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ORIGINAL ARTICLE

Effects of Different Cementation Systems on Pull-out Bond Strength of Fibre Post to Bioceramic Putty Using a 3D Prefabricated Root Canal Model of Immature Permanent Teeth: An *In-Vitro* Study

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ABSTRACT

Objective: The current study aimed to find the best cementation system for cementing the fibre post with BioCeramic putty: total-etch dual-cure hydrophobic resin cement (TC), Self-adhesive dual-cure hydrophilic resin cement (SC), with SC-modified with a bioceramic sealer (SCB), and glass ionomer cement (GIC).

Methods: An impression was captured from the immature premolar root canal, followed by scanning and the subsequent design of prefabricated root canal models for immature permanent teeth (PRCMs). A total of forty PRCM replicas were precision-printed using advanced 3D printing technology. Subsequently, etch PRCM underwent meticulous filling with BioCeramic putty and a fibre post. After two hours, the fibre posts were removed and treated with hydrofluoric acid for all groups. Subsequently, fibre posts of groups except the GIC group received silane solution application. The PRCMs were categorised into four groups based on the cementation system employed: TC Group (n=10), SC Group (n=10), SCB Group (n=10), and GIC Group (n=10). After 48 h, the specimens underwent pull-out strength testing using a universal testing machine, performed along an axis parallel to the longitudinal axis of the fibre post at a crosshead speed of 1 mm/min. Failure modes were scrutinised using a stereomicroscope. The acquired data were subjected to robust statistical analyses, employing one-way ANOVA and Tukey HSD tests with a significance level set at α=0.05.

Results: The One-way ANOVA test showed a significant difference in the pull-out bond strength of the groups ($p<0.001$). Accordingly, the Tukey HSD test revealed that the mean bond strength values were significantly higher in the TC group than in other groups. Adhesive failure had a higher frequency in SC and GIC groups, whereas mixed failure had a higher frequency in TC groups and 3.

Conclusion: The TC exhibited significantly superior bond strength to the other groups, particularly concerning the fibre post-cementation to BioCeramic putty.

Keywords: BioCeramic putty, cementation system, dual-cure resin cement, fibre post, glass ionomer cement

HIGHLIGHTS

- The total-etch dual-cure hydrophobic resin cement was the best adhesive for fibre posts with BioCeramic putty among the tested cement.
- The self-adhesive dual-cure hydrophilic resin cement, the self-adhesive dual-cure hydrophilic resin cement modified with a BioCeramic sealer, and the glass ionomer cement did not yield favourable results for cementing fibre posts with BioCeramic putty.
- Adhesive failure was more common in the self-adhesive dual-cure hydrophilic resin and glass ionomer cement groups. In contrast, mixed failure was more common in the total-etch dual-cure hydrophobic resin cement and the self-adhesive dual-cure hydrophilic resin cement modified with a BioCeramic sealer group.
- Fibre posts cementing with BioCeramic putty may have clinical benefits in restoring extensively damaged immature permanent incisors.

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INTRODUCTION

The apical barrier has recently emerged as a highly successful treatment for immature permanent teeth with necrotic pulps. The primary goal of this procedure is to establish a calcified tissue barrier, effectively sealing the open apex without necessitating an increase in tooth length (1). While calcium hydroxide has traditionally been utilised for this purpose, its potential to weaken the root structure of immature teeth has raised concerns (2).

The introduction of newer materials, such as calcium silicate cement, has revolutionised apical barrier procedures by offering a novel approach. These cements can fill immature root canals or as an apical barrier (3). Notably, this innovative technique has demonstrated an enhancement in the fracture resistance of immature teeth (2), showing promising results in terms of survival and periapical lesion healing in necrotic immature teeth (4).

The advent of premixed bioceramics, representing the fifth generation of calcium silicate cement types, has further advanced the field. These materials, including TotalFill BioCeramic sealer, RRM Paste, RRM Putty, and Fast putty, have been available in Europe since 2008 (5). Compared to mineral trioxide aggregate (MTA), premixed bioceramics exhibit superior colour stability, enhanced handling properties, increased biocompatibility, and comparable physical and chemical characteristics (6).

Fibre posts have become prevalent in endodontically treated permanent teeth restoration, particularly those with substantial coronal tissue loss, as they increase the fracture resistance of endodontically treated and restored teeth. This restoration is especially relevant for incisors where an aesthetic appearance is crucial. Moreover, one notable advantage of fibre posts is their comparable elasticity modulus to root dentine (7). Notably, the fibre posts' longevity in the molar region exceeds their longevity in the premolar region, which is higher than in the incisors. Therefore, fibre posts may be an excellent option for supporting posterior restorations (7). Importantly, whether achieving complete obturation of the immature root canal with calcium silicate cement or restoring it with a fibre post after apical sealing with a calcium silicate cement plug, both approaches have demonstrated enhanced fracture resistance in immature permanent teeth (8).

Various systems have been employed for cementing fibre posts to dentine, including dual-cure resin cement and glass ionomer cement (GIC) (9, 10). Resin cements are categorised as total-etch or self-adhesive based on their adhesion methodology to the dentin surface (11). Total-etch resin cement involves etching the root dentine, rinsing, drying, and applying an adhesive agent. On the other hand, self-adhesive resin cement streamlines the application process, allowing direct application to the dentinal surface through its unique components, which include acidic and resinous monomers in their organic matrix (12). GIC has also been recommended for fibre post-cementation due to its unique composition, facilitating chemical adherence to the dentinal surface with consistently positive outcomes (9).

Maintaining optimal function and longevity of the fibre post in terms of restoration and a secure coronal seal requires sufficient stability within the dentinal root (7). *In-vitro* studies often assume an idealised representation of immature teeth, featuring uniform root canals with a circular section that facilitates the selection of an appropriate prefabricated fibre post size. However, the clinical reality is often different, with the shapes of immature permanent roots being variable. Commonly, these roots exhibit a truncated cone shape with an irregular oval section, along with a wide internal surface in the root canal (8, 13). Consequently, securing a suitable fibre post for an immature root canal can be challenging, as it may necessitate the removal of additional inner dentine, rendering the tooth more susceptible to fracture (7). Furthermore, efforts to clean remnants of calcium silicate cement from the inner walls of the canal, aimed at providing a bonding surface between the fibre post and dentine, may result in additional removal of root dentine, potentially compromising tooth strength (14). These factors may limit the clinical use of fibre posts for restoring necrotic immature permanent teeth.

Returning to the published studies on fibre posts, we found no study that specifically cemented fibre posts with calcium silicate cement. Instead, all the studies focused on using various cement types and different methods of treating the fibre post surface to achieve optimal bonding between the root dentine and the fibre post.

Hence, this study represents the pioneering attempt to evaluate the feasibility of directly cementing a fibre post with BioCeramic putty inside a 3D prefabricated root canal model for immature permanent teeth (PRCM) utilising commonly used systems for bonding fibre posts to root dentine so that the calcium silicate cement reinforces the immature root canal, diminishes the internal space of the canal, and creates a circular section, making it more compatible with prefabricated circular-section fibre posts to make the restoring of immature permanent incisors becomes significantly more streamlined and efficient with the incorporation of fibre posts. The null hypothesis posits that there is no significant difference in the pull-out bond strength values when employing the four cementation systems: Total-etch dual-cure hydrophobic resin Cement (TC), Self-adhesive dual-cure hydrophilic resin Cement (SC), SC-modified BioCeramic sealer (SCB), and GIC.

MATERIALS AND METHODS

Ethical Statement and Settings

This experimental *in-vitro* study received ethical approval from the Damascus University's Local Research Ethics Committee (Approval No. UDDS-361-13032023/SRC-2654) and has been written according to the Preferred Reporting Items for Laboratory Studies in Endodontology (PRILE) 2021 guidelines (15). It was funded by Damascus University (funder No. 501100020595) and conducted following the Declaration of Helsinki.

Sample Size Calculation

Based on the data of a previous study (9), the sample size in the present study was calculated by G* Power 3.1.9.4 (Heinrich Heine Universität, Düsseldorf, Germany). The ANOVA study obtained a total sample size of 40 subjects from the four groups. This sample size achieves 0.6311 effect size (f) and 90% power to detect differences with a 0.05 significance level.

Sample Selection and Preparation

The current study involved one intact immature permanent human mandibular first premolar recently extracted for orthodontic reasons. The patient had provided informed consent that his extracted teeth would be undergone in the current study. The premolar was examined with a 2.5× magnification lens (Carson handheld, Ronkonkoma, New York, USA) to ensure that it was free of cracks, and a periapical X-ray ensured that it was free of anatomical abnormalities (Fig. 1).

An electronic digital calliper (Liaoning MEC Group, Dalian, China) measured the entire length of the premolar (18 mm) and the diameter of the apex in the mesial-distal (2.1 mm) and buccal-lingual directions (2.5 mm), demonstrating that the premolar was at the third stage of Cvek classification (16).

A traditional access cavity of the premolar was opened using a diamond bur mounted on a high-speed handpiece; then, the canal orifice was prepared utilising an orifice opener file (ORODEKA LTD. Xincheng, Jining, China). The pulp tissue was removed, and the dentinal walls of the root were prepared gently with an XP-Endo Finisher file (FKG Dentair, La Chaux-de-Fonds, Switzerland). Afterwards, the canal was irrigated with 5.25% sodium hypochlorite (Merck, Darmstadt, Germany), normal saline, and 17% ethylenediaminetetraacetic acid (EDTA) 17% solution (Meta Biomed, Cheongju, South Korea), using a 27 G needle (Sybron Endo, Orange, CA). Finally, the canal was dried with paper points (Gabadent, Guangdong, China). An impression of the entire length of the immature canal was taken (pulp chamber space and root canal) using light body silicon with catalyst (Silight; BMS Dental, Capannoli, Italy) and large-sized (#70) K-file (Mani, Inc., Tochigi, Japan) (Fig. 2a). The cementoenamel junction level was marked on the impression using a dental probe.

The impression was scanned with an intra-oral scanner (MEDIT I700; CAD Ray, Las Vegas, Nevada, USA) to start the digital design and exported as a stereolithography (STL) file. The STL file was imported to a designing application (Exocad; DentalCAD 3.0 Galway, Exocad GmbH, Darmstadt, Germany). The pulp chamber space was deleted, and an offset coping of the root canal space was the design of choice in the Exocad to make the 3D PRCM that mimics the internal space of the gently-prepared root canal from the cementoenamel junction level into the apex. The margin line was drawn at the level of the canal orifice. The insertion direction was parallel to the canal's longitudinal axis. The cement gap width was 0 mm, and the undercuts were blocked. Then, the shape of the 3D PRCM was free-formed to be a cylinder-like shape (Fig. 2b). Finally, the design was exported as an STL file to be 3D printed. The STL file was imported to the printer slicing application (Zenith). It was sliced to a layer thickness of (0.05 mm), and then it was exported as a (PWMA) file and transported to the 3D printer (Zenith D; Centerpoint, La Palma, California, USA) to initiate the printing process to print 40 similar copies of the 3D PRCM. The resin of choice was castable ZMD-1000B resin (Zenith Dentis Co., La Palma, California, USA) due to its rigid structure and readily available and used in a 3D printer. The printing parameters were set: a layer thickness of 50 μm and a printing angle of 0°. After printing, each 3D PRCM was washed with alcohol and light cured for 120 s in the 3D printer UV curing chamber, where it was ready to use (Fig. 2c). This procedure was achieved by a single practitioner (M.K.A.).

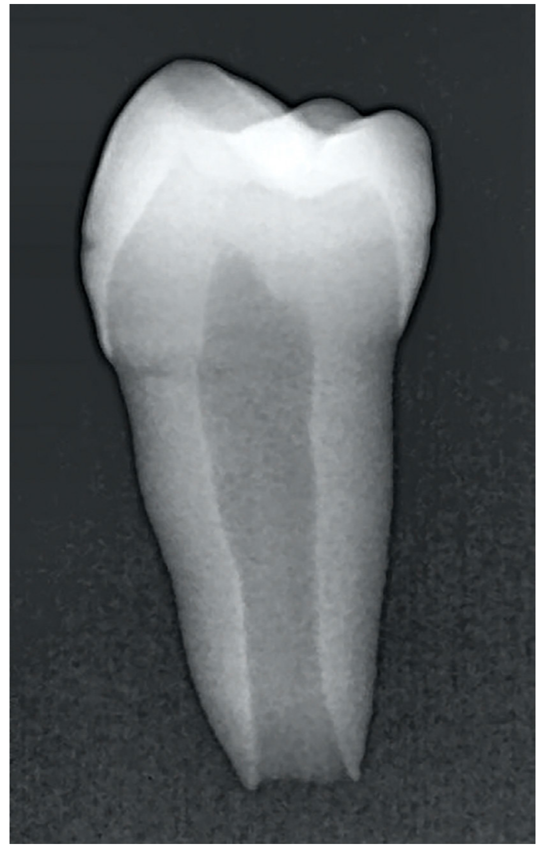

Figure 1. A radiograph of the extracted immature premolar

Materials Placement

Table 1 shows the materials used in the study.

Each PRCM was filled with BioCeramic putty (TotalFill BC RRM, FKG Dentaire Sàrl, Le Crêt-du-Locle, Switzerland), and a yellow-sized fibre post (1.2 mm diameter) (AAA Fiber Post, Bomaoer, Zhengzhou, China) was inserted in the middle of BioCeramic putty parallel to the longitudinal axis of the PRCM until each fibre post immerged to its middle (9 mm) within the BioCeramic putty (Fig. 3a). Then each PRCM was placed in a wet medium for two hours until the initial setting of the BioCeramic putty (5), after that the fibre posts were removed (Fig. 3b), cleaned, and had a surface treatment, then the PRCMs were divided into four groups according to the cementation system used.

Fibre Posts' Surface Treatment

10% hydrofluoric acid (HFA) (Angelus, Londrina, Brazil) was applied for 90 s on each fibre post (AAA Fiber Post) surface with a brush, rinsed with distilled water, and then air-dried for 10 s. Then, the Pre-Hydrolysed Silane Primer solution (Bisco, Inc., Irving Park Rd, Schaumburg, USA) was applied to the fibre posts for 60 s using a brush and was air-dried gently for 10 s. This technique (using HFA with silane solution) was used for fibre posts in groups 1, 2, and 3, while in group 4, HFA only was used without silane for fibre posts in group 4. The previous fibre post-surface treatment method was similar to the one described by Alshahrani et al. (17).

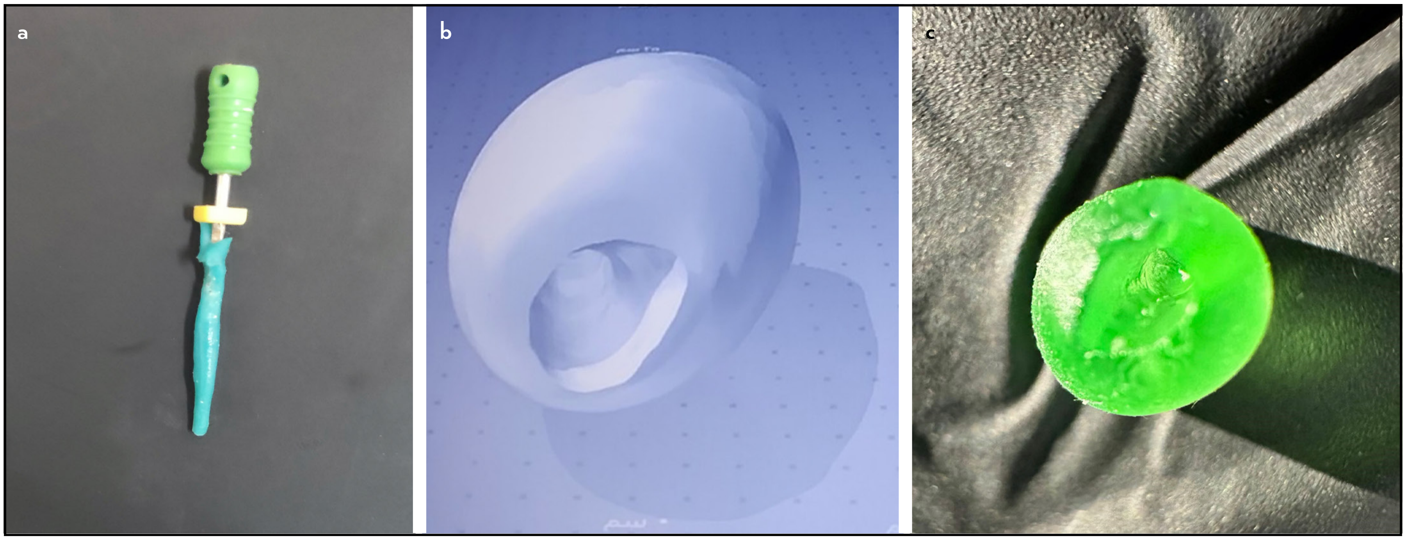

Figure 2. Steps of designing the PRCM; (a) the impression of the full-length space of the selected premolar's root canal (pulp chamber space and root canal space) using light body silicon and large sized K-file. (b) Final shape of PRCM that designed using the Exocad program and mimics the internal surface of root canal part of a gently-prepared immature premolar canal, and (c) the PRCM after 3D printing using green castable resin and curing

PRCM: Prefabricated root canal model

TC Group Preparation

The post space inside the BioCeramic putty was dried with paper points. Then, the post space was filled with 35% phosphoric acid (Ultradent, South Jordan, Utah, USA) by a micro tip for 20 s to etch the post space of BioCeramic putty, rinsed, and dried. Afterwards, Tetric N-Bond (Ivoclar Vivadent, Schaan, Liechtenstein) was applied throughout the post space using a small brush and paper points and light cured with a Dental LED Curing (Sichuan Xinhuaguang Medical Technology, Chengdu, China) for 20 s. Afterwards, a TC (NexCore) (Meta Biomed, Chungcheongbuk, Korea) was mixed according to the manufacturer's instructions and inserted into the post space with Lentulo spiral (Mani, Inc., Tochigi, Japan) mounted on a low-speed handpiece. Finally, the treated fibre posts were inserted into the post space and light-cured for 60 s.

SC Group Preparation

The post space inside the BioCeramic putty was dried with paper points and then cemented directly with SC (Embrace WetBond; Pulpdent, Watertown, Massachusetts, USA). It was mixed according to the manufacturer's instructions and inserted into the post space with a Lentulo spiral (Mani) mounted on a low-speed handpiece. Finally, the treated fibre posts were inserted into the post space and light-cured for 60 s.

SCB Group Preparation

In this group, the same procedures as group 2 were used. However, the SC was mixed with BioCeramic Sealer (TotalFill BC Sealer, FKG Dentaire Sàrl, Le Crêt-du-Locle, Switzerland) in a 3 SC:1 BioCeramic sealer ratio immediately before inserting the cement into the post space.

TABLE 1. The materials used in the present study

Material	Composition according to manufacturer	Usage
TotalFill® BC RRM	Calcium silicate, monobasic calcium phosphate, zirconium oxide, tantalum oxide and filler agents	To fill the PRCM in TC, SC, SCB and GIC Groups
Porcelain conditioner	Hydrofluoric Acid 10% - thickeners–red dye–water	To etch the fibre posts in TC, SC, SCB and GIC Groups
Silane	Ethanol – silane coupling agent	To apply on the fibre posts surface in TC, SC, and SCB Groups
NexCore	Bis-EMA–Bis-GMA–TEGDMA–UrethaneDimethacrylate–Triethyleneglycoldimethacrylate–Barium glass–ytterbium (III) fluoride – pyrogenic silicic acid	The cementation system of TC Group
Embrace WetBond	Diurethane dimethacrylate and other methacrylate-based monomers and oligomers–barium borosilicate glass–silica–oxidising agents–water–reducing agents–photo-initiators.	The cementation system of SC Group
TotalFill® BC Sealer	Premixed single syringe which contains calcium silicates, Calcium phosphate monobasic, zirconium oxide, tantalum oxide, and thickening agents.	To modify Embrace WetBond in SCB Group
Fuji I GIC	Powder – Calcium-alumina-fluorosilicate glass. Liquid – Polyacrylic acid	The cementation system of GIC Group

BC: BioCeramic, RRM: Root repair material, PRCM: Prefabricated root canal models, TC: Total-etch dual-cure hydrophobic resin cement, SC: Self-adhesive dual-cure hydrophilic resin cement, SCB: SC-modified with a bioceramic sealer, GIC: Glass ionomer cement, Bis-EMA: Bisphenol A-glycidyl methacrylate, Bis-GMA: Bisphenol A diglycidyl methacrylate ethoxylated, TEGDMA: Triethylene glycol dimethacrylate

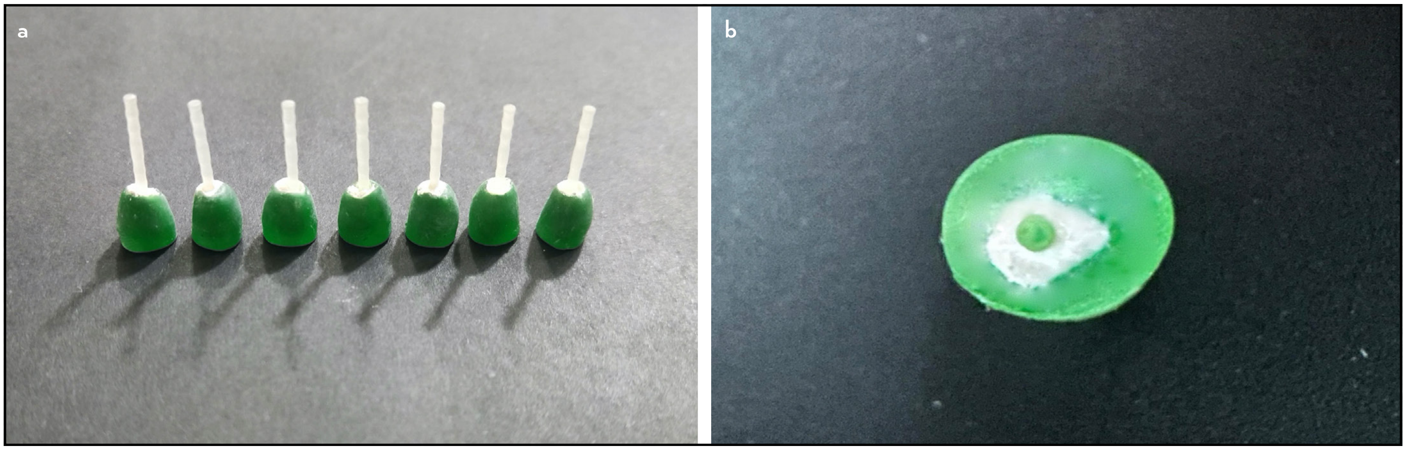

Figure 3. Filling the PRCMs with BioCeramic putty; (a) after fibre posts inserting, and (b) the post space after removing the fibre post

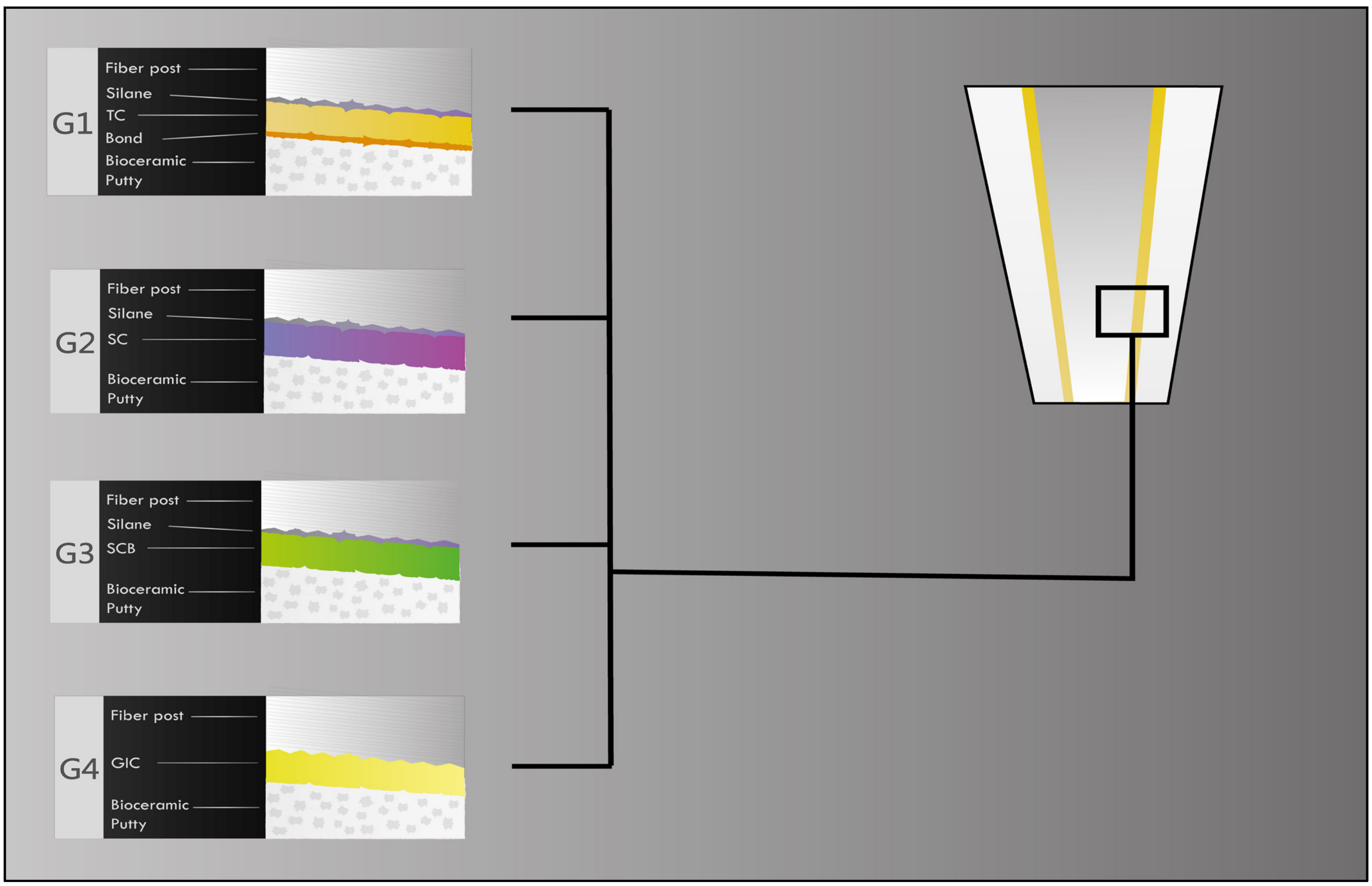

Figure 4. The layers of the bonding surface among the 4 groups

TC: Total-etch dual-cure hydrophobic resin cement, SC: Self-adhesive dual-cure hydrophilic resin cement, SCB: SC-modified with a bioceramic sealer

GIC Group Preparation

The post space inside the BioCeramic putty was dried with paper points and then cemented directly with GIC (Fuji I; GC Corporation, Tokyo, Japan), which was mixed according to the manufacturer's instructions and inserted into the post space with a Lentulo spiral (Mani) mounted on a low-speed handpiece. Then, the fibre posts were inserted into the spaces.

The previous methods of cement application were similar to those described by Li et al. (18). Figure 4 shows the bonding surface layers of each group.

Pull-out Test

The PRCMs of all groups were stored in distilled water at room temperature for 48 hours to ensure that all materials reached the final setting time. Then, the PRCM was fixed to the inferior compartment of the universal testing machine (Tinius Olsen Testing Machine, Horsham, Pennsylvania, USA). In contrast, the coronal part of the fibre posts was placed in the nipper attached to the superior compartment of the machine. The pull-out test was performed along an axis parallel to the longitudinal of the fibre post at a crosshead speed of 1 mm/min (Fig. 5). The maximum load causing dislodgement of the fibre post

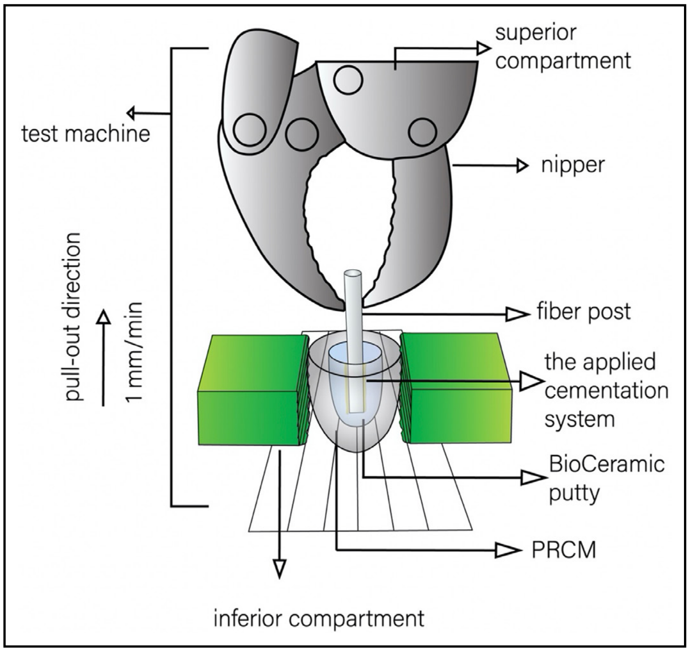

Figure 5. Schematic diagram of pull-out test set-up

PRCM: Prefabricated root canal model

from the BioCeramic putty inside the PRCM was recorded in Newtons (N). The previous method of performing the pull-out test was similar to the one described by Rezaei-Soufi et al. (19).

The principal investigator (Y.A.T.) performed the fibre posts surface treatment procedures, the cementation procedures, and the pull-out test.

Failure Mode

Each fibre post was investigated under 25× stereomicroscope magnification (Optical stereo microscope M series; Leica Microsystems GmbH, Wetzlar, Germany) to determine the failure mode. The failure mode was addressed into five groups: F1 (adhesive): no cement was observed on the post; F2 (adhesive): the post was partially covered with cement; F3 (adhesive): the post was completely covered with cement; F4 (mixed) (the post was partially covered with BioCeramic putty), and F5 (cohesive) (the post was completely covered with cement and BioCeramic putty). The previous failure mode detection method was similar to the one described by Rezaei-Soufi et al. (19). Moreover, the repetitions of each failure mode were converted into percentages for easier comparison of the results of the current study with other studies.

The previous procedure was performed by two blinded trained researchers (two professors, M.B.A. and J.A.) calibrated to the assessment criteria and kept unaware of the cementation system used in each sample. Subsequently, a third trained researcher (one professor, N.B.) randomly reviewed 10% of the cases. The results from this third evaluation concurred with the initial one, as confirmed by Cohen's κ test (K=0.970, p≤0.001).

Statistical Analysis

The collected data were tabulated and analysed using SPSS software (Version 20, IBM SPSS Inc., Chicago, IL, USA). Kolmogorov–Smirnov and Shapiro–Wilk tests indicated the normal distribution of pull-put bond strength values among the

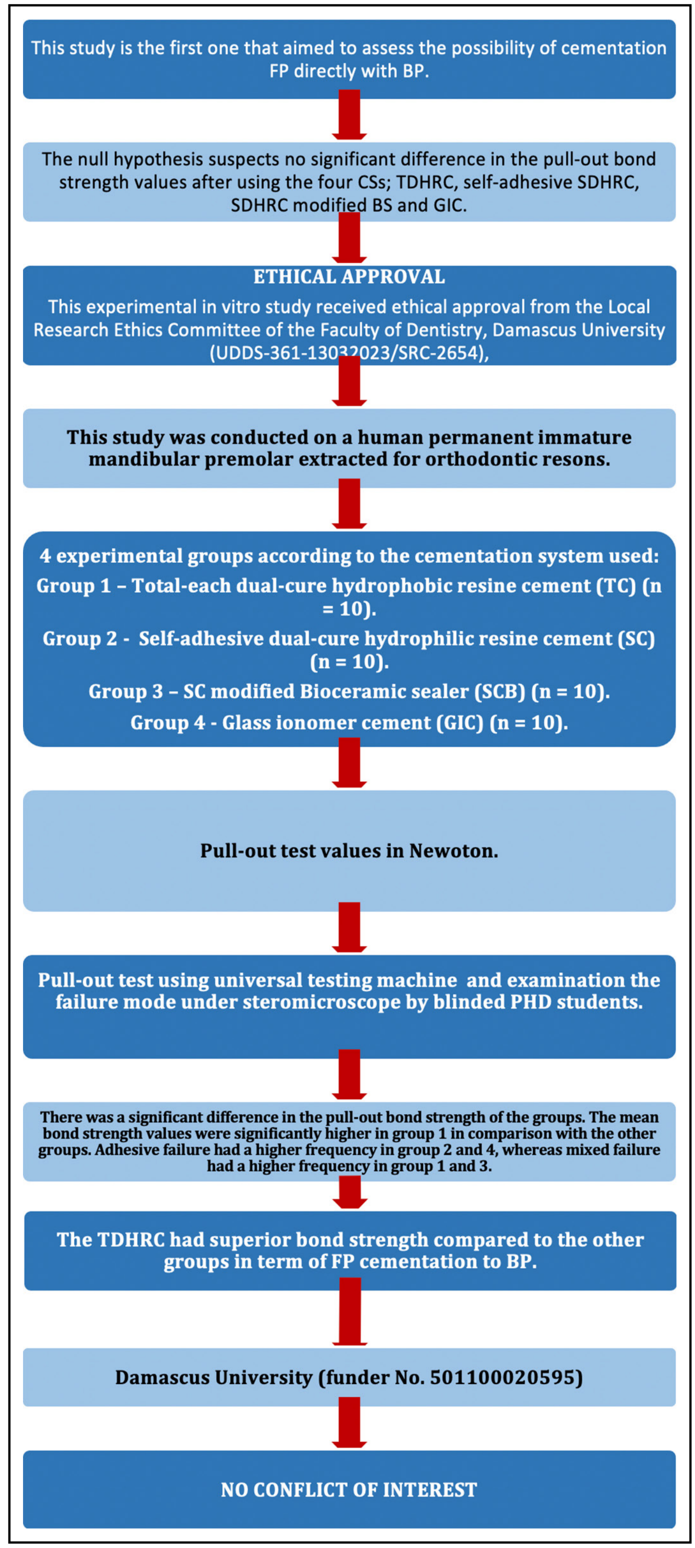

Figure 6. PRILE 2021 flow chart of the presented study

PRILE: Preferred Reporting Items for Laboratory Studies in Endodontology

four groups (p>0.05). Moreover, homogeneity of variance was assessed by using the Levene test, which indicated that variances were homogeneous among groups (p>0.05), so the comparison between groups regarding pull-put bond strength values was performed using the One-way ANOVA test. The pairwise comparisons were performed using Tukey's HSD test. The significance level was set at α=0.05.

TABLE 2. Comparison of pull-out bond strength values between groups

Group	Number	Mean (in Newton)	Standard deviation	Range	p^
TC Group	10	112.4	17.40	90.0–138.0	<0.001
SC Group	10	34	13.10	18.0–60	
SCB Group	10	41.2	12.03	27.0–60.0	
GIC Group	10	29.1	6.92	20.0–39.0	

^: One-way ANOVA test, *: Significant difference. TC: Total-etch dual-cure hydrophobic resin cement, SC: Self-adhesive dual-cure hydrophilic resin cement, SCB: SC modified with a BioCeramic sealer, GIC: Glass Ionomer cement

TABLE 3. Observed failure modes in groups

Failure modes	Groups								Total			
	TC group		SC group		SCB group		GIC group					
	n	%	n	%	n	%	n	%	n	%	n	%
Adhesive												
F1	0	0	2	20	1	10	8	80	11	27.5	30	75
F2	2	20	2	20	2	20	2	20	8	20		
F3	2	20	6	60	3	30	0	0	11	27.5		
Mixed												
F4	4	40	0	0	4	40	0	0	8	20		
Cohesive												
F5	2	20	0	0	0	0	0	0	2	5		

TC: Total-etch dual-cure hydrophobic resin cement, SC: Self-adhesive dual-cure hydrophilic resin cement, SCB: SC modified with a BioCeramic sealer, GIC: Glass Ionomer cement

RESULTS

Figure 6 describes the flow chart of this *in vitro* study.

Pull-out Bond Strength

Table 2 and Figure 7 show the descriptive statistics of pull-out bond strength in the groups, including mean, standard deviation, range, and the One-way ANOVA test result, where there was a significant difference in pull-out bond strength among the groups ($p<0.05$).

The Tukey HSD test was used in the pairwise comparisons and revealed that the mean values of bond strength were significantly higher in the TC group ($\bar{X}$=112.4 N) in comparison with SC, SCB, and GIC groups ($\bar{X}$=34 N, $\bar{X}$=41.2 N, and $\bar{X}$=29.1 N; respectively, $p<0.001$ in each pairwise comparison). Moreover, no difference was found among SC, SCB, and GIC groups ($p>0.005$ in each pairwise comparison).

Failure Mode

Table 3 illustrates the distribution of failure modes across the different groups. In general, adhesive failure (Fig. 8a) was the most prevalent, occurring in 75% of cases, followed by mixed failure (Fig. 8b) at 20% and cohesive failure (Fig. 8c) at 5%. The TC group exhibited 40% mixed failure, 40% adhesive failure,

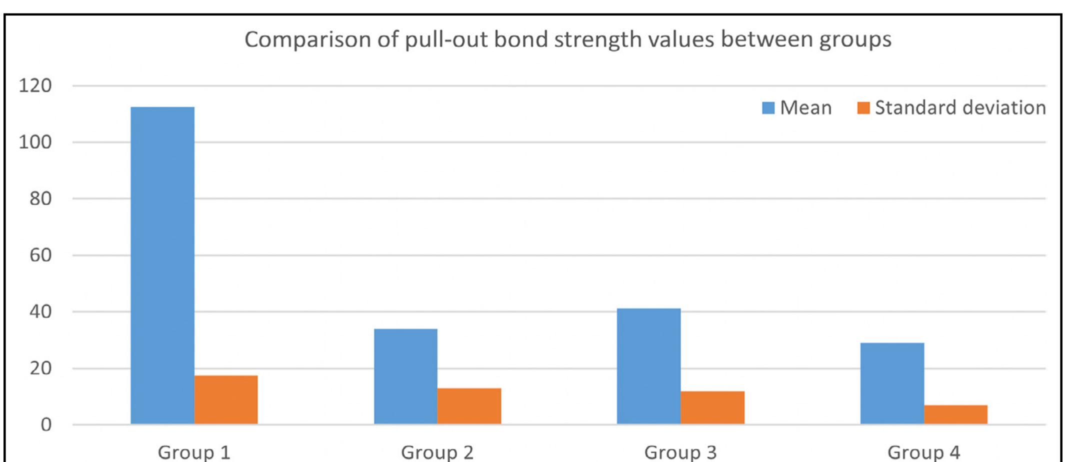

Figure 7. A diagram representing the mean and the standard deviation of pull-out bond strength values between groups

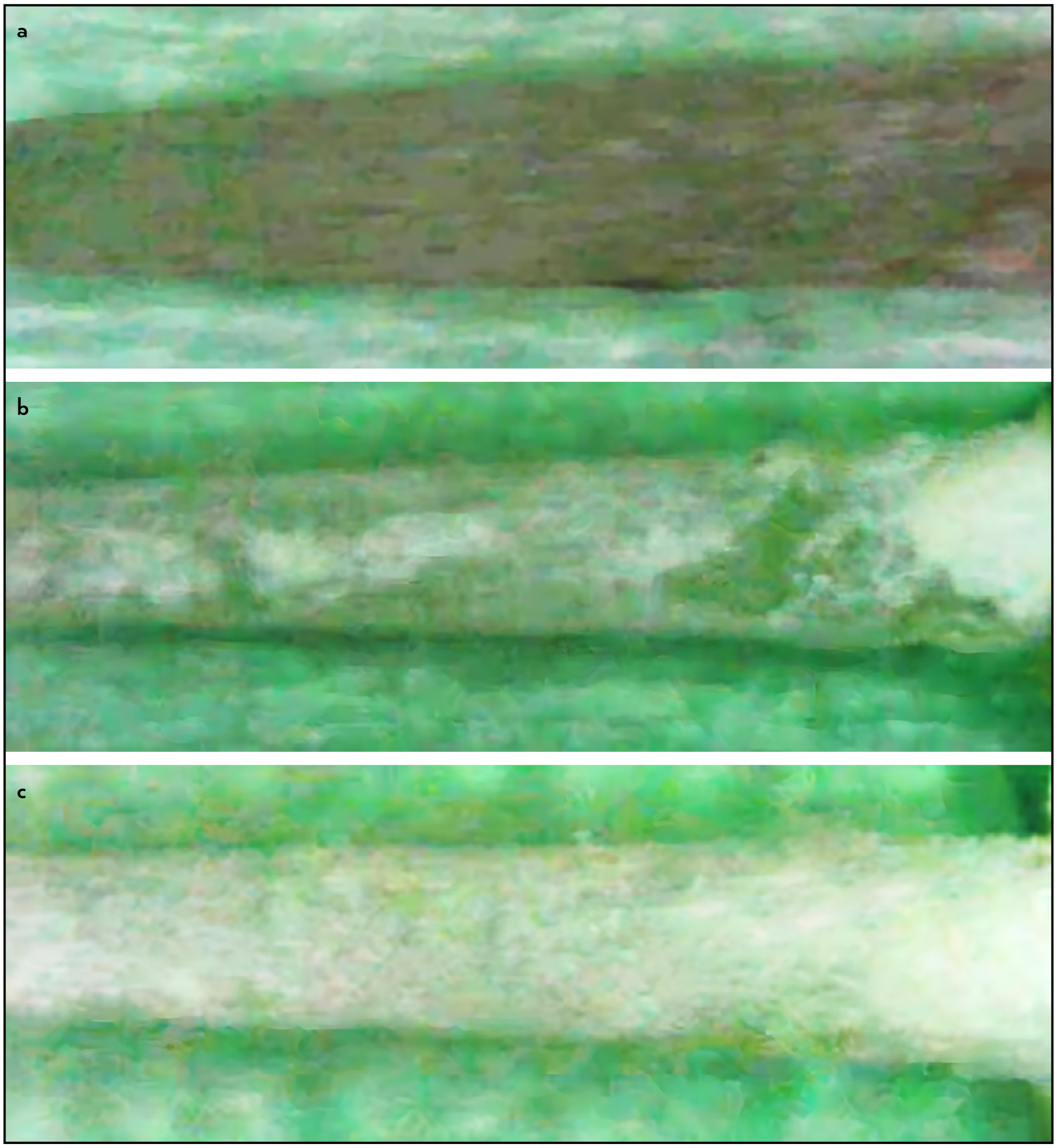

Figure 8. Failure modes under stereomicroscope; (a) adhesive failure, (b) mixed failure, and (c) cohesive failure

and 20% cohesive failure. Both the SC and GIC groups demonstrated 100% adhesive failure. For the SCB group, 60% of the failures were adhesive, and 40% were mixed failures.

DISCUSSION

Specific scenarios, such as immature teeth with open apices, thin truncated cone-shaped canals, and significant coronal tissue loss, may require calcium silicate cement as an obturation to support the fragile canal walls and a fibre post-supported restoration (13). In such cases, the cementation of the fibre post to the calcium silicate cement becomes inevitable. Therefore, it is imperative to evaluate the cementation of calcium silicate cement with fibre posts and identify a cementation system that ensures the most robust connection.

In this study, the employed 3D PRCM models emulate the internal space of full-length, gently prepared immature root canals and exhibit uniform shapes. This model provides an ideal setting for conducting the study under consistent material thickness conditions to enhance the results' accuracy and reliability.

A previous study (20) compared different obturation techniques using BioCeramic Sealer in 3D-printed replicas of C-shaped canals with C1 anatomy. The ability to consistently replicate the complex canal anatomy from the same shape was recognised as a significant strength of this *in-vitro* study, lending credibility to the findings by maintaining canal morphology as a controlled factor rather than a variable.

Various factors affecting the fibre post-cementation, including the post-type, cement utilised, and post-surface treatment, can influence cementation (21). The current study adopted fibre posts, which are glass fibre resin posts with quartz filler, a type known to yield higher bond strength than other variations (21, 22). The silane application enhances the wettability of fibre posts and facilitates a chemical bonding between resin cement and the glass component of the fibre post (21). However, the efficacy of silane alone may be limited in fibre posts, where the epoxy resin matrix prevents silane from effectively reaching the glass fibres (23). To overcome this limitation, HFA was applied to etch the fibre post surface, creating a rough matrix surface that facilitates silane penetration into the glass fibres (24). Notably, combining HFA etching with silane application is one of the most effective methods for surface treatment of fibre posts, significantly enhancing their bond with resin cement (17, 25).

To ensure the optimal effectiveness of the cementation system, a minimal and uniform thickness was adopted across all groups. After the BioCeramic putty's initial hardening and removing the fibre post, the post space was refilled with the cementation system and the fibre post without requiring specialised drills to avoid the risk of cracking the BioCeramic putty. This approach was designed to guarantee the minimal thickness of the cementation system, optimising the cementation of the fibre post (26).

The cementation system was considered the variable factor in the current study as it would directly interact with the new surface, i.e., the BioCeramic putty. Therefore, three commonly used cementation systems were selected for cementing the fibre post with root dentine. Additionally, an attempt was made to modify the HSARC with BioCeramic sealer to explore the potential enhancement of this cement's affinity for BioCeramic putty. Given that both Embrace WetBond cement and BioCeramic sealer are hydrophilic materials, this modification aimed to investigate the impact of their combination on the cementation of the fibre post with the BioCeramic putty.

Previous studies justified using pull-out tests as a more significant methodology to analyse bond strength between fibre posts and root canal dentine. Accordingly, fibre post-supported restorations fail when the whole fibre post pulls out of the post space so that the pull-out test can simulate the clinical failure mode (27, 28). Moreover, it reflects the tensile and shear bond strengths (27). It is worth mentioning that one of the objectives of the studies based on the push-out test is to evaluate the bond of the fibre post with the root dentine in each third, as the distribution and diameter of the dentinal canals differ between the coronal, middle, and apical thirds (29). In contrast, the current study aimed to evaluate the accurate overall bonding strength of the fibre post with a homogeneous material, BioCeramic putty, so this study adopted the pull-out test.

The current study's results rejected the null hypothesis. The TC group showed the highest pull-out bond strength, while the other groups had lower approximate values with no statistically significant differences.

The reason behind the TC superiority may be attributed to two factors; the first one is the use of phosphoric acid, which increases the wettability and surface porosity of calcium silicate cement, causing micro-retention zones during adhesion (30, 31). Moreover, applying phosphoric acid for 20 s is enough to make chemical and structural changes within the calcium silicate cement surface (32). Additionally, the phosphoric acid application seems more effective than acid treatment from hydrophilic acidic monomers of the self-etch adhesive system to make changes in the calcium silicate cement surface (33). The second factor is applying a bonding agent to the BioCeramic putty, which increases the bond strength of the resin cement to the BioCeramic putty (34). The study of Li et al. (18) met these results, where dual cure etch-and-rinse resin cement showed better bonding strength of fibre post to the dentinal root ($\bar{\chi}$=277.5 N) using the pull-out test compared with dual cure self-adhesive resin cement and GIC Fuji I ($\bar{\chi}$=218.6 N, and $\bar{\chi}$=73.2 N; respectively). Although the mean bond strengths in the previous study were more significant (about 2.5 times) than the values found in the current study, due to the difference in the surface nature, the judgment remains for long-term clinical studies to evaluate whether these bond strengths are sufficient. Similarly, Hursh et al. (35) revealed that the shear bond strengths of dual-cure resin cement to BioCeramic putty were lower than those of dual-cure resin cement to dentinal walls.

The decrease in the bond strengths of the fibre posts to the BioCeramic putty using self-adhesive cement can be attributed to two factors; the first one is the absence of the collagen fibrils, with which the monomers of the self-adhesive resin cement are combined in the BioCeramic putty surface, and thus this directly affects the mechanism of action of the self-adhesive resin cement (36), where the bond strength of self-adhesive resin cement is increased with the increasing of collagen fibres content (37, 38). The second factor is related to self-adhesive hydrophilic materials, where the hydrophilic monomers showed lower adhesive characteristics (39). Gao et al. (10) found similar results, where total-etch resin cement showed higher push-out bond strength to dentinal walls than self-etch resin cement. Accordingly, adding BioCeramic sealer to the SC did not significantly improve the bond strength of the fibre post to the BioCeramic putty. However, it did slightly increase the affinity of this cement for the BioCeramic putty, as the current results showed a change in the failure mode, as some mixed failure mode (F4) appeared in this group. In contrast, in the SC group, all failures were adhesion failures (F1, F2, and F3).

Upon revisiting the current study's results and the observed failure modes regarding the second and third groups, where SC was utilised, it is evident that both groups' standard deviation values were relatively high. This value reflects a deficiency in the performance of this cement with the BioCeramic putty, as previously mentioned, primarily attributed to inherent issues with the hydrophilic monomers. Consequently, it may be logically inferred that we should refrain from employing this cement with BioCeramic putty.

The lower bond strength found in the GIC group may be attributed to the lower cohesive strength of GIC Fuji I (18). Moreover, according to the failure modes presented in this group, the GIC was weekly cemented with the fibre post despite being roughened with HFA. On the contrary, this result differed from Lorenzetti et al. (9), as it was found that the GIC had higher bond strength values than total-etch resin cement and was similar to the self-adhesive resin cement during fibre post-cementation to the dentinal surface. The main reason for this difference is that Lorenzetti used chemically activated GIC (GC Gold Label 1 Luting & Lining), while in the current study, GIC Fuji I was used.

Returning to the failure modes evaluation, cohesive failure appeared with the TC group, which showed the highest bond strength. On the other hand, the adhesive failure correlated with other groups that showed the lowest bond strength, which was met with a previous review (7).

A novel concept for cementing a fibre post to BioCeramic putty involves introducing the pre-fabricated bioroot inlay (PBI). The process begins with an impression of the immature permanent canal, followed by the design and 3D PRCM. Subsequently, a calcium silicate cement, a suitable cementation system, and a fibre post are applied within the PRCM using the previously described method. The PRCM is then removed to obtain the PBI. Through the fibre post, the PBI can be easily carried, tried, and placed with an appropriate sealer inside the immature canal. Following this, crowns can be directly restored with the presence of the fibre post. This technique allows for achieving a tight apical seal, excellent adaptation of the fibre post into the irregular wide canals of immature teeth, and a solid foundation for coronal restoration in a single step.

This innovative approach has clinical implications, particularly in restoring immature permanents with irregular root canal sections that may not be suitable for round-section fibre posts. Implementing this technique could alleviate the limitations of restoring immature permanent teeth using fibre posts. Further investigation is warranted, particularly in the context of apical barrier procedures, to assess its support for the weak dentine structures of immature permanent teeth *in vitro* and to gauge its durability through clinical and radiographical success assessments.

The main limitation of this study was the inability to use a scanning electron microscope to observe cross-sections of the bond surfaces between the utilised cement and the BioCeramic putty and the inability to analyse finite elements of stress distribution to obtain more details about the cementation of fibre post to BioCeramic putty.

Further *in-vitro* investigations are required in terms of other cementation systems. Moreover, this study focused on selecting the appropriate cementation system for cementing fibre posts with BioCramic putty. It would be interesting to conduct further studies using standardised cementation systems to evaluate the cementation of fibre posts with other surfaces, such as comparing dentine as a control group with other calcium silicate cement surfaces like BioCeramic putty, Biodentine or MTA. Additionally, it is possible to select another sample of immature permanent teeth, prepare them to have uniform internal spaces and canal sizes, and then conduct the same study to investigate failure locations. This sample could include failures at the interface between the fibre post and the cement, between the cement and the BioCeramic, between the BioCeramic and the root dentine, or compound failures involving combinations of these modes.

Finally, further long-term clinical investigations of specific immature teeth that require the cementation of fibre posts to calcium silicate cement may help determine whether the obtained bonding strength is sufficient.

CONCLUSION

Despite the above-mentioned limitation of this *in-vitro* study, it can be revealed that the TC (Nexcore) had superior bond strength using a pull-out test compared to SC (Wetbond), SCB, and GIC (Fuji I) as cementation systems of fibre post to BioCeramic putty. Moreover, adhesive failure was more frequent in all groups than in mixed and cohesive failure.

Disclosures

Ethics Committee Approval: The study was approved by the Damascus University's Local Research Ethics Committee (no: UDDS-361-13032023/SRC-2654, date: 13/03/2023).

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