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Adhesive Durability Inside the Root Canal Using Self-adhesive Resin Cements for Luting Fiber Posts

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Clinical Relevance

Adhesive luting of fiber posts using self-adhesive resin cements resulted in reliable bond strength values even after aging, although product-specific differences could be observed and qualitative nanoleakage analyses revealed initial degradation effects.

SUMMARY

Objectives: The aim of the study was to investigate the effects of various self-adhesive resin cements on the push-out bond strengths and nanoleakage expression at the luting interfaces of fiber posts immediately and after one year of aging.

Methods and Materials: One hundred forty-four extracted human anterior teeth were endodontically treated. After post space preparation, fiber posts were luted using five commercially available self-adhesive resin (SAR) cements and a core build-up material applied with a self-etch adhesive (BF: Bifix SE/Rebilda Post, VOCO; CSA: Clearfil SA Cement/Rely X Fiber Post, 3M ESPE; RX: RelyX Unicem 2/Rely X Fiber Post, 3M ESPE; SPC: Speed Cem/FRC Postec, Ivoclar Vivadent; SMC: Smart Cem/X Post, Dentsply; RB: Rebilda DC-Futurabond/Rebilda Post; n=22). For each group, half of the specimens were subjected to thermocycling (TC) (5°C-55°C, 10,000 cycles) and stored humid for one year at 37°C. Push-out bond strength data of six slices (thickness 1 mm) per root and nanoleakage expression of representative specimens were evaluated after 24 hours (baseline) and after TC and storage for one year (aging), respectively.

Results: Bond strength differed significantly among resin cements ($p<0.0005$) and the location inside the root canal ($p<0.0005$), but not by aging ($p=0.390$; repeated-measures analysis of variance). SMC (14.6±5.8 MPa) and RX (14.1±6.8 MPa) revealed significantly higher bond strength compared to BF (10.6±5.4 MPa) and RB (10.0±4.6 MPa) but differed not significantly from SPC (12.8±4.8) MPa; CSA (6.1±4.6

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MPa) revealed significantly lower bond strength compared to all other investigated materials (p<0.05; Tukey Honestly Significantly Different). Qualitative nanoleakage analysis revealed more silver deposits at the interface in all groups after aging. For CSA, a large amount of silver deposits inside the cement was also observed at baseline and after aging.

Conclusions: Fiber post luting using SAR cements demonstrated reliable bond strengths. Product-specific differences and initial degradation effects could be demonstrated.

INTRODUCTION

Fiber-reinforced posts are often used for increasing the retention of the coronal restoration of severely destroyed endodontically treated teeth.[1,2] They have been recommended because of their elastic modulus, which is similar to that of dentin,[3] and it has been speculated that stress should be evenly distributed along post, luting cement, and dentin compared to more rigid post materials.[4,5] Conversely, clinical evidence that fiber posts reduce the occurrence of root fractures is missing.[6] Moreover, adhesively luted titanium as well as fiber posts revealed a comparable success rate after seven years in a controlled randomized trial.[7]

Adhesive luting inside the root canal is still challenging because of anatomic variability of the root canal dentin,[8] limited visibility, difficult moisture and application control, and the high C-factor, which might affect durable and stable bonding.[9,10] Consequently, adhesive luting of posts inside the root canal should be as simple as possible.

The most simplified adhesive strategy involves the use of self-adhesive resin cements where no previous application of bonding agents is required. These cements have acid-functionalized monomers, such as 4-methacryloxyethyl trimellitic anhydride and pyromellitic glycerol dimethacrylate, or phosphoric acid groups, such as 2-methacryloxyethyl phenyl hydrogen phosphate, 10-methacryloyloxydecyl dihydrogen phosphate, bis(2-methacryloxyethyl) acid phosphate, and dipentaerythritol pentaacrylate monophosphate, in their composition to achieve bonding to the tooth substrate.[11] As a consequence of the mixing process of self-adhesive resin cements, a pH ranging between 1.5 and 3 is created by the acidic monomers in order to demineralize the dentin.[11] These acidic groups then bind with calcium in the hydroxyapatite to form an ionic attachment between the methacrylate network and dentin. Ions released from the acid-soluble filler neutralize the remaining acidic groups to create a chelate-reinforced three-dimensional methacrylate network. Therefore, these materials become more hydrophobic during the polymerization process,[11] and it has been speculated that these products would be less prone to hydrolytic degradation than are simplified etch-and-rinse systems and self-etch adhesive systems. A recent meta-analysis[12] revealed positive effects of the use of self-adhesive resin cements for luting fiber posts inside the root canal compared to other adhesive strategies. Especially for less experienced operators, the use of this simplified self-adhesive technique seems to be advantageous.[13] However, there is still controversy regarding whether or not this simplified technique for bonding fiber posts is affected by degradation processes inside the root canal.

Previous studies revealed that lower bond strength after artificial aging of self-adhesive resin cements was also dependent on the type of cement, and they attributed this decrease in bond strength to the hydrolytic degradation of the polymer matrix. It was speculated that self-adhesive resin cements may not all adequately shift to neutrality and hydrophobicity, depending on the product used.[14-16] In contrast to that finding, two recent studies[17,18] could not detect any significant reduction of bond strength after artificial aging of self-adhesive resin cements.

Consequently, the aim of this study was to analyze the bond strength of five different self-adhesive resin cements for luting fiber posts—initially and after long-term storage and thermocycling—in comparison to a self-etch adhesive and dual-curing core build-up material. In addition, representative specimens of each group were analyzed using qualitative interfacial nanoleakage analysis. The null hypotheses tested were the following: 1) No differences in bond strength between the different resin cements exist; 2) Long-term water storage for one year and thermocycling do not affect the bond strength of the investigated materials; and 3) Location inside the root canal does not affect the bond strength of the tested materials.

METHODS AND MATERIALS

One hundred and forty-four sound human maxillary central incisors were obtained with written informed consent under an ethics-approved protocol (EA4/102/14) by the Ethical Review Committee of the Charité–Universitätsmedizin Berlin (Germany) and stored in 0.5% chloramine T solution until use. Crowns were removed and root canal preparations were performed at a working length of 1 mm from the apical foramen using a single length technique with MTwo rotary instruments (VDW, Munich, Germany) by one trained operator. Apical enlargement was performed to a size of 60/.02 using Flex Master rotary files (VDW) combined with irrigation (Endoneedle; Vedefar, Dilbeek, Belgium) using 1 mL of 1% NaOCl solution after every change of file size. The teeth were filled with warm, vertically condensed gutta-percha (Calamus Dual; Dentsply Maillefer, Ballaigues, Switzerland) and AH Plus sealer (Dentsply DeTrey, Konstanz, Germany) and stored in distilled water for 24 hours.

All root canals were enlarged with a slow-speed drill provided by the respective manufacturer of the fiber post systems that are presented in Table 1.

The depth of the post space preparation was 8 mm, leaving at least 4 mm of gutta-percha inside the canal to guarantee an apical seal. The post space was checked for cleanliness using an operating microscope (magnification 23×, OPMI pico; Zeiss, Jena, Germany). The following self-adhesive resin cements were used for luting fiber posts according to the manufacturers' recommendations (Table 1): Bifix SE/Rebilda Post (BF; VOCO, Cuxhaven, Germany), Clearfil SA Cement (Kuraray Dental, Osaka, Japan)/RelyX Fiber Post (3M ESPE, Seefeld, Germany) (CSA), RelyX Unicem 2/RelyX Fiber Post (RX; 3M ESPE), Speed Cem/FRC Postec Post (SpC; Ivoclar Vivadent, Schaan, Liechtenstein), and Smart Cem/X Post (SmC; Dentsply). The core build-up material Rebilda DC in combination with the self-etch adhesive Futurabond DC and the Rebilda Post (RB; all supplied by VOCO) served as the comparison group. Excess luting material was removed, and light-curing was performed using an LED curing unit (1200 mW/cm^2; Elipar Freelight 2, 3M ESPE) according to the manufacturers' recommendations. A core build-up (height 4 mm) was performed freehand using Rebilda DC (VOCO) in the BF and RB groups, Clearfil Core/New Bond (Kuraray Dental) in CSA and RX groups, Multicore Flow/Adhese DC (Ivoclar Vivadent) in the SpC group, and XP Bond/CoreX Flow (all Dentsply) for the SmC group, according to the manufacturers' recommendation, in order to seal the adhesively luted fiber post and to mimic the clinical situation during aging. Half of the samples from each group were subjected to push-out testing after 24-hour storage in 100% humidity (baseline) and the other half after thermocycling (10,000 cycles, 5°C-55°C) and storage for 12 months at 37°C in 0.9% NaCl solution (aging), which was changed weekly as previously described.[17]

After storage, all roots were cut into six slices of 1-mm thickness perpendicular to the long axis of the tooth using a band saw (Exakt Apparatebau, Noderstedt, Germany). Thickness of the slices was measured using a micrometer screw (Mitutoyo Messgeräte, Neuss, Germany), and the coronal (R1) and apical arc radius (R2) of the post segment were evaluated using a stereomicroscope (DV 4; Zeiss). Push-out testing was performed (Universal Testing Machine Zwick; Roell, Ulm, Germany) at a cross-head speed of 0.5 mm/min. The maximum stress was calculated from the recorded peak load divided by the computed surface. In order to calculate the exact bonding surface, the tapered design of the posts was considered and the formula of a conical frustum was applied, thus: $\pi(R_1 + R_2)\sqrt{(R_1 - R_2)^2 + h^2}$. A conical frustum is a frustum created by slicing the top of a core parallel to the base.

After the push-out test each specimen was observed using a stereomicroscope (DV 4) at 40× magnification to determine the failure mode. A scoring system was applied according to the failure modes: 1) adhesive failures between dentin and luting agent; 2) adhesive failures between post and luting agent, 3) mixed failures, and 4) cohesive failures inside the post.

For qualitative interfacial nanoleakage analysis two further specimens from each group were analyzed (n=2 from each aging interval). The roots were sectioned into six slices (thickness 1 mm) as described above after removing the core build-up. The obtained slices were covered with nail varnish, leaving 1 mm free at the interface, and immersed into 50 wt% ammoniacal silver nitrate ($AgNO_3$) solution for 24 hours; this step was followed by application of a photo development solution for eight hours.[19] Afterward the specimens were dried for one hour, glued with cyanoacrylate onto glass slides (Menzel, Niedersachsen, Germany), and ground under running water using 180-, 600-, 1200-, 2400-, and 4000-grit silicon carbide paper (LS2, Remet; Casalecchio di Reno, BO, Italy).[20] All interfaces were analyzed by light microscopy (E800; Nikon, Tokyo, Japan) at 600× magnification.

Data from the push-out tests were aggregated using the break variables "tooth" and "location." The alpha (Type I) error level was set to 0.05. A repeated-measures analysis of variance (ANOVA) with the interindividual factors "resin" and "thermocycling" (TC), and storage was applied at six (BF, CSA, RX, SpC, SmC, and RB) and two levels (initial bond strength and bond strength after storage) and

Table 1: *Composition of Materials Used, According to Manufacturers*

Adhesive Composition (Lot No.)	Luting Cement (Lot No.)	Composition of Luting Cement	Post Composition and Size (Lot No.)	Core Build-up Material Composition (Lot No.)	Adhesive Approach
Futurabond DC (VOCO): organic acids, Bis-GMA, HEMA, TMPTMA, BHT, ethanol, fluorides, CQ, amine, catalysts (0946262, 0946263)	Rebilda DC (VOCO) (09511232)	Bis-GMA, UDMA, DDDMA, BHT, dibenzoyl peroxide, CQ, silica, barium borosilicate glass ceramic, accelerators	Rebilda Post (VOCO): Solid composite of glass fibers, inorganic fillers, PDMA (0926167) Cor. Diam.: 2 mm Ap. Diam.: 1.02 mm Taper 5.3°	Rebilda DC (VOCO): Bis-GMA, UDMA, DDDMA, BHT, dibenzoyl peroxide, CQ, silica, barium borosilicate glass ceramic, accelerators (09511232)	Self-etch
	BiFix SE (VOCO) 0951036 1003252)	UDMA, GDMA, catalyst, initiator	Rebilda Post (VOCO): Solid composite of glass fibers, inorganic fillers, PDMA (0904227) Cor. Diam.: 2 mm Ap. Diam.: 1.02 mm Taper 5.3°	Rebilda DC (VOCO): Bis-GMA, UDMA, DDDMA, BHT, dibenzoyl peroxide, CQ, silica, barium borosilicate glass ceramic, accelerators (09511232)	Self-adhesive
	Speed Cem (Ivoclar Vivadent) (M31940)	DMA, acidic monomers, barium glass, ytterbium trifluoride, co-polymer, silicon dioxide, initiators, stabilizers, color pigments	FRC Postec (Ivoclar Vivadent): Glass fibers, aromatic and aliphatic DMA, ytterbium trifluoride Cor. Diam.: 2 mm Ap. Diam.: 1 mm Taper 5.18°	Multicore flow DMA, barium glass, ytterbium trifluoride, barium-aluminum-fluorosilicate glass, silicon dioxide, catalysts, stabilizers, pigments (N55968)	Self-adhesive
	RelyX Unicem 2 (3M ESPE) (L427307)	Alkaline and silanated fillers, initiator components, pigments, methacrylate monomers containing phosphoric acid groups, methacrylate monomers, stabilizers	RelyX Post (3M ESPE): Glass fibers (zirconia base), epoxy resin (117680909 127931002) Cor. Diam.: 1.6 mm Ap. Diam.: 0.8 mm Taper 4.58°	Clearfil Core (Kuraray Dental): TEGDMA, Bis-GMA, silanated glass filler, colloidal silica, catalysts, accelerators (41396)	Self-adhesive
	Smart Cem2 (Dentsply) (090330)	UDMA, DMA, TMA, phosphoric acid–modified acrylate resin, PENTA, proprietary photoinitiating system, proprietary self-cure initiating system	X Post (Dentsply): Quartz fibers, epoxy resin (648688B) Cor. Diam.: 1.67 mm Ap. Diam.: 0.8 mm Taper 2.65°	Core X Flow (Dentsply): UDMA, DMA, TMA, barium boron fluoroaluminosilicate glass, CQ, silicon dioxide, benzoyl peroxide (091021)	Self-adhesive
	Clearfil SA Cement (Kuraray Dental) (13BBA, 0013BB)	Bis-GMA, TEGDMA, MDP, hydrophobic aromatic and aliphatic DMA, silanated barium glass filler, DL-camphorquinone, benzoyl peroxide, initiator, pigments	Rely X Post (3M ESPE): Glass fibers (zirconia base), epoxy resin (117680909, 127931002) Cor. Diam.: 1.6 mm Ap. Diam.: 0.8 mm Taper 4.58°	Clearfil Core (Kuraray Dental): TEGDMA, Bis-GMA, silanated glass filler, colloidal silica, catalysts, accelerators (41396)	Self-adhesive

Abbreviations: Ap. Diam., apical diameter; BHT, butylhydroxytoluene; Bis-GMA, bisphenol A diglycidyl methacrylate; Cor. Diam., coronal diameter; CQ, camphorquinone; DMA dimethyl ammonium; DDDMA, dodecandiol-dimethacrylate; HEMA, 2-hydroxyethyl methacrylate; GDMA; glycerin dimethacrylate, MDP, 10-methacryloyloxydecyl dihydrogen phosphate; PENTA; dipentaerythritol pentaacrylate monophosphate; PDMA; polydecyl methacrylate; TEGDMA, triethylene glycol dimethacrylate; TMA; trimethyl aluminum; TMPTMA, trimethylolpropane; UDMA, urethane dimethacrylate

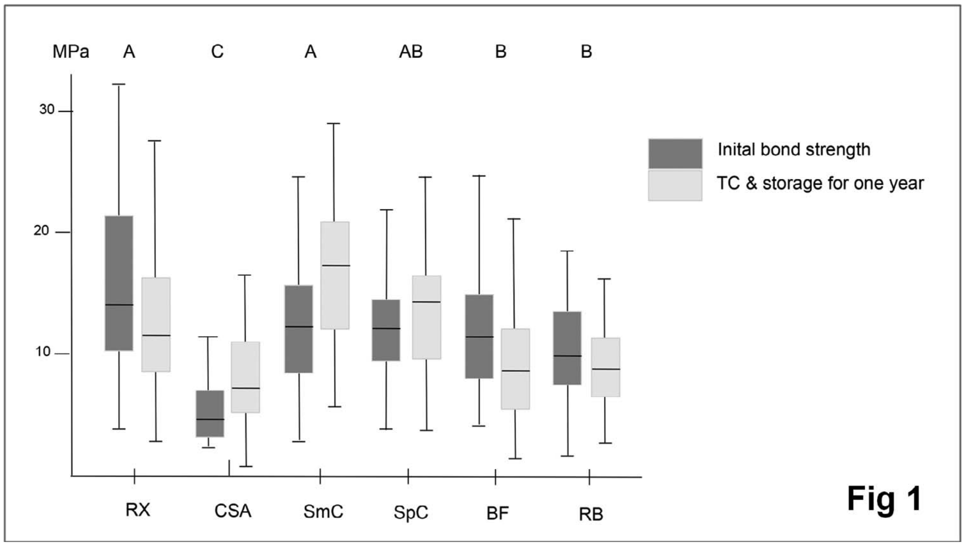

Figure 1. *Box plot demonstrating initial bond strength values as well as bond strength after TC and storage for all investigated materials. Uppercase letters indicate significant differences between materials for pooled data for baseline and aging (*$p<0.05$*; Tukey Honestly Significantly Different).*

location as intraindividual factor (coronal, middle, apical) was applied (SPSS, version 21.0, Chicago, IL, USA). Analysis of the failure modes was conducted using crosstabs and a Chi-square test.

RESULTS

Bond strength was significantly affected by the resin cement ($p<0.0005$) and the location inside the root canal ($p<0.0005$), but not by aging ($p=0.390$; repeated-measures ANOVA). A significant interaction was observed between the factors of resin cement and aging ($p<0.0005$; ANOVA).

Overall, SmC (14.6±5.8 MPa) and RX (14.1±6.8 MPa) revealed significantly higher bond strength compared to BF (10.6±5.4 MPa) and RB (10.0±4.6 MPa) but did not differ significantly from SpC (12.8±4.8 MPa); CSA (6.1±4.6 MPa) revealed significantly lower bond strength compared to all other investigated materials ($p<0.05$; Tukey Honestly Significantly Different) (Figure 1).

With respect to the significant interaction between the factors resin cement and aging, Figure 1 illustrates that bond strength was slightly decreased in groups RX, BF, and RB, whereas it was slightly increased in groups CSA, SmC, and SpC.

Bond strength was significantly affected by the location inside the root canal ($p<0.0005$; ANOVA) and demonstrated significantly higher bond strength in the coronal part of the root canal (12.4±6.8 MPa) compared to the middle (10.7±5.8 MPa) and apical (11±5.5 MPa) parts. No significant interaction for the factors of location and material has been observed ($p=0.104$; repeated-measures ANOVA).

The failure mode was significantly affected by the resin cement initially ($p<0.0005$) and after aging ($p=0.002$; Chi-square test) (Table 2). Most failures occurred between resin cement and dentin, with an increase of this failure mode after aging for four out of six groups.

Qualitative interfacial nanoleakage analyses (Figure 2a-l) showed an increasing amount of nanoleakage after one year, mainly on the dentin/cement interface for all groups. BF and RB exhibited slightly more silver deposits after aging than did RX, SmC, and SpC. For CSA, interfacial nanoleakage occurred more than in other groups, even inside the luting material at baseline and after aging (Figure 2c,d).

DISCUSSION

The first null hypothesis of the present study was rejected because the type of resin cement significantly affected bond strengths of fiber posts inside the root canal. Product-specific differences in bond strengths of self-adhesive resin (SAR) cements inside the root canal have also been reported previously.[14]

Three SAR cements revealed significantly higher bond strength values in the present study compared to a dual-cure core build-up material applied in combination with a self-etch adhesive. These data are in agreement with those of a previous meta-analysis[12] that also favored the use of SAR cements for luting fiber posts. Less technique sensitivity as well as moisture tolerance of SAR cements were supposed to contribute to the good performance of SAR cements inside the root canal. However, product-specific effects on bond strengths have been observed, and the investigated SAR cement CSA

Table 2: *Failure Modes of the Investigated Materials with Respect to Artificial Aging*

Resin Cement	Aging	Failure Modes, %				
		Adhesive Cement/Post	Adhesive Cement/Dentin	Mixed	Cohesive Post	Not Detectable
RX	Baseline	1.7	60.0	11.7	26.7	0
	Aging	3.3	73.3	20.0	1.7	1.7
CSA	Baseline	16.7	30.0	51.7	1.7	0
	Aging	8.3	63.3	26.7	1.7	0
SmC	Baseline	1.7	46.7	43.3	8.3	0
	Aging	3.3	70.0	15.0	6.7	5.0
SpC	Baseline	1.7	63.3	6.7	28.3	0
	Aging	10.0	60.0	23.3	6.7	0
BF	Baseline	0	75.0	21.7	3.3	0
	Aging	3.3	60.0	35.0	1.7	0
RB	Baseline	6.7	28.3	60.0	5.0	0
	Aging	6.7	45.0	48.3	0	0

Abbreviations: BF, Bifix SE; CSA, Clearfil SA Cement; RB, Rebilda DC/Futurabond DC; RX, RelyX Unicem 2; SmC, Smart Cem; SpC, Speed Cem.

seemed to benefit from additional adhesive application.[21]

Matrix composition of resin-based materials influences the degree of conversion and cross-link density and therefore may affect stress development during polymerization.[22] A previous study[23] that evaluated contraction stress, microhardness, and degree of conversion of three SAR cements revealed for Clearfil SA Cement significantly lower contraction stress compared to that associated with RelyX Unicem, but also significantly lower microhardness and degree of conversion. This may clarify the occurrence of low bond strength values of this cement obtained in the present study, in which the predominantly occurring failure mode for the initial samples was mixed (possibly indicating low mechanical properties of this cement). Moreover, interfacial nanoleakage analysis revealed a remarkably higher degree of interfacial silver deposits for the CSA, which is well correlated to the significantly lower bond strength values of this material. The polymer matrix of SAR cements becomes more hydrophobic over the setting time as a result of interactions with calcium ions from the tooth surface and alkaline filler particles.[11,24] The pH neutralization behavior shows a wide variability among SAR cements[25] and influenced significantly flexural strength and the degree of water sorption in a reverse manner.

Another study[26] investigated micromechanical properties of various SAR cements and revealed significantly higher Vickers hardness values for RelyX Unicem compared to Smart Cem 2, which again showed higher values compared to Clearfil SA Cement. The modulus of elasticity of Clearfil SA cement was also significantly lower compared to that of RelyX Unicem.[26] These results demonstrate high variation in micromechanical properties of SAR cements that might have also affected bond strength values in the present study.

In the present study, four different fiber posts from different manufacturers have been used (Table 1). This might have affected the results of the present study. However, when testing a post-and-luting system of one manufacturer, possible incompatibilities between post and luting material should be excluded, and the full potential of each system under laboratory conditions can be assessed.[27] Nonetheless, chemical interaction of co-polymerizing between methacrylate-based resins of the luting agents and highly cross-linked epoxy resin matrices of the posts is less likely.[28] Recently published data indicate that the degree to which both micromechanical interlocking and chemical bonding contribute to the bond strength between fiber posts and resin cements is currently not known.[29] However, it is assumed that micromechanical interlocking that is basically depending on the post-surface topography might be the most contributing factor.[29] Moreover, data from the literature[15,27,30,31] indicated that failure occurs frequently at the interface between root canal dentin and luting agent. The most frequent failure modes observed in the present study were also adhesive failures at the dentin/luting agent interface and mixed failures, and, thus, minimal effects of the various post types used on bond strength can be assumed.

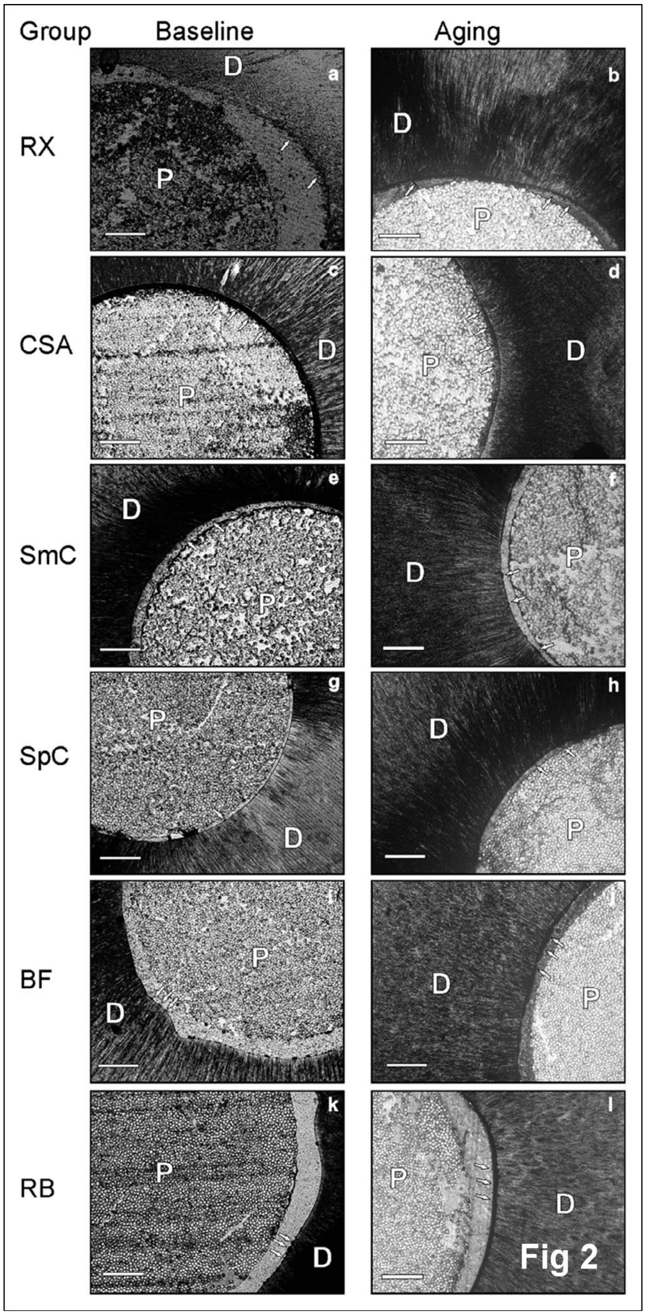

Figure 2. *Light microscopy images (original magnification, 200×) showing representative areas of the post/cement/dentin interface. At baseline a slight amount of silver deposits could be detected, mainly at the dentin/cement interface, for most of the groups (a,e,g,i,k); CSA demonstrated a large amount of silver staining at the interfaces and inside the luting cement at baseline and after aging (c,d). After aging, a slight increase in nanoleakage could be observed in all other groups (b,f,h,j,l). P, fiber post; D, dentin; white arrows indicate presence of silver nitrate at the luting interfaces; white bar = 100 μm.*

The second null hypothesis of this investigation can be accepted, because aging did not affect the bond strength of the investigated materials in the present study, although a significant interaction between these two factors has been observed. The present study subjected whole roots with a core build-up to aging. Previous studies[14,15] subjected slices of samples directly to TC and storage and revealed a significant decrease of bond strength for SAR cements. In general, hydrolytic degradation of the adhesive interface due to fluid movement through dentinal tubules together with residual water from the respective adhesive technique are considered the main factors responsible for the decrease in bond strength over time.[32,33] However, direct intraoral exposure of the post-composite-dentin interface is usually avoided by immediately restoring the tooth, which means that water is not in direct contact with the bonded post.[34,35] Therefore, for the present study design, we decided to subject whole roots with an adhesive core build-up to aging in order to mimic the clinical situation. Nonetheless, thermomechanical loading would have come closer to the clinical situation, but sample preparation in this case would have required crown restorations,[36] which is supposed to hamper specimen preparation for the push-out testing.[37] The use of whole roots might partially explain the results of the present study, in which no overall effects on bond strength of aging could be observed. Nonetheless, a significant interaction between the factors of aging and luting cement could be detected, again indicating product-specific differences between the investigated SAR cements. This effect has been demonstrated previously[38] with respect to the sorption characteristics of various SAR cements in a study in which Smart Cem 2 revealed significantly higher sorption after 168 hours of storage in distilled water when compared to RelyX Unicem 2. Water sorption and hygroscopic expansion are positively correlated for resin-based filling materials.[39] Notably, hygroscopic expansion due to water sorption after long-term incubation using SAR cements as core build-up material was considered to be reasonable as a means by which to provoke crack propagation in lithium disilicate crowns.[40] Thus, a higher hygroscopic expansion could have possibly contributed to the increase of bond strength of Smart Cem 2 after TC and storage in the present study. However, an increased amount of silver deposits has been observed in exemplary samples after aging, indicating that degradation of the interface occurred but did not result in bond strength decrease at the investigated stage.

The third null hypothesis must be rejected since bond strength was significantly affected by the location inside the root canal. The coronal part of the root canal revealed significantly higher bond strength compared to the other regions inside the root canal, which is in accordance with the findings of previous studies,[17,41] and a previous review[42] summarized that application of adhesive techniques in the apical part of the root canal is less predictable.

The thin push-out test is considered a valid method with which to analyze bond strengths of fiber posts to root canal dentin because the test demonstrated a more homogeneous stress distribution by finite element analysis, when compared to the microtensile bond strength, and less variability in mechanical testing.[43] Nevertheless, the contribution of friction to the detected bond strength values cannot be excluded.[44] If higher hygroscopic expansion leads to increased push-out values, the influence of friction will become more relevant, and correct positioning of the punch pin as well as the use of a pin that is only slightly smaller than the post is of importance. Therefore, we used three different pins according to the post diameter of the respective slice.

Qualitative interfacial nanoleakage analysis demonstrated a large amount of silver deposits even inside the luting material for CSA in combination with the lowest bond strength data, which might be explained with a lower degree in conversion (DC).[23,45] A lower DC is mainly combined with a weaker cross-linked polymer network, resulting in a material being more prone to hydrolytic degradation. Insufficient curing and residual uncured monomers of the material CSA might have resulted in silver staining inside this material at baseline. This phenomenon has been observed previously for CSA for the chemical-cure mode[46] and related to residual water on the dentin surface that affected the integrity of the SAR cement and created defects within the matrix. This might also be an explanation for the low bond strength data in the present study. A higher amount of silver uptake inside insufficiently cured materials has been also demonstrated previously.[47]

CONCLUSIONS

Within the limitations of this *in vitro* study it can be concluded that the push-out bond strength of the tested SAR cements and the control group of a core build-up material were durable after aging for one year. However, bond strength depended on the specific material compositions and characteristics that might have an impact on push-out bond strength values.

Regulatory Statement

This study was conducted in accordance with all the provisions of the local human subjects oversight committee guidelines and policies of Charité–Universitätsmedizin Berlin, in Berlin, Germany.

Conflict of Interest

The authors of this manuscript certify that they 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.

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