methods. Acid etching with solutions of hydrofluoric acid (HF) or ammonium bifluoride can achieve proper surface texture and roughness.[33-37] The glassy matrix is selectively removed, and crystalline structures are exposed. HF solutions between 2.5% and 10% applied for 2 to 3 minutes seem to be most successful.[35-37] The number, size, and distribution of leucite crystals influence the formation of microporosities that acid etching creates.[38] Leucite crystals grow during the cooling phase of the ceramic-firing process.[117] Some low-fusing ceramics and glass ceramics contain only minimal amounts of leucite crystals, which may inhibit the formation of highly-retentive microporosities with HF acid etching.[39] For the leucite-reinforced feldspathic porcelain IPS Empress, solutions of 9% HF applied for 60 seconds were most successful.[40] The lithium-disilicate glass-ceramic IPS Empress 2 has a high crystalline content and exhibits significantly higher bond strengths than IPS Empress independent from surface conditioning.[41] It seems that the ceramic microstructure has a significant influence on the fracture resistance of the composite-ceramic adhesion zone.[41]

Current ceramic-repair systems offer various treatment methods for intraoral repair of fractured veneering porcelain.[29,42] A combination of airborne particle abrasion (50 μm Al_2O_3), etching with HF acid, and application of a silane coupling agent is recommended.[43-46] Acid etchants that are less hazardous than HF acid are preferred intraorally. Szep et al[47] found that HF acid leaves an amorphous precipitate of fluoride on tooth structures, which may influence caries resistance and bonding interaction. Sole airborne particle abrasion provides insufficient bond strengths.[48,49] Excessive airborne particle abrasion induced chipping or a high loss of ceramic material[49,50] and is therefore not recommended for cementation of silica-based all-ceramic restorations. Kato et al[51] compared airborne particle abrasion with different acid-etching agents and found that HF acid and sulfuric acid-hydrofluoric acid provided the highest and most durable bond strengths. If a veneering-porcelain fracture extends to the framework, exposed metal should be pretreated for a sufficient resin bond of the repair composite to the metal surface (for example: Rocatec System; 3M ESPE, St. Paul, Minn.).[52-54]

Silane coupling agents

Application of a silane coupling agent to the pretreated ceramic surface provides a chemical covalent and hydrogen bond[55,56] and is a major factor for a sufficient resin bond to silica-based ceramics.[36-52,55-70] Silanes are bifunctional molecules that bond silicone dioxide with the OH groups on the ceramic surface. They also have a degradable functional group that copolymerizes with the organic matrix of the resin.[38,71] Silane coupling agents usually contain a silane coupler and a weak acid, which enhances the formation of siloxane bonds.[38] Silanization also increases wettability of the ceramic surface. In a study by Lacy et al,[48] airborne-particle–abraded silica-based ceramic was not retentive unless a silane coupling agent was applied. Some silane agents that contained carboxylic acid provided sufficient bond strengths even without HF acid etching, and others were successful after acid etching with phosphoric acid.[72] Sorensen et al[24] showed that ceramic etching and silanization significantly decreased microleakage, which was not achieved by exclusive silane treatment.

Studies on the efficacy of silanes after try-in procedures or resilanation of the ceramic restoration show differing results.[73,74] Residual organic contaminants may decrease bond strengths and should be removed before bonding, preferably with phosphoric acids or solvents such as acetone or alcohol. Silane primers can be categorized into 3 main groups: unhydrolyzed single-liquid silane primer, prehydrolized single-liquid silane primer, and 2- or 3-liquid silane primer. Silane coupling agents usually contain high amounts of solvents.[73] Single-bottle products have a limited shelf life and are susceptible to rapid solvent evaporation and hydrolization, making the silane solution useless. A good indicator is the appearance of the liquid; a clear solution is useful, whereas a milky-looking one should not be used. Many ceramic-bonding systems require separate silane treatment before the application of a bonding agent and the composite cement. Some manufacturers add a silane coupler to their bonding system that, whenever necessary, is mixed with the other bonding-agent components and applied in a single step (for example: Clearfil Porcelain Bond Activator and Clearfil SE Bond; Kuraray, Osaka, Japan). Silanes may have different chemical structures (for example: γ-methacryloxy propyltrimethoxy silane or 3-trialkyloxysilylpropyl methacrylate), which make it important to stay within 1 bonding system and not interchange components that may not be compatible.[87]

COMPOSITE CEMENTS

Resin-based composites are the material of choice for the adhesive luting of ceramic restorations.[75] Composite cements have compositions and characteristics similar to conventional restorative composites and consist of inorganic fillers embedded in an organic matrix (for example: Bis-GMA, TEGDMA, UDMA). Composite cements can be classified according to their initiation mode as autopolymerizing (chemically activated), photoactivated, or dual-activated materials.[75] Photoactivated composites offer wide varieties of shades, consistencies, and compositions.[75] Clinical application is simplified through long handling times before and rapid hardening after exposure to light. Shade, thickness, and transmission coefficient of the bonded ceramic restoration and the composite itself influence the conversion rate of the photo-activated material and limit its application to thin silica-based ceramics. Blackman et al[76] found polymerization beneath ceramic inlays to be safe up to 3 mm distance from the tip of a standard curing light. Dual-activated composites offer extended working times and controlled polymerization,[75] although chemical activators ensure a high degree of polymerization. Most dual-activated resin cements still require photopolymerization and demonstrated inferior hardness when light polymerization was omitted.[77,78] Various dual-activated resin cements showed no differences in resin-bond strengths between glass ceramics and enamel.[79] Autopolymerizing resin cements have fixed setting times and are generally indicated for resin bonding metal-based or opaque, high-strength ceramic restorations.[75]

Resin cements with reduced filler contents offer improved flow, increased surface wettability, and optimal positioning of the restoration.[75] However, filler-containing composite cements revealed higher bond strengths than resins without fillers,[51] and hybrid composites showed better results than microfilled composites.[58] A study by Hahn et al[81] revealed significantly less microleakage at the dentin/composite interface when high-viscous instead of low-viscous resin cements were used for cementation of ceramic inlays. Highly filled resin cements may improve abrasion resistance at the marginal area, reduce polymerization shrinkage, and facilitate removal of excess cement.[75] Highly filled and therefore viscous resin cements may require alternative cementation procedures such as the ultrasonic-insertion technique, in which application of energy through high-frequency vibrations changes the consistency of the resin cement to a thinner viscosity for the time of energy application and allows for optimal seating of the restoration.[75] The different viscosities have clinical advantages and disadvantages; whereas removal of excess material of low-viscosity composites may be difficult, high-

viscosity materials may be pulled out of the luting gap during cleaning.[75]

Wear and substance loss of composite cements after final insertion have been extensively studied in laboratory and clinical investigations that demonstrated a correlation of marginal gap width and depth of wear.[82,83] However, the effect of cement wear on the clinical long-term success of bonded restorations remains to be determined.

An interesting alternative to resin-based composites are resin-modified glass-ionomer cements that showed bond strengths to etched and silanated silica-based ceramics comparable to composite cements.[84] Other properties of these materials need to be investigated before they can be recommended for bonding of ceramic restorations without reservation.

TESTING CONDITIONS AND METHODS

The ceramic-composite bond is susceptible to chemical,[118,119] thermal,[120] and mechanical[121] influences under intraoral conditions. The simulation of such influences in the laboratory is compulsory to draw conclusions on the long-term durability of a specific bonding procedure and to identify superior materials and techniques. Long-term water storage[85] and thermocycling of bonded specimens are accepted methods to simulate aging and to stress the bonding interface. Most studies that apply these methods reveal significant differences between early and late bond strength values.[86-90] Application of mechanical cyclic loading (fatigue load) causes significant reduction of bond strengths.[63,91]

Material selection and clinical recommendations on resin bonding to ceramics are based on mechanical laboratory tests that show great variability in materials and methods.[41,94] Preferred bond strength tests are the 3-point bending test, the tensile and micro-tensile test, and the shear and micro-shear test. Øilo[92] discussed the accuracy and clinical relevance of the different testing methods. The most common testing method is the shear bond test; however, some researchers prefer modified tensile tests to eliminate the occurrence of nonuniform interfacial stresses typical to conventional tensile and shear bond tests. Their specific fracture pattern may cause cohesive failure in the ceramic,[93] which may lead to erroneous interpretation of the actual data and taint an absolute ranking of the tested methods and materials.[41,94]

ALUMINUM-OXIDE CERAMICS

The need for improved fracture strength of all-ceramic restorations led to the development of ceramics with an increased alumina content.[95] The aluminum oxide serves as reinforcement of the glassy matrix, compa-

rable to leucite crystals. In general, ceramics containing less than 15 wt% silica are not regarded as silica-based or silicate ceramics. In high-strength alumina- or zirconia-based ceramics, the aluminum oxide or zirconium oxide is not a reinforcement; it forms the matrix.[97]

High-strength aluminum-oxide ceramics are indicated in all areas of the mouth for copings and frameworks of full-coverage crowns and FPDs.[6] Such copings and frameworks are veneered with feldspathic porcelain to combine superior physical strength with optimal esthetic properties. Glass-infiltrated aluminum-oxide ceramic (for example: In-Ceram Alumina; Vita Zahnfabrik, Bad Säckingen, Germany) and densely-sintered high-purity aluminum-oxide ceramic (for example: Procera AllCeram; NobelBiocare, Goteborg, Sweden) are widely used representatives of this group. In-Ceram Spinell (Vita Zahnfabrik) is a glass-infiltrated spinel ceramic (containing the spinel oxide $MgAl_2O_4$) and is slightly weaker than In-Ceram Alumina, but it offers improved optical properties.[122] One third of the aluminum oxide is replaced by zirconium oxide in In-Ceram Zirconia (Vita Zahnfabrik), which is significantly stronger than In-Ceram Alumina.

Glass-infiltrated aluminum-oxide ceramic

In-Ceram Alumina incorporates a dry-sintered aluminum-oxide core that is infused with molten glass. The all-ceramic core offers a flexural strength of 450 MPa[96] after glass infiltration and is veneered with feldspathic porcelain for enhanced esthetics.

Acid etchants used for silica-based dental ceramics do not sufficiently roughen the surface of aluminum-oxide ceramics.[109] Airborne particle abrasion with Al_2O_3 is effective and practical for creating an activated and roughened surface on aluminum-oxide ceramic.[50] The application of a tribochemical silica coat that allows for chemical bonds to a silane coupling agent and to composite has been recommended.[50,103,104] The Rocatec System (3M ESPE) is an effective and user-friendly silica-coating method.[123] It includes 2 steps of airborne particle abrasion and the application of a silane coupling agent (ESPE-Sil; 3M ESPE) that bonds to the silica-coated surface and to resin. Other silica-coating methods were either ineffective for alumina ceramics or technically very complicated.[103-105]

Silanization of glass-infiltrated aluminum-oxide ceramic does not provide a chemical bond but may have a rewetting effect on air-particle-abraded alumina surfaces. Kern and Thompson[103] reported that this combination initially provided sufficient bond strengths with conventional Bis-GMA resin cements. However, bond strengths decreased significantly below clinically acceptable values after long-term storage and thermocycling. Silica coating and silane application with the Rocatec System provided a durable resin bond to glass-infiltrated aluminum-oxide ceramic with Bis-GMA composite-cements.[103,104,106]

A phosphate-monomer-containing resin cement (Panavia 21; Kuraray) provided strong and long-term durable resin bonds to air-particle-abraded glass-infiltrated alumina ceramic.[19,103,107,108] The adhesive functional phosphate monomer 10-methacryloyloxydecyl dihydrogen phosphate chemically bonds to metal oxides such as aluminum and zirconium oxides.[124] Some authors recommend Panavia without a silane or bonding agent,[103] whereas others suggest a silane coupling agent to increase wettability of the ceramic substrate.[106,108]

Densely-sintered aluminum-oxide ceramic

Densely-sintered high-purity aluminum-oxide ceramic[97] (for example: Procera AllCeram) offers a flexural strength of 610 MPa[98,99] and does not contain any silica. Similar to glass-infiltrated alumina ceramic, the surface of pure aluminum-oxide ceramic cannot be altered through conventional acid etching.[109] Airborne particle abrasion with a micro etcher (50 μm Al_2O_3 at 2.5 bar) revealed significantly higher bond strengths than acid etching with either 9.6% HF or 37% phosphoric acid, grinding with a diamond, or no treatment (control).[109] Blixt et al[110] found tribochemical surface treatment with the Rocatec System to be superior to other treatments; however, this study was limited to short-term observations.

ZIRCONIUM-OXIDE CERAMICS

Depending on the specific composition, fracture strength of sintered zirconia can exceed 1000 MPa.[100] A number of zirconium-oxide ceramic systems have been recently introduced, such as Cercon (Dentsply, Amherst, N.Y.), DCS system (DCS Dental AG, Allschwil, Switzerland), LAVA (3M ESPE) and Procera AllZirkon (NobelBiocare). Zirconium-oxide ceramic is indicated for conventional and resin-bonded FPDs, full-coverage crowns, implant abutments, and endodontic posts.[125-128] Zirconia endodontic posts offer a strong and esthetic alternative to metal posts and should be bonded with composite cements.[128-132] Full-coverage zirconium-oxide ceramic restorations and FPDs may not require adhesive cementation.[125] However, a sufficient resin bond has the aforementioned advantages and may become necessary in some clinical situations, such as compromised retention and short abutment teeth.[133] Conventional acid etching has no positive effect on the resin bond to zirconium-oxide ceramics. Derand and Derand[111] evaluated different surface treatments and resin cements and found that an autopolymerizing resin cement (Superbond C&B; Sun Medical) exhibited the significantly highest bond strengths regardless of surface treatment (silica coating, airborne particle abrasion, HF etching, or grinding with a diamond bur). Water storage

for 60 days had mixed effects on bond strengths. Kern and Wegner[112] evaluated different adhesion methods and their durability after long-term storage (150 days) and repeated thermocycling. Airborne particle abrasion, silane application, and a Bis-GMA resin cement resulted in an initial bond that failed spontaneously after simulated aging.[112] Silica-coating with the Rocatec System was equally insufficient.[112] Only the phosphate-modified resin cement Panavia 21 after airborne particle abrasion (110 μm Al_2O_3 at 2.5 bar) provided a long-term durable resin bond to zirconium oxide ceramic.[112] These findings were confirmed by a long-term study in which specimens were subject to 2 years water storage and repeated thermocycling.[113]

SUMMARY AND SUGGESTED CLINICAL GUIDELINES

The resin bond to silica-based ceramics is well documented through numerous in vitro investigations. Preferred surface treatment methods are acid etching with HF acid solutions (2.5% to 10% for 2 to 3 minutes) and subsequent application of a silane coupling agent. Adhesive cementation may not be required for final insertion of high-strength all-ceramic restorations with proper mechanical retention. However, some clinical situations and restorative treatment options mandate resin bonding and, therefore, adequate ceramic-surface conditioning. Preferred treatments for glass-infiltrated aluminum-oxide ceramic are either airborne particle abrasion with Al_2O_3 (50 to 110 μm at 2.5 bar) and use of a phosphate-modified resin cement (Panavia 21) or tribochemical surface treatment (Rocatec System) in combination with conventional Bis-GMA resin cement. The small number of long-term in vitro studies on the bond strength to densely-sintered aluminum-oxide ceramic does not allow for clinical recommendations. The few available studies on resin bonding to zirconium-oxide ceramics suggest the use of resin cements that contain special adhesive monomers. Compared with silica-based ceramics, the number of in vitro studies on the resin bond to high-strength ceramics is small. The rapidly increasing popularity of all-ceramic systems requires further research. Controlled clinical trials are needed before clinical recommendations can be given.

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