©Operative Dentistry, 2016, **41-2,** 179-188

# Strengthening of Porcelain Provided by Resin Cements and Flowable Composites

AO Spazzin • GB Guarda • A Oliveira-Ogliari
FB Leal • L Correr-Sobrinho • RR Moraes

### Clinical Relevance

Resin coating and use of resin-based luting agents with better physical properties generally improve the mechanical performance of porcelain.

## SUMMARY

**This study evaluated the effect of mechanical properties of resin-based luting agents on the strength of resin-coated porcelain. The luting agents tested were two flowable resin composites (Filtek Z350 Flow and Tetric-N Flow), a light-cured resin cement (Variolink Veneer [VV]), and a dual-cured resin cement (Variolink II) in either light-cured (base paste) or dual-cured (base + catalyst pastes [VD]) mode. Flexural strength ($\sigma_f$) and modulus of elasticity ($E_f$) of the luting agents were measured in three-point bending mode (n=5). Porcelain discs (Vita VM7) were tested either untreated (control) or acid etched, silanized, and coated with the luting agents. Biaxial flexural strength ($\sigma_{bf}$) of the porcelain discs was tested using a ball-on-ring setup (n=30). The $\sigma_{bf}$ of the resin-coated specimens was calculated at $z$-axial positions for multilayer specimens in the ball-on-ring test: position $z = 0$ (ceramic surface at the bonded interface) and position $z = -t_2$ (luting agent surface above ring). The $\sigma_f$ and $E_f$ data were subjected to analysis of variance and the Student-Newman-Keuls test (α=0.05). A Weibull analysis was performed for $\sigma_{bf}$ data. Weibull modulus ($m$) and characteristic strength ($\sigma_0$) were calculated. Linear regression analyses investigated the relationship between mechanical properties of the luting agents and the strengthening of porcelain. VD had higher and VV had lower mechanical strength than the other materials. At $z = 0$, all resin-coated groups**

Aloísio Oro Spazzin, DDS, MS, PhD, professor, School of Dentistry, Meridional Faculty (IMED), Passo Fundo-RS, Brazil

Guilherme Bottene Guarda, DDS, MS, PhD student, Department of Restorative Dentistry, Dental Materials Division, Piracicaba Dental School, State University of Campinas, Piracicaba-SP, Brazil

Aline Oliveira-Ogliari, DDS, MS, PhD student, School of Dentistry, Federal University of Pelotas, Pelotas-RS, Brazil

Fernanda Barbosa Leal, DDS, MS, PhD student, School of Dentistry, Federal University of Pelotas, Pelotas-RS, Brazil

Lourenço Correr-Sobrinho, DDS, MS, PhD, professor, Department of Restorative Dentistry, Dental Materials Division, Piracicaba Dental School, State University of Campinas, Piracicaba-SP, Brazil

*Rafael Ratto de Moraes, DDS, MS, PhD, professor, School of Dentistry, Federal University of Pelotas, Pelotas-RS, Brazil

*Corresponding author: Rua Gonçalves Chaves 457, 96015-160, Pelotas-RS, Brazil; e-mail: moraesrr@gmail.com

DOI: 10.2341/15-025-L

**had higher $\sigma_{bf}$ than the control group. No significant differences between the luting agents were observed for $\sigma_{bf}$ and $\sigma_0$. At $z = -t_2$, VD had the highest $\sigma_{bf}$ and $\sigma_0$, whereas VV had the poorest results. No significant differences in $m$ were observed across groups. A linear increase in flexural strength of the porcelain was associated with increased $\sigma_f$ and $E_f$ of the luting agents at position $z = -t_2$. In conclusion, resin coating and use of luting agents with better physical properties generally improved the mechanical performance of porcelain.**

## INTRODUCTION

Feldspathic porcelains are intrinsically fragile but might obtain additional strengthening when cemented to the dental structure using resin-based luting agents.[1,2] Feldspathic porcelain veneers thinner than 1 mm can be adhesively bonded to tooth tissues and present high clinical survival, with the adhesive cementation playing an important role on the clinical performance of these restorations.[3]

The strengthening of ceramics provided by bonding has been linked to mechanisms that include crack healing by resin infiltration[4] and induction of crack closure stresses by the polymerization shrinkage of resin-based agents.[5] However, *in vitro* investigations have demonstrated that the traditionally accepted hypotheses do not adequately describe the strengthening patterns observed.[1] Novel strengthening mechanisms insensitive to individual defect severity but sensitive to the surface texture have been identified whereby the strengthening is dependent on the creation of an interpenetrated resin-ceramic hybrid layer.[1,6] The magnitude of the strengthening has been also suggested to be dependent on the modulus of elasticity ($E_f$) of the resin-based luting agent.[6]

Commercially available resin-based luting agents present considerable variability regarding their interaction mechanism with dental tissues, formulation of organic and inorganic phases, and curing modes. All these factors might influence the characteristics of the polymer formed and confer different mechanical properties to the luting material as well as for the bonded veneer.[7] Light-cured resin-based luting agents are usually indicated for bonding porcelain veneers due to their improved color stability compared to dual-cured agents and for the high degree of C=C conversion achieved on light activation. Flowable resin composites and dual-cured resin cements are also available for the same purpose.[8] However, the performance of the resin-based luting agents with distinct polymerization modes on strengthening of porcelain veneers has not received attention. Different resin luting agents intrinsically have distinct physical properties that might impact the strengthening of porcelain on cementation.

The aim of this study was to evaluate the effect of flexural strength ($\sigma_f$) and $E_f$ of different commercially available resin-based luting agents on the strengthening of porcelain. The hypothesis tested was that resin-based luting agents with higher $E_f$ and $\sigma_f$ would provide higher strengthening for the porcelain.

## METHODS AND MATERIALS

### Mechanical Properties of the Resin-Based Luting Agents

The resin-based luting agents tested in the study are presented in the Table 1. The $E_f$ and $\sigma_f$ of the luting agents were measured in three-point bending mode. Bar-shaped specimens ($25 \times 2 \times 2$ mm) of each luting agent (n=5) were obtained using a split metallic mold covered with Mylar strip. Light curing was carried out according to the International Organization for Standardization Standard 4049 [9] using a light-emitting diode curing unit (Bluephase, Ivoclar Vivadent, Schaan, Liechtenstein) with irradiance of 1100 mW/cm$^2$, which was monitored throughout the experiment. For the VL group, only the base paste of Variolink II was used, whereas for the VD group, both base and catalyst pastes of Variolink II were mixed before use. The specimens were stored in distilled water at 37°C for 24 hours. The flexural test was performed on a mechanical testing machine (model 4411, Instron, Canton, MA, USA) at a crosshead speed of 1 mm/min. The $\sigma_f$ and $E_f$ were calculated by computer software (Blue Hill 2, Instron) according to the following equations:

$$\sigma_f = \frac{3PL}{2bd^2} \quad (1)$$

$$E_f = \frac{PL^3}{4bd^3D} \quad (2)$$

where $P$ is the load (N), $L$ the support span (20 mm), $b$ the width (mm), $d$ the specimen thickness (mm), and $D$ the deflection (mm).

### Preparation of Porcelain Discs

A total of 180 disc-shaped porcelain specimens were obtained. The porcelain powder (VM7 Transpa Dentine 2M2, batch no. 30270, Vita Zahnfabrik,

Table 1: *Description of the Resin-Based Luting Agents Tested*

| Material (Group Code) | Manufacturer | Composition[a] | Filler Content | Batch |
|---|---|---|---|---|
| Filtek Z350 Flow (ZF) | 3M ESPE (St Paul, MN, USA) | Bis-GMA, TEGDMA, Bis-EMA dimethacrylate polymer, silane-treated ceramic, silane-treated silica, ytterbium trifluoride, titanium oxide | 65 wt% 55 vol% | N144977 |
| Tetric-N Flow (TF) | Ivoclar Vivadent (Schaan, Liechtenstein) | Dimethacrylates (including TEGDMA), inorganic fillers, catalysts, stabilizers, pigments | 63 wt% 39 vol% | M63678 |
| Variolink Veneer (VV) | | Dimethacrylates, inorganic filler, catalysts, stabilizers, pigments | 60.1 wt%[b] 40 vol% | M37825 |
| Variolink II, light cured (VL) | | BisGMA, UDMA, TEGDMA | Base paste: 73.4 wt% 46.7 vol% | N53689 |
| Variolink II, dual cured (VD) | | Bis-GMA, UDMA, TEGDMA, inorganic fillers, catalysts, stabilizers, and pigments | Base paste: 73.4 wt% 46.7 vol% | N01558 |
| | | | Catalyst paste: 77.2 wt% 52 vol% | N16895 |

*Abbreviations: Bis-GMA, bisphenol-A glycidyl dimethacrylate; TEGDMA, triethyleneglycol dimethacrylate; UDMA, urethane dimethacrylate.*
[a] *As disclosed by the manufacturers.*
[b] *As quoted by Ozturk and others.*[20]

Bad Säckingen, Germany) was mixed with the modeling liquid (VM Modelling Liquid, batch no. 34240, Vita) to produce a thick slurry and condensed into a metallic mold (15-mm diameter, 0.9-mm thickness). The mold was overfilled and placed on a vibrating table for 90 seconds, and excess liquid was removed with an absorbent tissue. The surface was leveled with a razor blade to produce discs of uniform thickness. Each disc was removed carefully from the mold, placed on a refractory substrate, and fired in a ceramic furnace (Vacumat 40, Vita) according to the manufacturer's directions. The discs were cooled to room temperature and visually inspected. Discs with defects or visible cracks were discarded and replaced. The discs were manually wet ground on both sides with 320-grit SiC abrasive papers (Norton S.A., São Paulo, Brazil) to produce flat surfaces 0.8 $\pm$ 0.1 mm in thickness. Wet polishing was performed with 600- and 1200-grit SiC abrasive papers for 60 seconds on each surface. Final dimensions were checked with a digital caliper (Absolute Digimatic, Mitutoyo, Tokyo, Japan), and the porcelain discs were randomly divided into six groups (n=30) according to the resin-based luting agent tested. Untreated porcelain discs (no luting agent) were tested in the control group.

## Resin Coating of Porcelain Discs

The ground surfaces of the porcelain discs were etched with 10% hydrofluoric acid for 90 seconds (batch no. 479058D, Dentsply Caulk, Milford, DE, USA), washed for 60 seconds, and dried with water- and oil-free compressed air for 30 seconds. Two thin silane layers (RelyX Ceramic Primer, batch no. N136724, 3M ESPE, St. Paul, MN, USA) were applied and dried after 60 seconds with compressed air for 30 seconds. The resin-based luting agents were manipulated following the manufacturer's instructions, and a standard mass was applied onto the center of each disc. For the VL group, again only the base paste was used, whereas for the VD group, both base and catalyst pastes were used. A glass coverslip was lightly pressed to extrude the luting agent, and the resulting coverslip/luting agent/porcelain assembly was transferred to a leveled loading platform. The resin–porcelain specimens were centrally oriented, a controlled load of 5 N was applied, and excess luting agent was removed. Light curing was carried out for 60 seconds through the porcelain with the light guide tip positioned at the center of the disc. The specimens from the VD group also were light cured. The thickness of the luting agent layer applied to porcelain was measured, and resin–porcelain specimens with luting agent thickness outside the range between 100 and 150 μm were discarded and replaced by new resin–porcelain specimens. The specimens were dry stored for 24 hours in lightproof containers at 37°C.

**Biaxial Flexural Strength ($\sigma_{bf}$) Test**

The $\sigma_{bf}$ of the porcelain discs (control group) and resin–porcelain specimens was determined on the mechanical testing machine using a ball-on-ring setup. The discs were centrally placed on a 10-mm-diameter knife-edged support and loaded with a spherical indenter (4-mm diameter) at a crosshead speed of 1 mm/min. A thin section of rubber dam sheet was placed between the support and specimen to accommodate slight distortions in specimen geometry.[1,2,4,6,14] The $\sigma_{bf}$ (MPa) for the porcelain discs (control group) was calculated using the following equation[10,11]:

$$\sigma_{bf} = \frac{3P(1+v)}{4\pi t^2}\left[1 + 2ln\left(\frac{a}{b}\right) + \frac{1-v}{1+v}\left[1 - \frac{b^2}{2a^2}\right]\frac{a}{R^2}\right] \quad (3)$$

where $P$ is the fracture load (N), $v$ the Poisson ratio (0.25) of the porcelain,[12] $t$ the disc thickness (mm), $a$ the radius of the knife-edged support (mm), $b$ the radius of uniform loading at center (mm), and $R$ the radius of the disc-shaped specimen (mm).

The $\sigma_{bf}$ of the resin–porcelain specimens was calculated according to the analytical solutions described by Hsueh and others[13] and used in previous studies.[1,2,6,14,15] First, the modulus of elasticity of the porcelain ($E_1^*$) and resin-based luting agent ($E_2^*$) were calculated as a function of the Poisson ratio of the porcelain and luting agent:

$$E_1^* = \frac{E_1}{1 - v_1^2} \qquad E_2^* = \frac{E_2}{1 - v_2^2} \quad (4)$$

where $E_1$ is the modulus of elasticity of the porcelain,[12] $E_2$ is the measured modulus of elasticity of the resin-based luting agents, and $v_1$ and $v_2$ are the Poisson ratios of the porcelain (0.25)[12] and luting agents (0.27), respectively.[16] Thereafter, the neutral plane ($tn$) of the resin–porcelain specimens was calculated as a function of the porcelain and luting agent thicknesses ($t_1$ and $t_2$) and calculated moduli of elasticity ($E_1^*$ and $E_2^*$), respectively:

$$tn = \frac{E_1^*(t_1)^2 - E_2^*(t_2)^2}{2(E_1^* t_1 + E_2^* t_2)} \quad (5)$$

The $\sigma_{bf}$ of the resin–porcelain specimens was calculated at $z$-axial positions at the center of the discs, where the ceramic surface at the bonded interface was located at position $z = 0$ (equation 6) and the resin luting agent surface above the ring of the ball-on-ring setup was located at position $z = -t_2$ (equation 7):

$$\sigma_{bf} = \left.\begin{array}{l} \dfrac{-3P(1+v)(z-tn)}{2\pi(t_1+t_2)^3}\left[1 + 2ln\left(\dfrac{a}{b}\right) + \dfrac{1-v}{1+v}\left(1 - \dfrac{b^2}{2a^2}\right)\dfrac{a^2}{R^2}\right] \\ \times \left[\dfrac{E_1^*(E_1^* t_1 + E_2^* t_2)(t_1+t_2)^3}{(E_1^* t_1^2)^2 + (E_2^* t_2^2)^2 + 2E_1^* E_2^* t_1 t_2(2t_1^2 + 2t_2^2 + 3t_1 t_2)}\right] \end{array}\right] (z=0) \quad (6)$$

$$\sigma_{bf} = \left.\begin{array}{l} \dfrac{-3P(1+v)(z-tn)}{2\pi(t_1+t_2)^3}\left[1 + 2ln\left(\dfrac{a}{b}\right) + \dfrac{1-v}{1+v}\left(1 - \dfrac{b^2}{2a^2}\right)\dfrac{a^2}{R^2}\right] \\ \times \left[\dfrac{E_2^*(E_1^* t_1 + E_2^* t_2)(t_1+t_2)^3}{\left[(E_1^* t_1^2)^2 + (E_2^* t_2^2)^2 + 2E_1^* E_2^* t_1 t_2(2t_1^2 + 2t_2^2 + 3t_1 t_2)\right]}\right] \end{array}\right] (z=-t_2) \quad (7)$$

$$v = \frac{v_1 t_1 + v_2 t_2}{t_1 + t_2} \quad (8)$$

**Statistical Analysis**

Mechanical data from tests with the resin-based luting agents and porcelain discs passed normality and equal variance tests. Data for $\sigma_f$ and $E_f$ of the resin-based luting agents were separately analyzed using one-way analysis of variance followed by the Student-Newman-Keuls *post hoc* test ($\alpha$=0.05). A Weibull analysis was performed for the $\sigma_{bf}$ data using the software Weibull++ (Reliasoft, Tucson, AZ, USA). Weibull modulus ($m$) and characteristic strength ($\sigma_0$) were calculated based on the maximum likelihood method, and the 95% upper and lower confidence bounds were calculated using the likelihood ratio.[2,17] The $\sigma_{bf}$ and $\sigma_0$ means of the resin–porcelain specimens were plotted against the $\sigma_f$ and $E_f$ means of the resin-based luting agents; regression analyses were performed to investigate the relationship between the mechanical properties of the resin-based luting agents and the strengthening at axial positions $z = 0$ and $z = -t_2$ of the porcelain specimens.

## RESULTS

Results for the mechanical properties of the resin-based luting agents are presented in Table 2. The VD group in general had significantly higher $\sigma_f$ and $E_f$ than the other materials, followed by ZF. The other luting agents had intermediate results, whereas VV generally presented significantly lower $\sigma_f$ and $E_f$ than all the other luting agents.

Table 3 presents the results for $\sigma_{bf}$, $\sigma_0$, and $m$ for the different axial positions of the porcelain specimens ($z = 0$ and $z = -t_2$). At position $z = 0$, all resin-coated groups had significantly higher $\sigma_{bf}$ than the

Table 2: *Means (Standard Deviations) for Flexural Strength ($\sigma_f$) and Flexural Modulus ($E_f$) of the Resin-Based Luting Agents (n=5)*

| Luting Agent | $\sigma_f$, MPa | $E_f$, GPa |
|---|---|---|
| Filtek Z350 Flow | 99 (10) AB[a] | 4.7 (0.2) B |
| Tetric-N Flow | 81 (12) BC | 2.8 (0.4) C |
| Variolink Veneer | 66 (10) C | 2.0 (0.2) D |
| Variolink II, light cured | 88 (13) B | 3.3 (0.4) C |
| Variolink II, dual cured | 112 (17) A | 6.5 (0.5) A |

[a] *Distinct letters in each column indicate significant differences between groups ($p<0.05$).*

control group. The Weibull plot for position $z = 0$ is shown in Figure 1. No significant differences between the luting agents were observed for $\sigma_{bf}$ and $\sigma_0$. The Weibull modulus for all groups was similar, even for the control group. At position $z = -t_2$, the group VD had the highest $\sigma_{bf}$ and $\sigma_0$, whereas the group VV the lowest $\sigma_{bf}$ and $\sigma_0$. The other resin-based luting agents had intermediate results. The Weibull plot for position $z = -t_2$ is shown in Figure 2. No significant differences in $m$ were observed across groups.

Plots of the linear regression analyses between $\sigma_{bf}$ and $\sigma_0$ of the resin–porcelain specimens and flexural properties of the resin-based luting agents ($\sigma_f$ and $E_f$) are displayed in Figure 3 ($z$=0) and Figure 4 ($z$=$-t_2$). No significant association was observed between $\sigma_{bf}$ or $\sigma_0$ of the resin–porcelain specimens and properties of the resin-based luting agents at position $z = 0$. In contrast, all models showed a significant linear increase in $\sigma_{bf}$ and $\sigma_0$ of the resin–porcelain specimens associated with increased $\sigma_f$ and $E_f$ of the resin-based luting agents at position $z = -t_2$.

## DISCUSSION

Resin coating of the porcelain discs yielded an increase in flexural properties of around 100% in all groups regardless of the resin-based luting agent tested. The strengthening effect of resin-based luting agents on porcelain is in accordance with previous studies, suggesting that this effect occurs due to the formation of a porcelain–resin hybrid layer resulting from the interpenetration of the resin in the etched porcelain surface.[1,2,6] The mechanical properties of the resin-based luting agents can interfere with the reinforcement of porcelain. At axial position $z = 0$ (porcelain surface at bonded interface), no significant differences were observed among the different luting agents. The linear regression analysis at position $z = 0$ (Fig. 3) corroborates this finding. However, at axial position $z = -t_2$, both the biaxial flexural test and the linear regression analysis (Figure 4) indicate that resin-based luting agents with improved mechanical properties led to significantly higher flexural strength of the resin–porcelain assembly.

$E_f$ and $\sigma_f$ were in general significantly different among the resin-based luting agents evaluated. VD showed the highest results, while VV had the poorest mechanical performance. Explanation for these findings lies in the composition of the inorganic filler content of the luting agents. The resin cement Variolink II has the highest filler loading among the cements tested. VV, in contrast, has the lowest filler loading of the luting agents tested. Previous studies also have indicated a positive relationship between mechanical properties and filler content of resin-based particulate composites.[18-22] The mechan-

Table 3: *Means (95% Confidence Intervals) for Biaxial Flexural Strength ($\sigma_{bf}$), Characteristic Strength ($\sigma_0$), and Weibull Modulus (m) at Axial Positions $z = 0$ or $z = -t_2$ (n=30)*

| | Axial Position/Group | $\sigma_{bf}$, MPa | $\sigma_0$, MPa | $m$ |
|---|---|---|---|---|
| $z = 0$ | Control[a] | 63 (59–67) B[b] | 68 (63–73) B | 6.7 (4.6–9.2) A |
| | Filtek Z350 Flow (ZF) | 134 (126–142) A | 145 (135–155) A | 7.2 (4.9–9.9) A |
| | Tetric-N Flow (TF) | 126 (118–134) A | 136 (125–147) A | 6.0 (4.2–8.2) A |
| | Variolink Veneer (VV) | 131 (122–140) A | 142 (139–146) A | 5.4 (4.5–5.4) A |
| | Variolink II, light cured (VL) | 129 (117–141) A | 142 (125–161) A | 4.0 (2.8–5.4) A |
| | Variolink II, dual cured (VD) | 133 (121–145) A | 146 (129–165) A | 4.1 (2.8–5.5) A |
| $z = -t_2$ | ZF | 13.0 (11.8–14.2) B | 14.3 (12.6–16.2) B | 4.0 (2.8–5.4) A |
| | TF | 7.5 (7.0–8.0) C | 8.1 (7.4–8.9) C | 5.4 (3.7–7.5) A |
| | VV | 5.0 (4.6–5.4) D | 5.4 (4.9–5.9) D | 5.2 (3.6–7.1) A |
| | VL | 8.4 (7.5–9.3) C | 9.4 (8.1–10.7) C | 3.6 (2.5–4.9) A |
| | VD | 18.6 (16.5–20.7) A | 20.7 (17.9–23.8) A | 3.5 (2.4–4.8) A |

[a] *The control specimens were porcelain discs without luting agent, with no calculation for different z-axial positions.*
[b] *Distinct letters in each column indicate significant differences between groups (data for $z$=0 and $z$=$-t_2$ are not interrelated).*

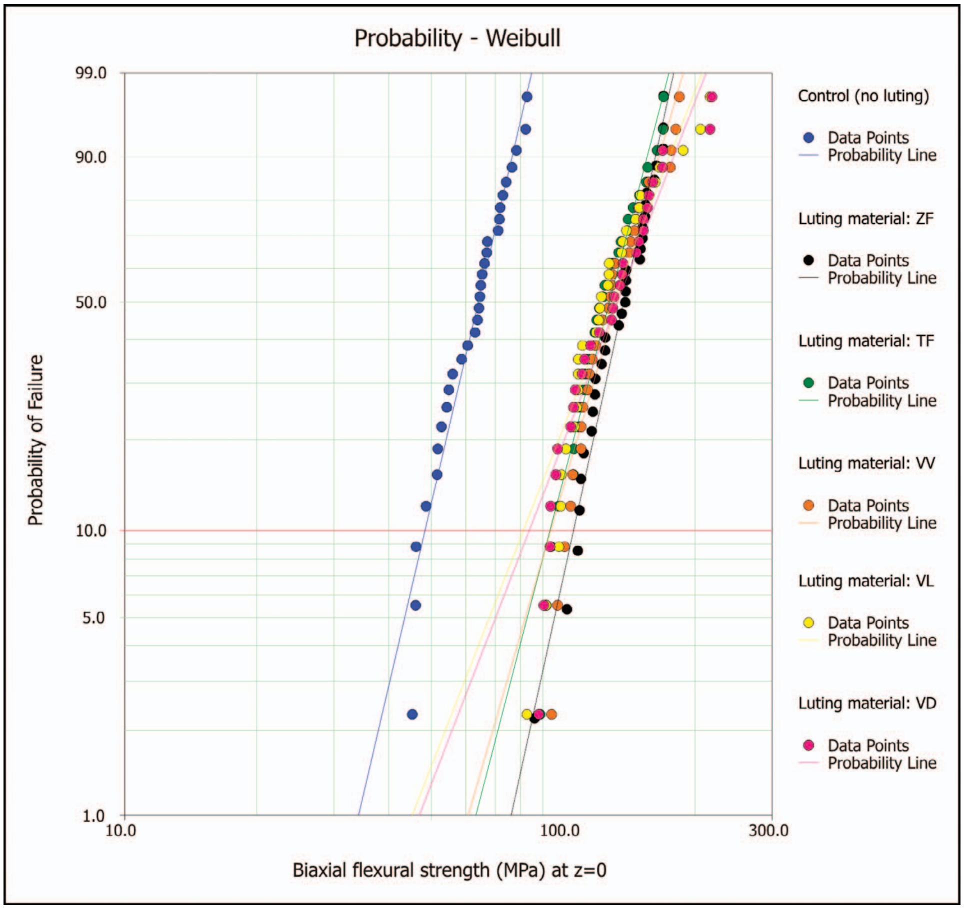


Figure 1. *Probability of failure (Weibull analysis) for all groups at axial position* z = 0*.*

ical performance of composites can be improved by increasing their filler content, assuming that integrity is maintained between the resin matrix and filler particles mediated through silane coupling agent.[23] On the other hand, the viscosity will increase as well, thus limiting the film thickness of the luting material.[24]

Differences in degree of C=C conversion between the resin-based luting agents might also have a role in their mechanical strength. The dual-cured resin cement tested, for instance, had significantly higher flexural properties in the dual-cured mode (base + catalyst pastes) compared to the light-cured mode (base paste only). This finding is explained by the higher filler loading of the catalyst paste compared to the base paste, but certainly the additional redox curing contributed to the improved strength by increasing C=C conversion and polymer cross-linking. It has been shown that dual-polymerized resin cements are dependent on light curing for improved polymerization[25,26] and that the C=C conversion tends to be higher in the dual-cure than in the self-cure mode alone.[25-27] However, the present findings further suggest that the monomer conversion in the dual-cure mode might be higher than in the light-cure mode alone. Distinct degrees of C=C conversion between the light-activated luting agents tested might additionally exist because differences in the composition of the resin phase also affect the polymerization extent of resin-based luting agents.[28]

Increased strength associated with resin coating of porcelain has been identified to be linearly dependent on the $E_f$ of resin-based luting agents.[6] It has been suggested that adhesive cementation of porcelain laminate veneers with resin-based luting agents with better mechanical performance could result in increased clinical performance.[1,6] Although this result is yet to be verified in clinical trials, findings of the present study show that at the porcelain surface in the bonded interface (position $z$=0), the mechanical properties of the resin-based luting agents do not have a role on the strengthening effect. In other words, the resin coating itself was preponderant over the mechanical properties of the luting agents tested at position $z$ = 0. One could expect that materials with higher filler loading

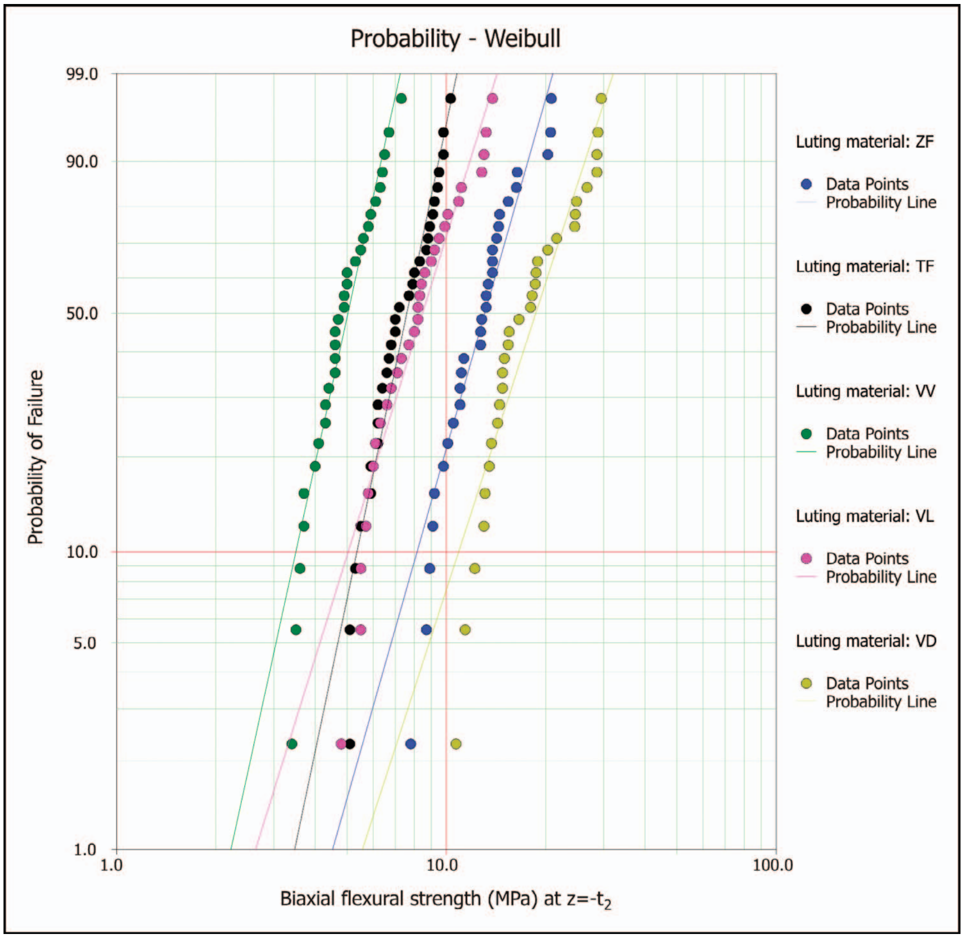


Figure 2. *Probability of failure (Weibull analysis) for all resin-coated groups at axial position* z $= -t_2$.

would positively impact the strengthening mechanism. However, highly filled composites are more viscous and may differ from less viscous materials in terms of their potential to generate intimacy between the porcelain surface defects and the infiltrating polymer.[29] In addition, the difference in $E_f$ among the resin-based luting agents tested, although significant statistically, was not appreciable, with means varying from 2.0 to 6.5 GPa, whereas the previously quoted study evaluated luting agents with $E_f$ varying between 4.9 and 16.8 GPa.[6] The lower range of moduli of elasticity and luting agent viscosity could explain the similar strength results at position $z = 0$. Studies using model resin-based luting agents with controlled properties could better address that issue.

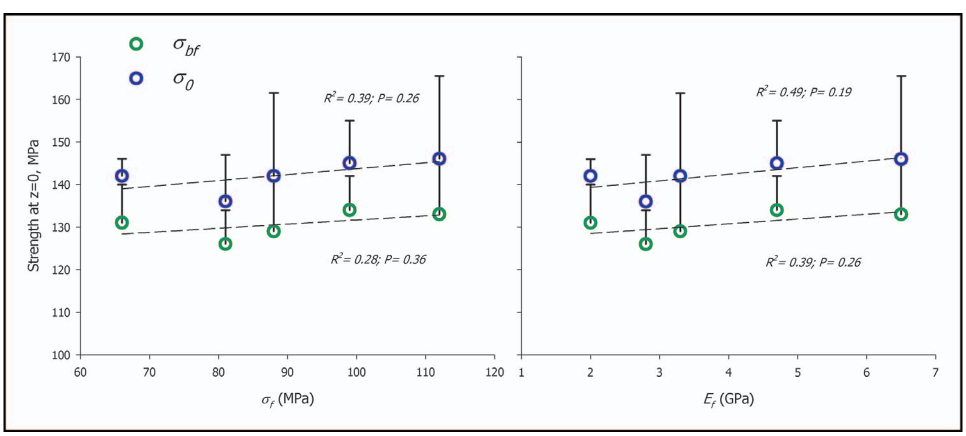


Figure 3. *Linear regression plots with stress ($\sigma_{bf}$ and $\sigma_0$) at axial position* z = *0 as dependent variable. Symbols are means ± 95% confidence intervals. Coefficients of linear regression ($R^2$) and their respective* p*-values are displayed for each condition. No significant association was observed between flexural strength of the resin–porcelain specimens and flexural properties ($\sigma_f$ and $E_f$) of the resin-based luting agents.*

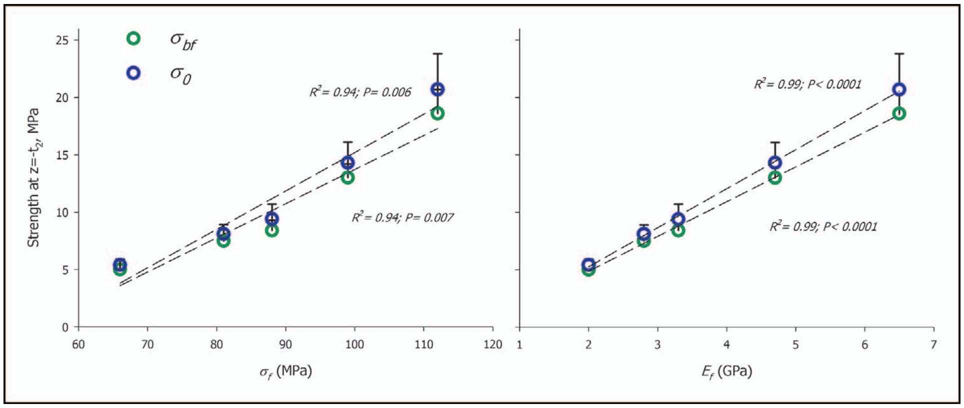


Figure 4. *Linear regression plots with stress ($\sigma_{bf}$ and $\sigma_0$) at axial position z = $-t_2$ as dependent variable. Symbols are means ± 95% confidence intervals. Coefficients of linear regression ($R^2$) and their respective* p*-values are displayed for each condition. All models showed a significant linear increase in flexural strength of the resin–porcelain specimens associated with increased $\sigma_f$ and $E_f$ of the resin-based luting agents.*

In contrast to axial position $z = 0$, the mechanical properties of the resin-based luting agents were significantly associated with the strengthening at position $z = -t_2$. This finding indicates that the mechanical strength of the resin-based luting agent is indeed important for the overall mechanical performance of the bonded porcelain. This is in accordance with previous studies[1,30] that indicated that the strengthening of porcelains by resin coating was independent of a controlled defect population, although the strengthening observed was attributed to the elastic behavior of the resin. The mathematical methods used here[13] enable calculating biaxial flexure stress at axial positions throughout the resin–porcelain specimen during failure. The $\sigma_{bf}$ observed at position $z = -t_2$ was considerably below the $\sigma_f$ and elastic limits of the resin-based luting agents tested. This means that it is unlikely that failure during loading initiated at the resin surface or within the bulk of the luting agent, as previously proposed.[1] However, the overall porcelain strengthening provided by resin coating may be dependent on the mechanical behavior of the luting agent interpenetrating the porcelain. Luting agents with better physical properties (higher $\sigma_{bf}$ at position $z = -t_2$) could better withstand the intraoral loading and maintain an adequate bonding to the tooth structure, ultimately preventing early failure of the porcelain restoration.

The resin–porcelain specimens were dry stored before being subjected to biaxial flexural testing. A previous study[2] showed that storage in water for 24 hours of specimens similar to those tested here may be detrimental to the mechanical performance of resin-coated porcelain. The study showed reductions of approximately 2% and 10% of $\sigma_f$ at axial positions $z = -t_2$ and $z = 0$, respectively, and a 7.4% reduction in $\sigma_0$ at $z = 0$ for silane-treated porcelain coated with resin cement. Interesting was the fact that $m$ of the resin cement–porcelain specimens was reduced up to 45% after short-term water storage, a finding that was attributed to hydrolytic effects acting over ceramic bonds and polymer matrix. However, the comparisons between luting materials in that study were generally not affected within dry- and wet-stored groups. In addition, the porcelain surfaces were alumina abraded before luting,[2] whereas the specimens tested here were acid etched. It is known that alumina sandblasting may lead to the creation of a surface topography more challenging for a proper infiltration of resin cements as compared to acid etching,[31,32] particularly if no unfilled resin (adhesive) is applied to the ceramic. Therefore, lower hydrolytic effects taking place in the first 24 hours after bonding to acid-etched porcelain could occur, although this effect still has to be determined.

The hypothesis tested was partially accepted because improved mechanical properties of the resin-based luting agents were associated with improved flexural strength of the luted porcelain at position $z = -t_2$ but not at position $z = 0$. As a consequence, the present results suggest that the strength and performance of resin-luted thin porcelain restorations could be enhanced by the use of resin-based luting agents with better mechanical properties. However, proper interpenetration of the resin–cement on the etched porcelain surface also is relevant. One of the limitations of the methods used here is that tooth abutments are not employed in the biaxial testing, and the interaction of the luting agent with dentin/enamel is also important for the mechanical performance of bonded porcelain. Ongoing studies using experimental resin-based luting agents with controlled mechanical properties may better address the effect of resin coating on the mechanical performance of porcelain; the results will be shown in a separate report.

## CONCLUSIONS

Within the limitations of this *in vitro* study, the following conclusions can be drawn:

- Resin coating was associated with porcelain strengthening.
- Resin-based luting agents with better mechanical properties might positively interfere with the strengthening of the resin–porcelain assembly.
- Similar mechanical performance was observed at the porcelain surface in the bonded interface for resin–porcelain specimens with different resin-based luting agents.

### Acknowledgements

The study was partially supported by FAPERGS/Brazil (protocol 0902063) and CNPq/Brazil (protocol 503897/2012-4).

### Regulatory Statement

This study was conducted in accordance with all the provisions of the local human subjects oversight committee guidelines and policies of Federal University of Pelotas in Brazil.

### Conflict of Interest

The authors have no proprietary, financial, or other personal interest of any nature or kind in any product, service, and/or company that is presented in this article.

*(Accepted 30 April 2015)*

### REFERENCES

1. Fleming GJ, Maguire FR, Bhamra G, Burke FM, & Marquis PM (2006) The strengthening mechanism of resin cements on porcelain surfaces *Journal of Dental Research* **85(3)** 272-276.
2. Addison O, Marquis PM, & Fleming GJ (2008) Adhesive luting of all-ceramic restorations—The impact of cementation variables and short-term water storage on the strength of a feldspathic dental ceramic *Journal of Adhesive Dentistry* **10(4)** 285-293.
3. Layton DM, & Walton TR (2012) The up to 21-year clinical outcome and survival of feldspathic porcelain veneers: Accounting for clustering *International Journal of Prosthodontics* **25(6)** 604-612.
4. Marquis PM (1992) The influence of cements on the mechanical performance of dental ceramics *Bioceramics* **5** 317-324.
5. Nathanson D (1993) Principles of porcelain use as an inlay/onlay material In: Garber DA, Goldstein RE (eds) *Porcelain and Composite Inlays and Onlays: Esthetic Posterior Restorations* Quintessence, Chicago 23-32.
6. Addison O, Marquis PM, & Fleming GJ (2007) Resin elasticity and the strengthening of all-ceramic restorations *Journal of Dental Research* **86(6)** 519-523.
7. Manso AP, Silva NR, Bonfante EA, Pegoraro TA, Dias RA, & Carvalho RM (2011) Cements and adhesives for all-ceramic restorations *Dental Clinics of North America* **55(2)** 311-332.
8. Archegas LR, Freire A, Vieira S, Caldas DB, & Souza EM (2011) Colour stability and opacity of resin cements and flowable composites for ceramic veneer luting after accelerated ageing *Journal of Dentistry* **39(11)** 804-810.
9. ISO-Standards (2000) ISO 4049-2000 Dentistry—Polymer-based filling, restorative and luting materials. *Geneve: International Organization for Standardization*.
10. Rosenstiel SF, Gupta PK, Van der Sluys RA, & Zimmerman MH (1993) Strength of a dental glass-ceramic after surface coating *Dental Materials* **9(4)** 274-279.
11. Pagniano RP, Seghi RR, Rosenstiel SF, Wang R, & Katsube N (2005) The effect of a layer of resin luting agent on the biaxial flexure strength of two all-ceramic systems *Journal of Prosthetic Dentistry* **93(5)** 459-466.
12. Zeng K, Oden A, & Rowcliffe D (1998) Evaluation of mechanical properties of dental ceramic core materials in combination with porcelains *International Journal of Prosthodontics* **11(2)** 183-189.
13. Hsueh CH, Lance MJ, & Ferber MK (2005) Stress distributions in thin bilayer discs subjected to ball-on-ring tests *Journal of the American Ceramic Society* **88(6)** 1687-1690.
14. Addison O, & Fleming GJ (2008) Application of analytical stress solutions to bi-axially loaded dental ceramic-dental cement bilayers *Dental Materials* **24(10)** 1336-1342.
15. Addison O, Sodhi A, & Fleming GJ (2010) Seating load parameters impact on dental ceramic reinforcement conferred by cementation with resin-cements *Dental Materials* **26(9)** 915-921.
16. De Jager N, Pallav P, & Feilzer AJ (2004) The apparent increase of the Young's modulus in thin cement layers *Dental Materials* **20(5)** 457-462.
17. Griggs JA, & Zhang YL (2003) Determining the confidence intervals of Weibull parameters estimated using a more precise probability estimator *Journal of Materials Science Letters* **22(24)** 1771-1773.
18. Czasch P, & Ilie N (2013) In vitro comparison of mechanical properties and degree of cure of a self-adhesive and four novel flowable composites *Journal of Adhesive Dentistry* **15(3)** 229-236.
19. Kim KH, Ong JL, & Okuno O (2002) The effect of filler loading and morphology on the mechanical properties of contemporary composites *Journal of Prosthetic Dentistry* **87(6)** 642-649.
20. Ozturk E, Hickel R, Bolay S, & Ilie N (2012) Micromechanical properties of veneer luting resins after curing through ceramics *Clinical Oral Investigations* **16(1)** 139-146.
21. Masouras K, Silikas N, & Watts DC (2008) Correlation of filler content and elastic properties of resin-composites *Dental Materials* **24(7)** 932-939.
22. Ilie N, & Hickel R (2009) Investigations on mechanical behaviour of dental composites *Clinical Oral Investigations* **13(4)** 427-438.
23. Braem M, Finger W, Van Doren VE, Lambrechts P, & Vanherle G (1989) Mechanical properties and filler

fraction of dental composites *Dental Materials* **5(5)** 346-348.

24. Beun S, Bailly C, Dabin A, Vreven J, Devaux J, & Leloup G (2009) Rheological properties of experimental Bis-GMA/TEGDMA flowable resin composites with various macrofiller/microfiller ratio *Dental Materials* **25(2)** 198-205.

25. Moraes RR, Boscato N, Jardim PS, & Schneider LF (2011) Dual and self-curing potential of self-adhesive resin cements as thin films. *Operative Dentistry* **36(6)** 635-642.

26. Aguiar TR, de Oliveira M, Arrais CA, Ambrosano GM, Rueggeberg F, & Giannini M (2015) The effect of photopolymerization on the degree of conversion, polymerization kinetic, biaxial flexure strength, and modulus of self-adhesive resin cements *Journal of Prosthetic Dentistry* **113(2)** 128-134.

27. Moraes RR, Faria-e-Silva AL, Ogliari FA, Correr-Sobrinho L, Demarco FF, & Piva E (2009) Impact of immediate and delayed light activation on self-polymerization of dual-cured dental resin luting agents *Acta Biomaterialia* **5(6)** 2095-2100.

28. Moraes RR, Sinhoreti MA, Correr-Sobrinho L, Ogliari FA, Piva E, & Petzhold CL (2010) Preparation and evaluation of dental resin luting agents with increasing content of bisphenol-A ethoxylated dimethacrylate *Journal of Biomaterials Applications* **24(5)** 453-473.

29. Fleming GJ, Hooi P, & Addison O (2012) The influence of resin flexural modulus on the magnitude of ceramic strengthening *Dental Materials* **28(7)** 769-776.

30. Addison O, Marquis PM, & Fleming GJ (2007) Resin strengthening of dental ceramics- the impact of surface texture and silane *Journal of Dentistry* **35(5)** 416-424.

31. Borges GA, Sophr AM, de Goes MF, Sobrinho LC, & Chan DC (2003) Effect of etching and airborne particle abrasion on the microstructure of different dental ceramics *Journal of Prosthetic Dentistry* **89(5)** 479-488.

32. Valentini F, Moraes RR, Pereira-Cenci T, & Boscato N (2014) Influence of glass particle size of resin cements on bonding to glass ceramic: SEM and bond strength evaluation *Microscopy Research and Technique* **77(5)** 363-367.