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Original Article

Bond strength and void formation of self-adhesive resin cement with polyethylene fiber posts in the root canal systems

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KEYWORDS
Self-adhesive resin cement;
Micro-CT;

Abstract *Background/purpose:* Compromised structure in endodontically treated teeth requires reliable luting agents to ensure durable post-restoration. This study investigated the bonding strength and void formation of self-adhesive resin cement (SARC) used with polyethylene fiber posts in endodontically treated teeth, an essential aspect of post-endodontic

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Push-out bond strength;
Polyethylene fiber post

restorations, especially when the remaining tooth structure is compromised.
Materials and methods: Thirty-five extracted single-rooted human mandibular premolars were divided into five groups (n = 7 per group) based on different cementation protocols: Group 1 and 2 received SARC with adhesive pretreatment, Group 3 and 4 received SARC without adhesive pretreatment, and Group 5 received conventional adhesive resin cement (CAR). Micro-computed tomography (Micro-CT) was used to evaluate void formation and distribution, while push-out bond strength (POBS) testing and scanning electron microscopy (SEM) were performed to assess bond strength and analyze failure modes.
Results: Micro CT analysis revealed, SARC with or without adhesive successfully demonstrated the smallest void volume in coronal and apical regions ($P < 0.05$). Furthermore, void distribution patterns in the SARC groups were smaller and more consistent. In POBS, results exhibited no significant differences among the groups ($P > 0.05$), indicating comparable bond strength across the materials. SEM analysis revealed that cohesive failure within the polyethylene posts was predominant across all groups.
Conclusion: These findings indicate the clinical viability of SARC, especially without adhesive pretreatment as an effective and simplified post-cementation method, particularly in cases with restricted visibility. This approach offers reduced void formation, contributing to improved long-term durability of the restoration.

Introduction

Post-endodontic restorations are particularly challenging in cases of extensive tooth loss due to the increased risk of root fractures. Selecting an appropriate post system is essential to reinforce the remaining tooth and improve bonding performance. Fiber-reinforced posts have garnered increasing attention in restorative dentistry owing to their favorable mechanical properties and reliable intracanal retention.[1–3] Polyethylene fiber posts, composed of high-molecular-weight polyethylene, exhibit high elasticity, considerable tensile strength, and an elastic modulus similar to dentin. These properties enhance adaptation to canal morphology and improve fracture resistance and mechanical retention.[4–6] Clinically, these posts are indicated for the restoration of endodontically treated teeth, particularly when esthetic and preservation of tooth structure are of primary concern. Their woven configuration further allows intimate adaptation to canal walls and effective stress distribution.[5–9] Compared to glass fiber posts, polyethylene fiber posts exhibit greater flexibility and dentin compatibility, though this may compromise rigidity in extensive restorations. Although carbon fiber posts offer superior mechanical strength, their dark coloration limits aesthetic suitability in visually critical areas.[6,10]

Another challenge lies in selecting an optimal adhesive material, which is essential for successful post-endodontic restorations.[11–13] Self-adhesive resin cement bonds effectively to root canal dentin through methacrylate monomers modified with carboxylic acid or phosphate, enabling substrate demineralization, infiltration, and formation of micromechanical and chemical bonding.[14–18] The presence of fillers neutralizes acidity, while functional acid monomers and a dual polymerization mechanism enable bonding to the dentin structure without pretreatment.[12,19]

The bonding strength between SARC and CAR remains debatable, with several studies reporting either comparable or inferior performance of SARC.[11,20,21] Although SARC simplifies clinical procedures, its efficacy may be limited by inadequate smear layer removal, reduced monomer infiltration, and suboptimal micromechanical retention. In contrast, CAR with etch-and-rinse and bonding steps demonstrated more consistent bond strengths due to hybrid layer formation and deeper resin tag penetration.[22,23] Nevertheless, a recent study suggests that SARC may exhibit mechanical properties comparable to CAR, supporting its increased clinical utilization.[24]

Bonding effectiveness is influenced by multiple factors, especially the moist environment of root canals. Internal factors, including smear layer formation and residual obturation materials, may compromise bonding by interfering with the resin-dentin interface.[3,25] Studies have reported that applying a universal adhesive containing functional monomers before cementation can improve the mechanical properties of SARC.[26–29] However, debonding of fiber-reinforced posts remains a frequent issue, often due to limitations of the adhesive system.[23] Inadequate polymerization during light curing may expand the cement layer, contributing to shrinkage and increased pressures, which may lead to restoration failure.[13,15,18]

Although polyethylene fiber posts offer many clinical advantages, limited studies have investigated their long-term effectiveness, likely due to their relatively infrequent application in endodontically treated teeth. Studies have shown contradictory outcomes: one study reported some discouragement regarding their use,[30] while another reported a high survival rate.[31] These inconsistencies may be ascribed to non-standardized evaluation methods, limited clinical studies, and variations in materials and techniques.[30,31] Additionally, the adhesively challenging surface characteristics of polyethylene fiber posts, along with the absence of standardized surface protocols, present challenges to achieving durable bonding. Most prior research has focused on alternative post systems, leaving the adhesive behavior and clinical relevance of polyethylene fiber posts underexplored. Therefore, this study aims to evaluate the bonding ability of self-adhesive resin cement with polyethylene fiber post to the root canals, through Micro CT analysis to assess interfacial adaptation and push-out bond testing for bond strength assessment.

Materials and methods

Tooth preparation

Thirty-five extracted human mandibular premolars with single, straight roots and completely developed apices were selected for this study. The sample size (n = 35) was determined based on a priori power analysis using the package pwr in RStudio software (version 2023.06.01), confirming that 7 samples per group were sufficient to detect a large effect size (0.8) with 80 % power at a 5 % significance level. All procedures followed the Declaration of Helsinki and were approved by the Ethics Committee of the Dentistry Faculty of Hasanuddin University (No.0187/PL.09/KEPK FKG-RSGM UNHAS/2024). Teeth extracted due to orthodontic or periodontal indications, straight root canals with length ranging from 14 to 16 mm. Previously treated teeth, root fractures, or caries were excluded. Specimens were preserved in saline for up to six months. A low-speed diamond bur (Komet; Henry Schein, Melville, NY, USA) was used to crown-section approximately 1—2 mm coronal to the cement-enamel junction. The working length was set to 1 mm from the apex.

The root canals were instrumented using the One Curve single-file instrument (Micro-Mega, Besançon, France) with an X-smart endodontic motor (Dentsply Sirona, York, PA, USA). Irrigation of the root canal was performed with 2 mL of 5.25 % sodium hypochlorite solution and 17 % ethylenediaminetetraacetic acid (EDTA) solution (MD-Cleanser; Meta Biomed, Cheongju-si, Republic of Korea), and subsequently dried with paper points (Dentsply Maillefer, Tulsa, OK, USA). The root canals were obturated using the lateral condensation technique with gutta-percha (Dentsply Maillefer) and a resin-based sealer (Adseal, Meta Biomed). After 24 h, gutta-percha was partially removed using Peeso reamer burs (Mani, Utsunomiya, Japan), preserving a 4 mm apical barrier. Final irrigation was performed with distilled water.

Table 1 Experimental grouping and cementation protocols.

Group	Group code	Cement type	Etched	Adhesive application	Cementation procedure
1	SARC-R/adhesive	Self-adhesive resin cement (RelyX™ U200; 3M™ ESPE, St. Paul, MN, USA)	None	One-step adhesive (single bond universal, 3M™ oral care), light-cured for 20s.	Cement applied, polyethylene fiber post (construct, Kerr, Brea, CA, USA) inserted, light-cured for 20s.
2	SARC-M/adhesive	Self-adhesive resin cement (Maxcem Elite™ chroma; Kerr, Brea, CA, USA)	None	One-step adhesive (single bond universal, 3M™ oral care), light-cured for 20s.	Cement applied, polyethylene fiber post (construct, Kerr) inserted, light-cured for 20s.
3	SARC-R	Self-adhesive resin cement (RelyX™ U200; 3M™ ESPE)	None	None	Cement applied, polyethylene fiber post (construct, Kerr) inserted, light-cured for 20s.
4	SARC-M	Self-adhesive resin cement (Maxcem Elite™ chroma Kerr)	None	None	Cement applied, polyethylene fiber post (construct, Kerr) inserted, light-cured for 20s.
5	CAR-R	Conventional resin cement (RelyX™ Ultimate; 3M™ ESPE)	37 % phosphoric acid (Super etch; Skydental, Vernon, CA, USA) (15s)	One-step adhesive (single bond universal, 3M oral care), light-cured for 20s.	Cement applied, polyethylene fiber post (construct, Kerr) inserted, light-cured for 20s.

SARC-R/adhesive = self-adhesive resin cement RelyX™ U200 with adhesive pretreatment; SARC-M/adhesive = self-adhesive resin cement Maxcem Elite™ Chroma with adhesive pretreatment; SARC-R = self-adhesive resin cement RelyX™ U200 without adhesive pretreatment; SARC-M = self-adhesive resin cement Maxcem Elite™ Chroma without adhesive pretreatment; CAR-R = conventional resin cement RelyX™ Ultimate.

Cementation procedure

The samples were randomly divided into five groups (n = 7 per group), which were categorized as SARC-R/adhesive, SARC-M/adhesive, SARC-R, SARC-M, and CAR-R (Table 1). Each group followed a specific cementation protocol as follows: group 1 SARC-R/adhesive (RelyX™ U200; 3M™ ESPE, St. Paul, MN, USA) and group 2 SARC-M/adhesive (Maxcem Elite™ Chroma; Kerr, Brea, CA, USA): The Canal wall was dried using a paper point (Dentsply Maillefer). A universal one-step (Single Bond Universal; 3M™ Oral Care, St. Paul, MN, USA) was applied with a microbrush for 20 s, air-thinned for 5 s, and light-cured for 10 s. Self-adhesive resin cement was then applied into the canal using an automix tip. The polyethylene fiber tape (Construct, Kerr, Brea, CA, USA) was inserted, held in position for 1 min, and light-cured for 20 s using a Valo curing unit (Ultradent, South Jordan, UT, USA). Group 3 SARC-R (RelyX™ U200; 3M™

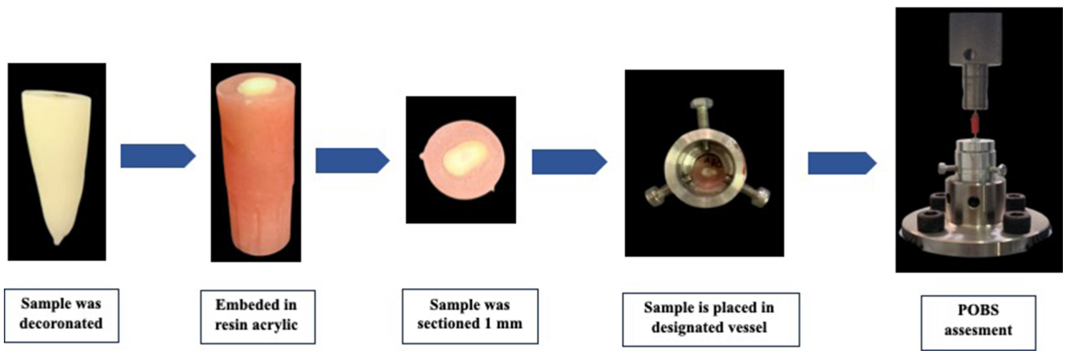

Figure 1 The schematic of the push-out bond strength (POBS) examination.

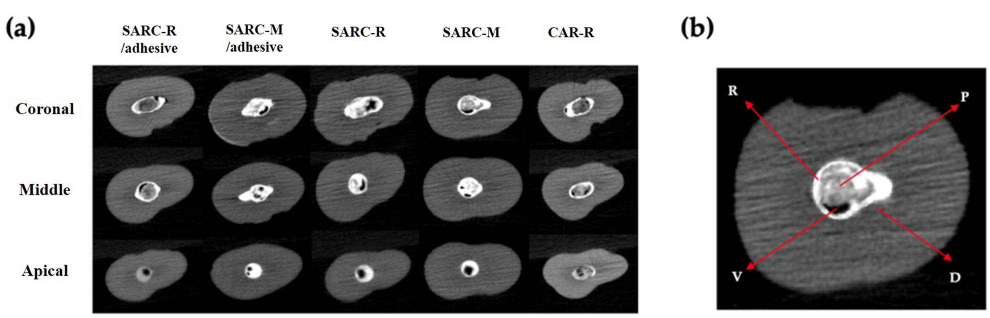

Figure 2 (a) Representative micro-CT cross-sectional interval 30μm from the coronal, middle, and apical regions of polyethylene fiber-post with different resin cement; (b) Representative image of void formation detected in SARC-R. R: resin cement, P: polyethylene fiber-post, V: void formation, D: dentin; SARC-R/adhesive: self-adhesive resin cement RelyX™ U200 with adhesive pretreatment; SARC-M/adhesive: self-adhesive resin cement Maxcem Elite™ Chroma with adhesive pretreatment; SARC-R: self-adhesive resin cement RelyX™ U200 without adhesive pretreatment; SARC-M: self-adhesive resin cement Maxcem Elite™ Chroma without adhesive pretreatment; CAR-R: conventional resin cement RelyX™ Ultimate.

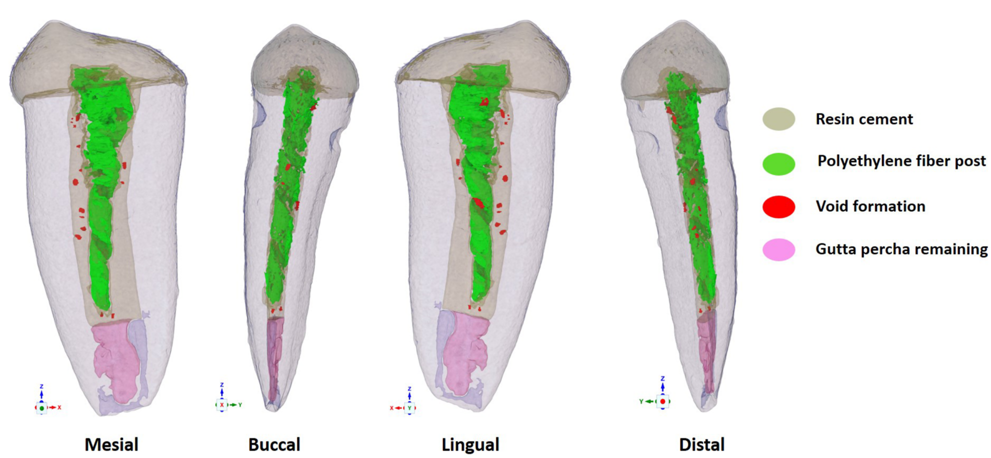

Figure 3 The three-dimensional image of a polyethylene fiber post with resin cement is presented from various aspects.

Table 2 Volume void across the coronal, middle, and apical regions between groups (mm^3).

Group	Median (min - max)		
	Coronal (*P*-value = 0.027*)	Middle (*P*-value = 0.081)	Apical (*P*-value = 0.001**)
SARC-R/adhesive	0.34 (0.06—1.08)[b]	0.08 (0.02—0.35)[a]	0.13 (0.08—0.37)[bc]
SARC-M/adhesive	0.07 (0.03—0.59)[a]	0.17 (0.04—1.84)[a]	0.12 (0.01—0.23)[ab]
SARC-R	0.23 (0.02—0.72)[ab]	0.14 (0.03—0.29)[a]	0.04 (0.01—0.27)[a]
SARC-M	0.1 (0.01—0.33)[a]	0.02 (0.02—0.36)[a]	0.36 (0.08—0.58)[bc]
CAR-R	0.17 (0.05—0.54)[ab]	0.12 (0.09—0.54)[a]	0.33 (0.18—0.89)[c]

Different superscript letter indicated the statistically significant difference between resin cements = ($P < 0.05$*; $P < 0.01$**); df (degree of freedom) = 4; SARC-R/adhesive = self-adhesive resin cement RelyX™ U200 with adhesive pretreatment; SARC-M/adhesive = self-adhesive resin cement Maxcem Elite™ Chroma with adhesive pretreatment; SARC-R = self-adhesive resin cement RelyX™ U200 without adhesive pretreatment; SARC-M = self-adhesive resin cement Maxcem Elite™ Chroma without adhesive pretreatment; CAR-R = conventional resin cement RelyX™ Ultimate.

Table 3 Post-hoc pairwise comparison of volume void across the coronal, middle, and apical regions between groups.

Region	Group		*P*-value
Coronal	SARC-R/adhesive	SARC-M/adhesive	0.038*
		SARC-R	0.165ns
		SARC-M	0.026*
		CAR-R	0.073ns
	SARC-M/adhesive	SARC-R	0.456ns
		SARC-M	0.535ns
		CAR-R	0.259ns
	SARC-R	SARC-M	0.62ns
		CAR-R	0.902ns
	SARC-M	CAR-R	0.62ns
Middle	SARC-R/adhesive	SARC-M/adhesive	0.318ns
		SARC-R	0.902ns
		SARC-M	0.165ns
		CAR-R	0.259ns
	SARC-M/adhesive	SARC-R	0.535ns
		SARC-M	0.026*
		CAR-R	0.71ns
	SARC-R	SARC-M	0.073ns
		CAR-R	0.805ns
	SARC-M	CAR-R	0.011*
Apical	SARC-R/adhesive	SARC-M/adhesive	0.165ns
		SARC-R	0.011*
		SARC-M	0.318ns
		CAR-R	0.053ns
	SARC-M/adhesive	SARC-R	0.259ns
		SARC-M	0.073ns
		CAR-R	0.001**
	SARC-R	SARC-M	0.004**
		CAR-R	0.002**
	SARC-M	CAR-R	0.535ns

Significance codes = $P < 0.05$*; $P < 0.01$**; ns = not significant; SARC-R/adhesive = self-adhesive resin cement RelyX™ U200 with adhesive pretreatment; SARC-M/adhesive = self-adhesive resin cement Maxcem Elite™ Chroma with adhesive pretreatment; SARC-R = self-adhesive resin cement RelyX™ U200 without adhesive pretreatment; SARC-M = self-adhesive resin cement Maxcem Elite™ Chroma without adhesive pretreatment; CAR-R = conventional resin cement RelyX™ Ultimate.

ESPE) and group 4 SARC-M (Maxcem Elite™ Chroma; Kerr): No adhesive pretreatment was used. After drying the canal, self-adhesive resin cement was directly applied. Polyethylene fiber tape (Construct, Kerr) was inserted, held for 1 min, and light-cured for 20 s. Group 5 CAR-R (RelyX™ Ultimate; 3M™ ESPE): The canal was etched with 37 % phosphoric acid (Super etch; Skydental, Vernon, CA, USA) for 15 s, rinsed, and gently air-dried. A universal adhesive (Single Bond Universal; 3M™ Oral Care) was applied with a microbrush for 20 s, air-thinned for 5 s, and light-cured for 10 s. Conventional resin cement was placed into the canal. Polyethylene fiber tape (Construct, Kerr) was inserted, held for 1 min, and light-cured for 20 s. Subsequently, all 35 roots were built up with Dentocore (Itena Clinical, Paris, France) to a coronal height of 3—4 mm.

Micro-CT analysis

A micro-CT scanner (SkyScan 1176; Bruker micro-CT, Kontich, Belgium) was used to scan all samples at a resolution of 13.7 μm, 80 kV, and 300 μA, with a 0.5 mm Al + Cu filter. Image reconstruction was performed using NRecon v.1.6.3 software from Bruker micro-CT. The coronal third, middle third, and apical third were selected for post-assessment. The region of interest (ROI) was defined at the interface between the root dentin, resin cement, and polyethylene fiber post. To facilitate spatial analysis, the root canal was divided into coronal, middle, and apical thirds based on the post length along the longitudinal axis. Segmentation was performed in MIMICS software (Materialise Interactive Medical Image Control System, version 21.0) using Hounsfield Unit (HU) based grayscale thresholding within the defined ROI. This approach enabled material differentiation and void detection based on radiodensity, following the HU-density estimation. Manual corrections were applied as needed to ensure accurate segmentation. The number and volume of voids were quantified in each region. All segmentation and measurements were performed by a single trained operator to maintain consistency. Three-dimensional visualization of the segmented regions was performed using ANSYS SpaceClaim 2024 software for qualitative assessment.

Push-out bond strength (POBS) analysis

The POBS testing was carried out using a Universal Testing Machine (UTM, Autograph AGSX 50 KN; Shimadzu, Kyoto, Japan). Each sample was embedded in a self-curing acrylic resin (Jet Tooth Shade, Lang Dental Manufacturing Co., Wheeling, IL, USA) and sectioned into 1,5 mm-thick slices at 1 mm, 4 mm, and 7 mm apical to the cementoenamel junction. Slice thickness was confirmed using a digital caliper (Mitutoyo, Suzano, SP, Brazil) with a precision of 0.01 mm. Each root slice was positioned on a custom-made stainless steel jig with a central opening slightly larger than the post diameter, allowing for unobstructed displacement curing testing. A cylindrical stainless steel plunger pin with a diameter of 0.8 mm was precisely aligned and centered over the post to ensure contact with the post material, avoiding contact with the surrounding dentin.

Push-out bond strength was assessed in coronal and apical regions by applying a load in an apical to coronal direction at a crosshead speed of 0.5 mm/s until bond failure was observed. POBS values in megapascals (MPa) were determined by dividing the debonding force (N) by the

Table 4 Distribution of the number of voids between resin cements.

Region	Void	Resin cements - n (%)				
		SARC-R /adhesive	SARC-M/adhesive	SARC-R	SARC-M	CAR-R
Coronal	1	1 (14.29)	0 (0)	0 (0)	0 (0)	2 (28.57)
	2	2 (28.57)	4 (57.14)	1 (14.29)	3 (42.86)	2 (28.57)
	3	3 (42.86)	2 (28.57)	4 (57.14)	1 (14.29)	2 (28.57)
	4	1 (14.29)	1 (14.29)	2 (28.57)	1 (14.29)	1 (14.29)
	5	0 (0)	0 (0)	0 (0)	2 (28.57)	0 (0)
	Total	7 (100)	7 (100)	7 (100)	7 (100)	7 (100)
Middle	1	1 (14.29)	0 (0)	0 (0)	0 (0)	0 (0)
	2	3 (42.86)	4 (57.14)	2 (28.57)	2 (28.57)	2 (28.57)
	3	1 (14.29)	1 (14.29)	3 (42.86)	2 (28.57)	1 (14.29)
	4	1 (14.29)	2 (28.57)	1 (14.29)	2 (28.57)	2 (28.57)
	5	1 (14.29)	0 (0)	1 (14.29)	1 (14.29)	2 (28.57)
	Total	7 (100)	7 (100)	7 (100)	7 (100)	7 (100)
Apical	1	1 (14.29)	1 (14.29)	1 (14.29)	0 (0)	4 (57.14)
	2	3 (42.86)	3 (42.86)	3 (42.86)	3 (42.86)	1 (14.29)
	3	3 (42.86)	2 (28.57)	1 (14.29)	2 (28.57)	1 (14.29)
	4	0 (0)	1 (14.29)	1 (14.29)	0 (0)	0 (0)
	5	0 (0)	0 (0)	1 (14.29)	2 (28.57)	1 (14.29)
	Total	7 (100)	7 (100)	7 (100)	7 (100)	7 (100)

n = sample size; SARC-R/adhesive = self-adhesive resin cement RelyX™ U200 with adhesive pretreatment; SARC-M/adhesive = self-adhesive resin cement Maxcem Elite™ Chroma with adhesive pretreatment; SARC-R = self-adhesive resin cement RelyX™ U200 without adhesive pretreatment; SARC-M = self-adhesive resin cement Maxcem Elite™ Chroma without adhesive pretreatment; CAR-R = conventional resin cement RelyX™ Ultimate.

Table 5 Comparison of the push-out bond strength between resin cements.

Variable	Sides	Resin cements	n	(Mean ± SD)	*F* (4,30)	*P*-value
POBS (MPa)	Coronal	SARC-R/adhesive	7	(6.72 ± 2.09)		0.881
		SARC-M/adhesive	7	(8.75 ± 9.26)		
		SARC-R	7	(8.37 ± 3.5)	0.291	
		SARC-M	7	(8.79 ± 6.73)		
		CAR-R	7	(9.86 ± 2.91)		
	Apical	SARC-R/adhesive	7	(5.84 ± 4.14)		0.702
		SARC-M/adhesive	7	(6.99 ± 2.68)		
		SARC-R	7	(7.74 ± 6.57)	0.547	
		SARC-M	7	(4.77 ± 3.02)		
		CAR-R	7	(6.37 ± 2.17)		

One-way ANOVA ($P < 0.05$: significant); F (4,30); n = sample size; POBS = Push-out bond strength; SARC-R/adhesive = self-adhesive resin cement RelyX™ U200 with adhesive pretreatment; SARC-M/adhesive = self-adhesive resin cement Maxcem Elite™ Chroma with adhesive pretreatment; SARC-R = self-adhesive resin cement RelyX™ U200 without adhesive pretreatment; SARC-M = self-adhesive resin cement Maxcem Elite™ Chroma without adhesive pretreatment; CAR-R = conventional resin cement RelyX™ Ultimate.

Table 6 Post-hoc pairwise comparison of the push-out bond strength between resin cements.

Region	Group		*P*-value
Coronal	SARC-R/adhesive	SARC-M/adhesive	0.502ns
		SARC-R	0.585ns
		SARC-M	0.493ns
		CAR-R	0.301ns
	SARC-M/adhesive	SARC-R	0.899ns
		SARC-M	0.989ns
		CAR-R	0.712ns
	SARC-R	SARC-M	0.888ns
		CAR-R	0.62ns
	SARC-M	CAR-R	0.722ns
Apical	SARC-R/adhesive	SARC-M/adhesive	0.6ns
		SARC-R	0.385ns
		SARC-M	0.623ns
		CAR-R	0.81ns
	SARC-M/adhesive	SARC-R	0.728ns
		SARC-M	0.313ns
		CAR-R	0.776ns
	SARC-R	SARC-M	0.179ns
		CAR-R	0.528ns
	SARC-M	CAR-R	0.466ns

ns = not significant; SARC-R/adhesive = self-adhesive resin cement RelyX™ U200 with adhesive pretreatment; SARC-M/adhesive = self-adhesive resin cement Maxcem Elite™ Chroma with adhesive pretreatment; SARC-R = self-adhesive resin cement RelyX™ U200 without adhesive pretreatment; SARC-M = self-adhesive resin cement Maxcem Elite™ Chroma without adhesive pretreatment; CAR-R = conventional resin cement RelyX™ Ultimate.

interfacial surface area between the post and dentin. The bonded surface was determined using the following formula:

$$N = \pi \times k \ (r1 + r2)$$

where r1 is the post radius at the coronal region, r2 is the radius at the apical region, and k is the height calculated using the following formula:

$$[h2 + (r1\text{-}r2)2]\ ^{1}/_{2}$$

The H is the thickness of each layer in millimeters. The POBS testing procedure is illustrated in the schematic figures (Fig. 1).

Failure mode evaluation

Following the POBS assessment, the failure modes were categorized through observation using a scanning electron microscope (SEM; JEOL JSM 6510, Tokyo, Japan). The failure modes to be examined were Type I: Adhesive failure at the interface of dentin and resin cement, with no cement remaining on the dentin surface; Type II: Adhesive failure between the resin cement and the polyethylene fiber post, identified by the absence of resin cement on the post; Type III: Cohesive failure of the resin cement, indicated by fracture lines within the cement layer, with cement remants adherent to both the post and the dentin walls; Type IV: Cohesive failure in the polyethylene fiber post, evidence by structural damage of fracture within the fiber post itself: Type V: Mixed failure, a combination of two or

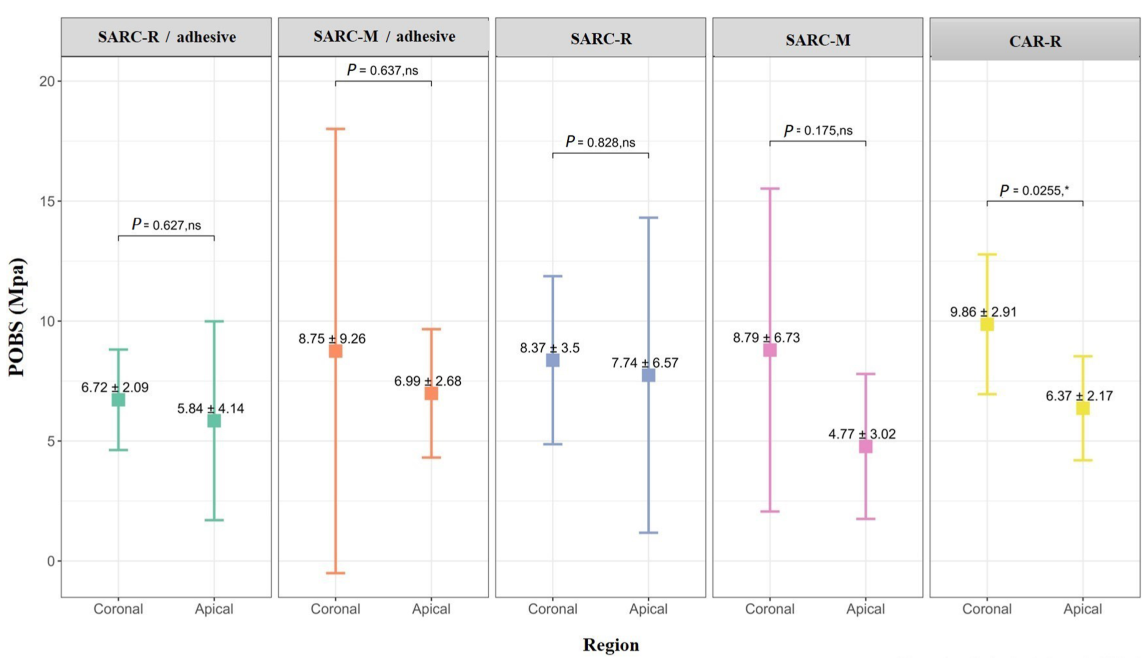

Figure 4 Comparison of POBS between groups in the coronal and apical regions using an independent t-test. Significant codes: $P < 0.05$*; ns: not significant; POBS: Push-out bond strength; SARC-R/adhesive: self-adhesive resin cement RelyX™ U200 with adhesive pretreatment; SARC-M/adhesive: self-adhesive resin cement Maxcem Elite™ Chroma with adhesive pretreatment; SARC-R: self-adhesive resin cement RelyX™ U200 without adhesive pretreatment; SARC-M: self-adhesive resin cement Maxcem Elite™ Chroma without adhesive pretreatment; CAR-R: conventional resin cement RelyX™ Ultimate.

more failure types according within single specimen, typically involving both adhesive and cohesive component across the interfaces.[13,27,32]

Statistical analysis

All statistical analyses were performed by RStudio software 2023.06.01. The Shapiro—Wilk test was applied to assess the normality of the data distribution. Micro-CT data were performed using the Kruskal—Wallis test, while the POBS were analyzed through one-way ANOVA, followed by a Post-Hoc LSD test, with $P < 0.05$ indicated as statistically significant.

Results

Micro-CT analysis

The cross-sectional micro-CT images of samples cemented with various resin cements are shown in the comparative analysis of volumetric voids at the coronal, middle, and apical regions associated with polyethylene fiber posts cemented with SARC or CAR (Fig. 2). A three-dimensional representation of a polyethylene fiber post cemented with one of the resin cements used in this study, viewed from the mesial, buccal, lingual, and distal aspects (Fig. 3).

Volume void

As the micro-CT volume data were not normally distributed, non-parametric statistical methods were applied. The Kruskal—Wallis test was used to compare void volumes among the experimental groups. Three-dimensional micro-CT analysis revealed void volume (mm^3) in the coronal, middle, and apical regions (Table 2), followed by post-hoc pairwise comparisons (Table 3). In the coronal region, SARC-M/adhesive exhibited the smallest void volume, although not significantly different compared to SARC-M. This indicates that SARC-M, regardless of adhesive, provided the best results compared to other materials. In the apical region, SARC-R demonstrated the lowest void volume and was significantly different from SARC-M and CAR-R, indicating superior performance in that area.

Distribution of void formation

Void formation across various resin cements was evaluated in terms of distribution patterns (Table 4). In this study, the maximum number of voids observed was five. In the coronal and apical regions, voids of 2 and 3 predominated across most materials. In the middle region, showed a more consistent dominance of 2 voids. SARC-M/adhesive and SARC-M exhibited smaller and more stable void distributions, whereas CAR-R showed a greater tendency to form larger voids, particularly in the coronal and apical regions.

Push-out bond strength (POBS) analysis

The POBS test demonstrated no statistically significant differences in bond strength among the resin cement groups in either the coronal or apical regions, indicating comparable bond strength (Table 5), followed by post-hoc pairwise comparison (Table 6). In the coronal region, CAR-R showed the highest bond strength (9.86 ± 2.91 MPa), whereas SARC-

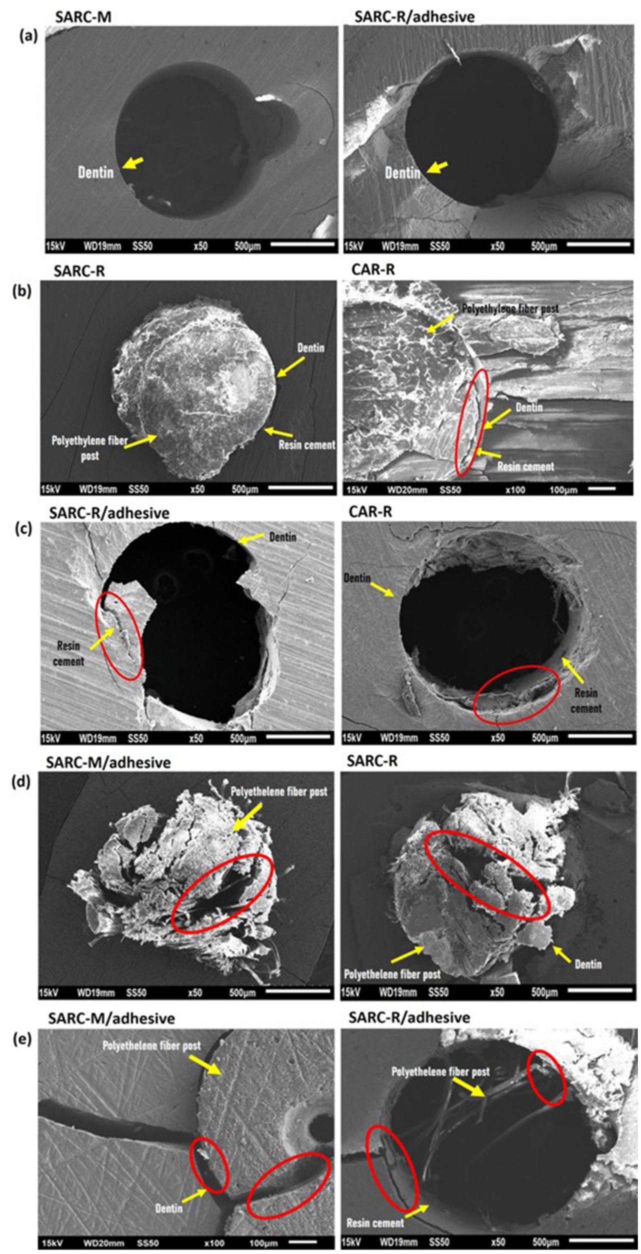

Figure 5 SEM images of samples: (a) failure mode type I from SARC-M and SARC-R/adhesive, (b) failure mode type II SARC-R and CAR-R, (c) failure mode type III from SARC-R/adhesive and CAR-R, (d) failure mode type IV from SARC-M/adhesive and SARC-R, (e) failure mode type V from SARC-M/adhesive and SARC-R/adhesive. SARC-R/adhesive: self-adhesive resin cement RelyX™ U200 with adhesive pretreatment; SARC-M/adhesive: self-adhesive resin cement Maxcem Elite™ Chroma with adhesive pretreatment; SARC-R: self-adhesive resin cement RelyX™ U200 without adhesive pretreatment; SARC-M: self-adhesive resin cement Maxcem Elite™ Chroma without adhesive pretreatment; CAR-R: conventional resin cement RelyX™ Ultimate.

R/adhesive exhibited the lowest (6.72 ± 2.09 MPa). In the apical region, SARC-R (7.74 ± 6.57 MPa) showed the highest strength, while SARC-M presented the lowest. Although differences in value were observed, no significant differences were found among groups. Furthermore, SARC-based groups demonstrated consistent bond strength across regions, whereas CAR-R demonstrated a significant difference from coronal to apical (Fig. 4).

Failure mode evaluation

Scanning Electron Microscopic (SEM) images revealed various types of failure modes observed in the samples (Fig. 5). Failure modes distribution across various material groups (Table 7), with type 4 failure mode exhibiting the highest prevalence across all groups, observed in both coronal (48.57 %) and apical (42.86 %) regions. Although some variations were noted among groups, the statistical analysis showed no significant differences.

Discussion

Self-adhesive resin cement is the most commonly selected adhesive material for bonding fiber posts as an intracanal retention, primarily due to its favorable mechanical properties and long-term performance.[2,4–7] However, precise adhesive application can be challenging, particularly in inaccessible locations, which may hinder the optimal bonding and contribute to void formation. These voids may compromise interfacial integrity, accelerate degradation, and reduce the longevity of indirect restoration.[1,3,13,15,18,21]

This study evaluated bond strength and void formation in the use of SARC and CAR for polyethylene fiber posts. The findings revealed differences in material behavior, particularly regarding void volume and distribution, bond strength across different root regions, and failure modes. Micro-CT analysis showed that SARC, with or without adhesive, produced significantly smaller void volumes than CAR in both coronal and apical regions. Nevertheless, voids were distributed across all root regions, likely due to air entrapment during mixing.[1,33,34] Moreover, the mixing technique appears to exert a greater influence on void formation than the polymerization mechanism.[1] The reduced void formation observed in the SARC group may also be attributed to its simplified, single-step application, which minimized operator-induced variability and improved cement flow and adaptation, particularly in limited-access areas.[24] Clinically, these advantages may contribute to more predictable outcomes. However, limitations of SARC should also be acknowledged, including its sensitivity to dentine moisture, reduced micromechanical interaction due to the absence of pretreatment, and technique-sensitive handling.[23]

The complete elimination of void formations remained challenging due to limited access within the root canal. A slow and controlled cement application technique is recommended to minimize air entrapment, and using a material-specific mixing tip can further reduce the risk.[35] The resin cements used in this study were a dual-syringe system with self-mixing tips that vary in shape and length depending on the manufacturer.

Regarding bond strength, CAR exhibited the highest value in the coronal region, with a notable decrease in the apical region. This variation may be related to anatomical differences, particularly the greater density and diameter of dentinal tubules in the coronal third.[36,37] Consequently, etching with 37 % phosphoric acid may more effectively remove the smear layer and enhance adhesive penetration in this region.[28,38] In the SARC-M/adhesive, the relatively high standard deviation observed in the coronal region may be attributed to variability in resin cement adaptation, the influence of the additional adhesive layer on the flow and polymerization, and technique sensitivity during post-

Table 7 The distribution of failure modes between resin cements.

Region	Resin cements	Failure mode				
		Type 1	Type 2	Type 3	Type 4	Type 5
		n (%)	n (%)	n (%)	n (%)	n (%)
Coronal	SARC-R/adhesive	0 (0)	1 (14.29)	0 (0)	5 (71.43)	1 (14.29)
	SARC-M/adhesive	1 (14.29)	3 (42.86)	0 (0)	3 (42.86)	0 (0)
	SARC-R	0 (0)	2 (28.57)	0 (0)	3 (42.86)	2 (28.57)
	SARC-M	2 (28.57)	1 (14.29)	0 (0)	2 (28.57)	2 (28.57)
	CAR-R	1 (14.29)	0 (0)	0 (0)	4 (57.14)	2 (28.57)
	Total	**4 (11.43)**	**7 (20)**	**0 (0)**	**17 (48.57)**	**7 (20)**
Apical	SARC-R/adhesive	1 (14.29)	2 (28.57)	1 (14.29)	2 (28.57)	1 (14.29)
	SARC-M/adhesive	0 (0)	0 (0)	0 (0)	5 (71.43)	2 (28.57)
	SARC-R	2 (28.57)	3 (42.86)	0 (0)	2 (28.57)	0 (0)
	SARC-M	2 (28.57)	0 (0)	1 (14.29)	3 (42.86)	1 (14.29)
	CAR-R	0 (0)	3 (42.86)	1 (14.29)	3 (42.86)	0 (0)
	Total	**5 (14.29)**	**8 (22.86)**	**3 (8.57)**	**15 (42.86)**	**4 (11.43)**

n = sample size; SARC-R/adhesive = self-adhesive resin cement RelyX™ U200 with adhesive pretreatment; SARC-M/adhesive = self-adhesive resin cement Maxcem Elite™ Chroma with adhesive pretreatment; SARC-R = self-adhesive resin cement RelyX™ U200 without adhesive pretreatment; SARC-M = self-adhesive resin cement Maxcem Elite™ Chroma without adhesive pretreatment; CAR-R = conventional resin cement RelyX™ Ultimate.

placement procedures. Moreover, the coronal third is more accessible and receives higher light exposure during polymerization, which may influence the curing process and further increase inter-sample variation. Although a previous study reported superior bond strength of CAR over SARC,[13] the findings of this study revealed no significant difference between CAR and SARC.

Although no significant differences in bond strength were observed, failure mode analysis offered further insight into the integrity of the bonded interfaces. Cohesive failure within the polyethylene fiber posts was the most prevalent across all the groups, indicating a strong bonding between the cement and post.[39,40] This contrasts with previous studies reporting predominantly adhesive failures, likely due to the difference in the fiber post types. The polyethylene fiber posts used in this study, composed of aligned polymer chains, possess a low modulus, low density, and high impact resistance, facilitating their adaptation to root canal morphology.[6] However, their flexibility may increase susceptibility to cohesive failure during the push-out bond strength testing procedure. In addition, the cohesive failure pattern may reflect a stress distribution that favors internal failure within the post, rather than adhesive failure. The woven, high-strength polymer structure of the polyethylene fiber post may facilitate energy dissipation after loading.

Overall, this study suggests that SARC outperforms CAR, with SARC-M demonstrating lower void volume compared to SARC-R, indicating improved handling and greater application stability. Although no significant differences in bond strength were observed between SARC-M and SARC-R, the absence of a thermocycling process may have limited the assessment of long-term adhesion durability. Previous studies have reported the bond strength of SARC-M following thermocycling, emphasizing the need to simulate oral conditions.[13] Additionally, while SARC-M exhibited lower microhardness and tensile strength compared to SARC-R and CAR-R, it demonstrated higher compressive strength and modulus elasticity compared to SARC-R.[20]

Performance differences between SARC-M and SARC-R may be attributed to their distinct functional monomers. Previous studies have reported that 10-methacryloyloxydecyl dihydrogen phosphate (MDP-10), present in universal adhesive, enhances bonding by forming stable calcium—phosphate complexes through chemical interaction with hydroxyapatite.[28] However, in this study, pretreating SARC-R with universal adhesive did not improve bond strength. Instead, it showed the lowest bond strength in the coronal region. This may reflect chemical interference with phosphoric acid methacrylate in SARC-R, thereby potentially reducing the efficiency of adhesive resin cement to the dentin substrate.[28] Otherwise, pretreated SARC-M with adhesive showed improved bond strength and exhibited the smallest void volume. Glycero-Phosphate Dimethacrylate (GPDM) in SARC-M forms ionic bonds with calcium in dentin, while MDP-10 enhances chemical bonding, contributing to superior adhesion.[41]

This study demonstrated that SARC groups generally exhibited higher bond strength in the coronal region, although the differences were not statistically significant. Conversely, the CAR group showed significant differences between the coronal and apical regions. Void volume and distribution influenced bond strength, with smaller voids correlating with improved performance. Notably, SARC without adhesive pretreatment showed comparable bond strength and the lowest void volume results, suggesting favorable adaptation and interface integrity.

In summary, these findings support the clinical viability of SARC as a simplified cementation approach, particularly in areas with restricted access and visibility. To strengthen the clinical relevance, future studies are encouraged to incorporate aging protocols, such as thermocycling, to simulate clinical conditions and assess long-term bond durability of the adhesive interface.

Declaration of competing interest

The authors declare no conflict of interest relevant to this study.

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