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Effect of resin cement, aging process and root level on the bond strength of the resin-fiber posts

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I certify that I am the sole author of this thesis, and that any assistance I received in its preparation has been fully acknowledged and disclosed in the thesis. I have cited any sources from which I used ideas, data, or words, and labeled as quotations any directly quoted phrases or passages, as well as providing proper documentation and citations. This thesis was prepared by me, specifically for the M.Sc.D. degree and for this assignment.

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EFFECT OF RESIN CEMENT, AGING PROCESS AND ROOT LEVEL ON THE BOND STRENGTH OF THE RESIN-FIBER POSTS

A Thesis Presented
By
KHALID SALMAN ALMULHIM, B.D.S.

Submitted to the College of Dental Medicine of Nova Southeastern University in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE IN DENTISTRY

June 2014

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Dedication

To my parents, Mr. Salman Almulhim and Mrs. Badriah Almulhim, thank you for your unconditional support with my studies. With your encouragement and guidance I have been able to accomplish my goals. To my family, my lovely daughter Rose, and my beloved wife Noorah Almulhim, for being there for me throughout the entire program. Thank you for believing in me. I could not have accomplished this without you.

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ABSTRACT

EFFECT OF RESIN CEMENT, AGING PROCESS AND ROOT LEVEL ON THE BOND STRENGTH OF THE RESIN-FIBER POSTS

DEGREE DATE: June 16th, 2014

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Background. Little is known about the long-term clinical bonding effectiveness of the Fiber-reinforced composite (FRC) posts cemented with self-etch adhesive systems. Bond stability and longevity of the cemented post are adversely affected by physical and chemical factors over time, such as expansion and contraction stresses caused by thermal changes and occlusal load. This clinical condition can be simulated *in vitro* by thermocyclic loading; and bonding effectiveness can be evaluated by applying the micropush out test. Therefore, more *in vitro* studies are needed to evaluate the bond strength of the fiber posts cemented with different resin cement systems after simulating the artificial aging induced by thermocycling. The aim of this study was to compare the microtensile bond strength of two different resin cement systems (total etch, and self-etch resin cement system) used for cementation of fiber reinforced composite posts in three different aging periods using thermocycling. **Methods**. Following IRB approval, sixty freshly extracted bicuspid single rooted natural teeth were endodontically treated, and the post-spaces were prepared to receive a fiber-post cemented with either a total etch resin cement (Rely-X Ultimate) or with a self-etch resin cement (Rely-X Unicem). No thermocycling, 20,000 and 40,000 cycles was used to age the specimens. Teeth were randomly allocated into six different groups: G1 – Control: Rely-X Ultimate cement with no thermocycling. G2: Rely-X Ultimate cement with 20,000 thermocycling. G3: Rely-X Ultimate cement with 40,000 thermocycling. G4: Rely-X Unicem cement. G5: Rely-X Unicem cement. G6: Rely-X Unicem cement. Microtensile bond strength determined using a micro-push out test on a universal testing machine (MTS). Additionally, the failure mode of each specimen was observed under a stereomicroscope (Olympus) at 40x magnification. Finally, one representative sample was randomly selected from each of the five failure modes for scanning electron microscope (SEM) examination of the surface morphology in order to obtain SEM images of the failure patterns at 29-70x magnifications. Statistical analysis: Nested general linear and generalized linear model was created to look for statistical significance. Level of significance was set at $P < 0.05$. **Results**. No significant differences were found on the bond strength between the two types of resin cement systems (total etch and self-etch). Regarding the thermocycling effect, the bond strengths of the group of

40,000 cycles was significantly lower than the 20,000 cycle group. In addition, the bond strengths of the specimens collected from the coronal third of the root were significantly lower than the specimens from the apical third. A Fisher's Exact test was applied to evaluate the failure mode differences, and showed statistically significant differences between the groups. **Conclusions**. The bond strength to the root canal dentin did not vary with the type of resin cement systems (total-etch vs self-etch). The microtensile bond strength values of FRC posts were significantly affected by increasing the thermocycling, and were significantly different among the different longitudinal levels of the root canal.

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Chapter 1

Introduction

1.1 Dental Posts:

1.1.1 Overview and Classifications:

Retaining the coronal restoration in endodontically treated teeth is the primary purpose of the dental post.[1] Currently, there are two types of posts: the custom-made cast post, and the prefabricated post. The cast metal posts have been traditionally used for years to restore endodontically treated teeth. It can be made of gold, or non-precious alloy, and usually has a tapered, smooth sided shape, which helps to conserve the tooth structure, and reduce the possibility of post-perforation.[2] The main disadvantage of this type is that it exhibits the least amount of retention. A classic retrospective study by Sorensen and Martinoff (1984),[3] evaluated 1273 endodontically treated teeth, and 19.2% of the samples were restored with cast post and cores; 12.7% of the posts failed, 36% of these failures were due to the loss of retention. In a more recent study, Weine and collaborators,[4] using the ferrule effect, treated 138 teeth with cast post and cores, and retrospectively evaluated them for 10 years. A failure rate of 6.5% was found, with at cause mainly due to debonding. Another disadvantage of the cast posts is the more time involved in its laboratory fabrication, which can also lead to additional laboratory costs.[2] In addition, a poorly seated cast post may be noticed because of inadequate laboratory casting techniques.[3] The prefabricated posts can be made from a number of materials, consisting mainly of: metallic (stainless steel, nickel chromium, and titanium alloy), non-metallic tooth colored posts (ceramic, carbon-fiber, fiber-reinforced composite posts).[1]

The main advantages of FRC posts are: the more surface roughness that can be added on the post, (such as post serrations) the contact surface area between the post and the root dentin, and the decreased costs and time required.[4] The prefabricated posts can be tapered, which is self venting, allowing the excess of the cement to flow out. On the other hand, the parallel-sided post does not allow the cement to escape easily as the tapered type, allowing the hydrostatic pressure to prevent the post from seating.[2]

1.2 Fiber Reinforced Composite Post (FRC):

1.2.1 Overview:

In 1990, Duret and colleagues,[5] described the first non-metallic material to fabricate a fiber post, by using the carbon-fiber reinforcement principle; however in order to improve the esthetic outcomes, tooth-colored fiber posts were introduced, having composite materials as its main component. The FRC post systems were introduced in 1997,[6] with the intention to avoid root fractures because its modulus of elasticity was close to the dentin substrate.[7] Another esthetic fiber post is the silica-fiber post, which is translucent and more tooth colored; these posts are also called glass-fiber and quartz-fiber posts.[8]

1.2.2 Advantages and Disadvantages:

Placement of the FRC post has the ability to reduce the incidence of non-retrievable root fracture when compared to the conventional cast post.[9] Conversely, higher coronal failures occurred with the use of fiber posts, which is still more favorable than a root fracture.[10] Moreover, the stress distribution and the fracture patterns were more favorable in teeth restored with fiber posts.[11] Nam and coworkers, [12] found that endodontically treated premolars have significantly higher fracture resistance when they were restored with fiber posts. Also, Gesi and researchers, [13] found that fiber posts were easier to retrieve in comparison with the metallic post when endodontic treatment was indicated. Also, the development of FRC posts fulfilled the esthetic requirements that were lacking by the older metallic prefabricated and cast post systems. Several prospective and retrospective studies were performed to evaluate the longevity and the survival rate of the fiber post systems. A long-term retrospective study of clinical performance of fiber posts recorded a 7-11% failure rate, where 48.08% of the failures were related to bonding procedures (post debonding and crown dislodgment).[14] Malferrari and colleagues, [15] observed 1.7% of fiber posts debonded within 30 months. On the other hand, Piovesan and colleagues, [16] evaluated 97 months of clinical service and found that fiber post fracture was the most prevalent reason of failure. Grandini and researchers,[17] observed periapical lesion failures in teeth restored with fiber posts over 30 months of clinical service in a range of 4%.

1.2.3 The Mechanical Properties:

Generally, post fiber reinforcement has been described to increase the modulus of elasticity and toughness on root canal treated teeth.[18] The mechanical properties of FRC posts are highly affected by many factors such as: (1) the type, architecture (unidirectional, bidirectional, or woven), and geometric orientation of the fibers, (2) the composition of the resin matrix, (3) the ratio of fiber to resin matrix; and (4) the adhesion between the fibers and the resin matrix.[7] Moreover, the fatigue properties are highly affected by the degradation in an aqueous environment, which might affect the matrix-fiber adhesion and reduce the flexural strength.[19] The resin matrix used in FRC posts is either epoxy or methacrylate resin. Semi-interpenetrating polymer network (IPN) can also be used as a resin matrix to enhance the adhesion between FRC posts and resin cements.[1]

1.3 Resin Cement Systems:

1.3.1 Overview:

Resin cements are used in many clinical situations; its primary function is to fill the void between an indirect restoration (crown or post) and tooth retaining the restoration in place to prevent any dislodgment during function.[20] There are various types of resin cements with specific characteristics that match the different clinical situations. Among the materials available as resin cements, it can be found: resin, glass-ionomer, resin-modified glass-ionomer, polycarboxylate, zinc phosphate, zinc oxide eugenol, and zinc oxide non-eugenol cements. The incorrect election and manipulation of the specific resin cement could have an important impact on the restoration's longevity.[20] The methacrylate-based resin cements were introduced in the early 1950's with several shortcomings; its only superior characteristic was the low solubility.[21] It can be said that modern resin cements are an important part of today's dental practice, mainly because of their versatility, high compressive and tensile strengths, low solubility, and their favorable esthetic characteristics. Yet, there are still major shortcomings including: the removal of the cement excess, the retrieval of the failed restorations, technique sensitivity, and the high cost associated.[22]

1.3.2 Classifications and Comparisons:

Resin cements are used in specific clinical situations, such as post cementation, ceramic restorations, indirect composite restorations, veneers, metal as well as metal-ceramic restorations that need extra retention.[23] The resin cements can be classified according to the mechanism of matrix formation: (1) self or auto cured; (2) light cured; and (3) dual cured. Based on the bonding procedure, it can be classified into: (1) total etch three-step resin; (2) total etch two-step resin; (3) self-etch resin; and (4) dual-cured resin cement systems.[24] The total etch or self-etch resin cement systems used during the cementation of the fiber reinforced composite post should have an optimum adhesion between the resin cement and the dentin lining the canal space.[20]

Due to their technique sensitivity, care must be taken with the handling of the adhesive cement in order to achieve accurate bonding. Therefore, total etch adhesive systems are more complex and technique sensitive compared to the self-etch adhesive systems.[24] Findings on the bonding performance of self-etch adhesive cements are not consistent due to the limited number of laboratory studies carried out using this type of resin cement.[25]

1.4 Adhesion:

1.4.1 Overview and Controversies:

Bond stability has shown to be one of the concerns of the self-etch adhesive cements. Some authors reported an incremental increase in the retentive strength of the posts cemented with self-etch resin cements.[26] Conversely, others found a significant reduction in retention and an increase in the interfacial nano-leakage.[27] On the other hand, no significant change in the retention and seal was observed for the etch-and-rinse adhesive system tested as a control. A literature review of *in vitro* studies by Radovic and colleagues, [28] concluded that when using self-etch resin cement, the adhesion to dentin and various restorative materials is satisfactory and comparable to other multistep resin cements; while adhesion to enamel appears to be a weak link in their bonding properties. In order to clarify these aspects, further investigation of the adhesion durability between dentin, resin cement and the post by long-term testing of the bond strength to the fiber posts cemented with self-etch cements is desirable.

1.5 Different Root Levels:

1.5.1 Overview:

Bond strength variations can be noticed when measured on differentl longitudinal levels of the root canal. Accessory root canals, areas of resorption, attached or embedded free pulp stones can all be found in the apical portion of the root canal.[29] Moreover, the dentin histology is highly heterogeneous, and present high variations in the number of dentinal tubules, irregular structure of secondary dentin, and presence of a cementum-like tissue on the root canal wall. All these variations and irregularities in the structure of the root canal dentin could affect the penetration of the adhesives into the dentinal tubules.[29]

1.5.2 Controversies:

Literature is lacking on reporting the effects on any part of the root canal when testing the bond strength.[30, 31] Bitter and researchers,[26] denote an increase in the bond strength in the apical portion of the root. In a more recent study, Chang and collaborators,[32] reported a significant decrease in the bond strength at the middle and apical level of the root. Moreover, Calixto and colleagues,[33] reported that the self-etch resin cements exhibited lower bond strength on the apical third of the root when compared to the total etch resin cement. In accordance, Ferrari in 2000[34] found that the dentin surface area available for bonding increased by 202% after etching coronally, 156% in the middle third, and 113% in the apical third of the root dentin.

1.6 Bond Strength and Test Methods:

1.6.1 Overview and Comparison:

To measure the bond strength of adhesive systems, a variety of methods are currently available, including microtensile, shear, pull-out and push-out tests. The micropush out bond strength test first used in 1996 to evaluate bonding to root canal dentin is believed to provide a better estimation of the actual bonding effectiveness than a conventional shear bond strength test.[35] This is because by using a micropush out test, failure occurs parallel to the post-cement-dentin interface, which resembles the clinical condition.[36] In addition, the micropush out test has been considered to be more accurate than the microtensile test for testing bonded posts because of the high number of premature failures occurring during specimen preparation.[31]

The pull-out tests are considered one of the reliable techniques to measure the bond strength between fiber post and root dentin. It shows better stress distribution than any other tests; however, a large sample size will be needed in order to test the hypothesis, which makes it more costly and thus less popular.[37]

1.6.2 Parameters:

There are some parameters that can influence the bond strength test results, such as the geometry of the specimens. The hour-glass shape of specimens used in the microtensile test, which is one of the reasons of the premature failures occurred during testing, is different from the slice or disc shape of specimens used in the micropush out test.[38] These variations in the experimental design make it difficult to compare the different types of tests, and might show contradictory results.[39] Other variables are size of the bonded surface area, loading configuration, and type of composite, which can all give rise to different stress distributions at the bonded interface.

1.7 Thermocycling:

1.7.1 Overview:

Among the laboratory tests that are used to evaluate the long-term behavior of the cemented posts, thermocycling represents a widely used laboratory aging methodology to simulate the thermal changes and aging of the materials in the oral cavity. It involves chemical and mechanical degradation pathways with hot water possibly accelerating the hydrolysis of the adhesive layer.[40] Also, the repetitive contraction/expansion stresses are generated on the tooth/restoration interface due to the higher thermal coefficient of the restorative material compared to the tooth structure. This might lead to crack creation then propagation, and changing the gap dimension.[40]

1.7.2 Number of Cycles:

According to the International Organization of Standardization,[41] applying 500 thermocycles in water between 5 ^{o}C to 55 ^{o}C is generally considered the essential test for aging the dental materials. In 2001, researchers conducted a meta-analysis summarizing the data published between 1992 and 1996, and reported that there is no significant effect of thermocycling on the bond strength.[42] Most of the included studies in that meta-analysis were carried out following the ISO standard of 500 cycles. However, previous studies[27,43,44] concluded that 500 cycles does not to simulate the intraoral aging. De Munck and coworkers,[40] reported that 10,000 cycles will be a reasonable approximation of 1 year of clinical service. In 1999, Gale and colleagues,[45] published a list of recommendations for the thermocycling simulation, and suggested applying 10,000 cycles to represent an equivalent of service of one year.

1.8 Purpose of the Study:

Little is known about the long-term clinical bonding effectiveness of FRC posts cemented with self-etch adhesive system. Bond stability and longevity of the cemented post are adversely affected by the physical and chemical factors over time, such as expansion and contraction stresses caused by thermal changes and occlusal load. This clinical condition can try to be replicated *in vitro* by thermocycling loading, and bonding effectiveness can be evaluated by applying the micropush out test.[27] Therefore, more *in vitro* studies are needed to evaluate the bond strength of the fiber posts cemented with different cement strategies after simulating the artificial aging induced by thermocycling. The aim of the present study was to compare the microtensile bond strength of two different resin cement systems (total etch, and self-etch) used for cementation of fiber reinforced composite posts in three different aging periods using thermocycling.

1.9 Specific Aims and Hypothesis:

- To evaluate and compare the microtensile bond strength of two different resin cement systems (total etch, and self-etch) used for cementing fiber reinforced composite (FRC) posts under thermocycling.
- To evaluate and compare the microtensile bond strength of resin cement systems used for cementing FRC posts under different periods of thermocycling (0, 20,000 and 40,000).
- To evaluate and compare the microtensile bond strength of the resin cement system used for cementing FRC posts under thermocycling at three different levels of the root (coronal, middle, and apical).

Null Hypothesis:

- There is no difference in the microtensile bond strength of the two different resin cement systems used for cementing FRC posts under thermocycling.
- There is no difference in the microtensile bond strength of the two different resin cement systems when measured in three different aging periods.
- There is no difference in the microtensile bond strength of the two different resin cement systems in three different root levels (coronal, middle, and apical).

1.10 Location of study:

The design, preparation and data collection of the study took place at:

Bioscience Research Center, Room 7356
Nova Southeastern University
Health Professions Division
College of Dental Medicine
3200 South University Drive
Fort Lauderdale, Florida 33328-2018

Chapter 2

Materials and Methods

2.1 Experimental Design:

2.1.1 Pilot Study:

A pilot study was conducted using one sample for each study group. All equipment and techniques were reviewed and the operator was calibrated to be familiar with the system.

2.1.2 Sample Size Calculation:

The G Power Statistics Software was used to calculate the sample size. A power analysis was conducted using data from Radovic I et al.[46] After IRB approval, forty two sound human premolars were divided into six groups. The mean of the microtensile strength measurement in the control group (etch-and-rinse adhesive resin cement group) was 12.70, the standard deviation was 4.33. The mean of the same measurement in the test group (self-etch adhesive resin cement group) with the highest significance was 8.68, and its standard deviation was 5.29. After using the two-way ANOVA option in G Power software, the total sample size for each group was 8.

2.1.3 Sample Preparation:

Sixty extracted human premolars with a single root canal were selected for the study cleaned and kept in distilled water. The selection criteria for the extracted teeth was the similarity of the external morphology of the root (conical in shape) and fully developed apices; the teeth were free of caries and fractures, absence of previous endodontic treatments or crowns, and used within 1 year of extraction.[46] The crown of each tooth was removed by means of low speed diamond saw (Isomet, Bueher, Lake Buff, IL, USA) 2mm above the cemento-enamel junction under water cooling. Pulp tissue was removed with a barber broach. The working lengths were measured by subtracting 1 mm from the length at which the tips of #10 or # 15 K-files (Dentsply Tulsa Dental, Tulsa, OK, USA) were visible at the apical foramina. All the root canals were instrumented by the same operator. Canals were cleaned and shaped by using rotary instruments (ProTaper system, Dentsply Tulsa Dental, Tulsa, OK, USA) in which the sequence of the rotary files was: SX, S1, S2, F1, F2, F3. A 1 ml 6% solution (Clorox, Oakland, CA, USA) was used as the irrigation solution. Final irrigation was 17% EDTA for 1 minute with a 27-gauge needle followed by 6% sodium hypochlorite for 1 minute with a 27-gauge needle.[47] Canals were obturated utilizing a warm vertical technique[48] using Protaper F3 gutta percha cones (Dentsply DeTrey Gmbh, Konstanz, Germany) and sealer AH-Plus (Dentsply DeTrey Gmbh, Konstanz, Germany).

2.1.4 Post Space Preparation and Cementation:

The endodontically treated roots were stored in distilled water in an incubator set at 37 degrees C until use. The post space was prepared to a length of 10mm. In order to reproduce a clinical situation, the gutta-percha removal procedure was performed and quantified according with De Mello's work.[49] The methodology consists of gutta-percha removal until reaching the determined working length of post space (10mm). Radiographic images were taken to reveal the remaining gutta-percha; and if there was evidence of gutta-percha material in the prepared post space, the root canal was instrumented until further examination revealed no radiopaque material. In addition, a Global Endodontic Microscope (Global Surgical Corporation, St. Louis, MO, USA) at 2.0X magnification power was utilized to inspect for gutta-percha/sealer remnants to the extent permitted by the microscope. Two different types of resin cements were used in this study, a total etch resin cement (Rely-X Ultimate, 3M ESPE, Seefeld, Germany) and a self-etch resin cement (Rely-X Unicem, 3M ESPE, Seefeld, Germany). The components of each type of luting cement are listed in table 1. Size 2 (red, 1.6mm diameter) fiber posts (RelyX fiber post, 3M ESPE, Germany) were cemented according to the manufacturer instructions (table 2).

2.2 Experimental Groups:

The teeth were randomly divided into six groups *(n=10)* according to the luting cement used for fiber post cementation and number of thermocycles.

The thermocycling procedure between 5-55°C in deionized water with a 30 second dwell time was performed for 20,000 cycles (for groups 2 and 5), and for 40,000 cycles (for groups 3 and 6).[27]

Study Groups (table 3):

Group 1: Total etch adhesive cement system (Rely-X Ultimate) - No thermocycling (Control group)

Group 2: Total etch adhesive cement system– 20,000 thermocycles

Group 3: Total etch adhesive cement system– 40,000 thermocycles

Group 4: Self-etch adhesive cement system (Rely-X Unicem) – No thermocycling

Group 5: Self-etch adhesive cement system - 20,000 thermocycles

Group 6: Self-etch adhesive cement system - 40,000 thermocycles

2.3 Micro Push-out Test:

The roots were sectioned into a series of 1mm thick slices, perpendicular to the tooth axis from the apical to the coronal direction using a slow speed diamond saw (Isomet, Bueher, Lake Buff, IL, USA) under water-cooling (Fig. 1). A mark was placed on the apical aspect of the root before sectioning each slice (Fig. 2 and 3). Six 1.0-mm thick slices were obtained from each root (Fig. 4). A digital caliper was used to measure the thickness of each slice (Fig. 5). Two slices were obtained from each third of each root (coronal, middle, and apical).

Ten teeth were used per group, thus 60 slices were obtained per group. The slice was positioned on the universal testing machine (MTS) (Fig. 6) with the apical aspect facing a custom-made fixture, which consisted of a 1-mm diameter cylindrical plunger (Fig. 7). A shear stress was applied on the slice from its apical aspect to avoid any movement of the post due to the taper of the canal (Fig. 8). The push-out load was applied at a crosshead speed of 0.5mm/min in an apical-coronal direction until bond failure occured (Fig. 9 and 10).

Microtensile bond strength was calculated for each specimen by using the following formula:

$$Debond\ stress = \frac{Debonding\ force\ (N)}{A}$$

$$\boxed{A = \pi(R + r)\,[(H^2 + (R - r)^2]^{0.5}}$$

Where: A=area of the post-dentin surface.[25]

π: 3.14 (constant)

R: coronal radius

r: apical radius

H: thickness of the slice in millimeters.

2.4 Fracture Analysis:

After testing the bond strengths, the failure mode of each debonded specimen was analyzed under a stereomicroscope (Olympus, Tokyo, Japan) at 40x magnification. The samples were rinsed in 95% alcohol solution (Walgreens Isopropyl Alcohol, Walgreen, USA) then air-dried. The failure modes were classified into the following five categories:

1. Adhesive failure between post and resin cement (Fig. 11).
2. Adhesive failure between dentin and resin cement (Fig. 12).
3. Cohesive failure within dentin (Fig. 13).
4. Cohesive failure within post (Fig. 14).
5. Mixed failure - combination of failure that occurred both at the interface between dentin/resin cement and post/resin cement (Fig. 15 and 16).

2.5 Scanning Electron Microscopy (SEM) Analysis:

One representative sample was randomly selected from each of the five failure modes for scanning electron microscope (SEM) examination of the surface morphology in order to obtain SEM images of the failure patterns. The specimens were prepared and the interface between dentin, resin cement and fiber post were analyzed.

The failure modes were classified into the following five categories:

1. Adhesive failure between post and resin cement (Fig. 17).
2. Adhesive failure between dentin and resin cement (Fig. 18).
3. Cohesive failure within dentin (Fig. 19).
4. Cohesive failure within post (Fig. 20).
5. Mixed failure - combination of failure that occurred both at the interface between dentin/resin cement and post/resin cement (Fig. 21).

2.6 Data and Statistical Analysis:

To look for differences between groups with microtensile bond strength, a nested general linear model was created. All post hoc tests were carried out using Tukey test with a probability level set at $\alpha=0.05$ for statistical significance.

To examine differences between groups for fracture analysis, a nested generalized linear model was created. All post hoc tests were carried out using a Bonferroni adjustment with a probability level set at $\alpha=0.05$ for statistical significance.

For both models the independent variables were: (1) the type of resin cement systems (total etch, and self-etch), (2) the three different aging periods (0, 20,000 and

40,000 thermocycles), and (3) the three different levels of the root (coronal, middle, and apical).

Chapter 3

Results

3.1 Microtensile Bond Strength:

Descriptive statistical analysis means and standard deviations of the microtensile bond strength for each group are given in three different tables according to the root level (table 4,5 and 6). Robust general linear models were created and tested. The main effects were type of cement (total etch vs. Self etch) and thermocycling (no thermocycling, 20,000 and 40,000), while the interaction was type of cement by thermocycling. Results are as follows:

3.1.1 Apical Findings (Table 4):

No significant effect for type of cement ($p = 0.850$)

No significant effect for thermocycling ($p = 0.205$)

No significant interaction effect ($p = 0.071$)

3.1.2 Middle Findings (Table 5):

No significant effect for type of cement ($p = 0. 667$)

No significant effect for thermocycling ($p = 0. 193$)

No significant interaction effect ($p = 0.212$)

3.1.3 Coronal Findings (Table 6 and 7):

No significant effect for type of cement (p = 0.779)

A significant effect for thermocycling (p = 0.024) was noticed. Results showed that 40,000 thermocycles had a lower stress threshold than 20,000 thermocycles (mean difference = -2.14)[95%CI (-4.09 to -0.19)]

No significant interaction effect (p = 0.161)

To compare between all groups regardless of the root levels, we tested the assumptions for the random-effects by general linear models. The data met the assumptions for normality but not for equal variance. So a clustered-robust general linear model was conducted and created. The main effects were type of cement (total etch vs. Self etch), thermocycling (No thermocycling, 20,000 and 40,000), and tooth section (apical, middle and coronal). Linear contrasts and pairwise comparisons using a Bonferroni adjustment were used to compare group differences. Results are shown in tables 8,9 and 10. Significant differences were found in regards to the thermocycling effect (between the 40,000 and the 20,000 groups), and also in regards to the root level (between the coronal and the apical).

3.2 Failure Mode:

For evaluating the failure mode differences between groups, a Fisher's Exact test was created.

3.2.1 Apical Findings (Table 11):

A significant difference was found. Pearson chi2(20) = 50.3160 Pr = 0.000. The failure mode category 1 was significantly higher in the total etch groups 1,2 and 3 than the self etch groups 4,5 and 6. The failure mode category 2 was significantly higher in the self etch groups than the total etch groups.

3.2.2 Middle Findings (Table 12):

A significant difference was found. Pearson chi2(20) = 39.7816 Pr = 0.005. The failure mode category 1 was significantly higher in the total etch group 3 than the other failure modes. The failure mode category 5 (mixed failure) was significantly higher in the groups 1,5 and 6 than the other failure modes.

3.2.3 Coronal Findings (Table 13):

No significant difference was found, Pearson chi2(20) = 25.1506 Pr = 0.196.

Chapter 4

Discussion

This study evaluated and compared the bond strength of two different types of cements used to cement the FRC posts using the push out test. The micro push-out test is considered a reliable method to evaluate the different variables that can affect the retention of the post.[38] A shear stress, at the cemento-dentinal interface and the cement-post interface, is expected after the push-out test, which produce less premature failures compared to the microtensile technique.[50] Unlike the other types of tests, the micro push-out test has a higher ability to realistically record low levels of bond strength, which decrease the premature failures and limit the data variations. Some authors fault the original push-out test,[51] and question the ability to record the bond strength accurately due to the highly non-uniform stress distribution during the loading. However, this limitation was overcome by the use of the micro push-out test, which included loading thinner, 1mm thick specimens, instead of loading thicker, more non-uniform ones. Finally, the micro push-out test enabled to evaluate the differences of the bond strength in different regions inside the root canal.

The two different resin cements were selected because of the different conditioning methods (total etch and self etch). Moreover, the RelyX Unicem was considered one of the most tested resin cements in the previous studies,[50] while little information is available in literature about the RelyX Ultimate. Previous studies clarified that both types of resin cements can obtain a good adhesion to the root dentin, but revealed some controversial results. The first null hypothesis was accepted, as the bond strength did not vary with the type of resin cement. This is in agreement with the previous study by Mazzoni and colleagues,[27] who found that the initial bond strength values of both total etch and self etch groups before thermocycling were not significantly different. Conversely, other studies concluded that the adhesion achieved after applying the phosphoric acid etching is stronger than just using the self-etch resin cement. [52] On the other hand, Bitter and collaborators,[26] reported higher push-out bond strength of the RelyX Unicem compared with other resin cements, including the total etch cements. The process of demineralization of the root canal dentin of both the phosphoric acid in RelyX Ultimate, and the methacrylated phosphoric esters in RelyX Unicem, did not show any significant effect on the bond strength. Tay and colleagues,[53] found that the thickness of the smear layer did not adversely affect the adhesion capacity of the self-etch adhesive systems. Another factor that was thought to affect the adhesive capacity is the hybrid layer. Some authors reported limited infiltration of some self-adhesive resin cements into the root dentin, resulting in the lack of hybrid layer creation.[54] This lack of hybrid layer, together with the high viscosity of the cement, might decrease the bond strength of the selected self-etch resin cements.[52] Other factors that could decrease the bond strength to the root dentin include the non-uniform adaptation of the cement and an incomplete polymerization. Therefore, the lower bond strength values will be more obvious in the deepest regions of the root (more apical than coronal). Tay and colleagues,[55] evaluated the permeation of resin into different types of dentin, and found that the control of moisture after the application and removal of phosphoric acid, as well as the incomplete infiltration of the resin into dentin, significantly affect the bond strength. However, in the present study, a significant difference was found between the bond strengths on the coronal compared to the apical regions. The specimens taken from the coronal third of the root had lower bond strengths compared to the apical third regardless of the type of cement used, which is in agreement with other authors[26, 56] who concluded that the bond strength to root canal dentin is more related to the area of solid dentin than the density of dentinal tubules. This finding can also be explained due to the easier accessibility of water from the coronal level of the root, since no coronal restorations were performed in the present study. Another factor that might affect the bond strength is the configuration (C)-factor (ratio of bonded to unbounded areas of cavities). The C-factor can vary depending on the diameter and the length of the canal, which can range from 20 to 100, and might exceed 200, which represent unfavorable clinical situation. The higher the C-factor is, the more shrinkage stresses, which might exceed the resin-dentin bond strength and cause debonding.[33]

4.1 Effect of Thermocycling on the Bond Strength:

In vivo studies are considered the ultimate testing method, providing more reliability in reproducing the oral conditions. However, due to the lack of the clinical trials, the laboratory tests with aging simulation provide an approximation on simulating the oral environment; however laboratory tests lack of a direct translation with clinical setting. Thermocycling is widely used to mimic the thermal changes and water exposure found in the oral cavity during eating, drinking, or breathing. This process will generate repetitive contraction/expansion stresses at the tooth-biomaterial interface, which might end up affecting the adhesive stability. Due to the contradictory results in some previous studies, concerns are still arising on the ability of the thermal testing to simulate the oral environment. A bond strength increase was previously noticed when using RelyX

Unicem for cementing fiber posts.[26] This observation was explained because the thermal stress occurring during the laboratory test would increase the chemical polymerization of the material, and thus, promote complete setting reaction. Another explanation was that the moisture tolerance of the self-etch resin cements might favor the adhesion to the root dentin. However, this is in contrast to the findings obtained in our study. Our second null hypothesis was rejected, as the bond strength was significantly lower when applying 40,000 thermocycles, regardless of the type of resin cement. In the present study, the roots were not isolated or embedded in acrylic resin in order to directly expose the bonded interface with different temperature. Also, another important difference is the amount of thermocycles applied on the bonded specimens (5,000 vs 40,000). Most of the previous studies[26,50] did not observe any significant decrease in the bond strength after such a limited thermocycling (3,000-6,000). De Muck and collaborators,[40] suggested that 10,000 thermocycles is considered a reasonable approximation of 1 year of clinical service, and reported that the resin cements don't appear to be affected after thermocycling for up to 20,000 cycles. So, applying 40,000 thermocycles was also in agreement with a previous study by Mazzoni and coworkers,[27] and this increase affected the adhesive performance, particularly to the self-etch resin cement. In the present study, the 40,000 thermocycling group showed significantly lower bond strength compared to the 20,000 group, specifically in the coronal third of the root, which can be explained, as previously mentioned, due to the easier accessibility of water from the coronal level of the root, since no coronal restorations were performed in the present study.

4.2 Effect of the Different Root Level on the Bond Strength:

The highly heterogeneous dentin histology, involving the different density of dentin, variations in the number of dentinal tubules, irregular structure of secondary dentin, accessory root canals, areas of resorption; all these variations and irregularities in the structure of the root canal dentin will affect the penetration of the adhesives into the dentinal tubules, resulting in decreasing the bond strength.[29] The third null hypothesis in the present study was rejected in which the bond strengths were significantly affected by the region of the root canal, regardless of the type of resin cement used. The specimens taken from the coronal third of the root had lower bond strengths compared to the apical third regardless of the type of resin cement used, which is in agreement with other authors[26, 56] who concluded that the bond strength to root canal dentin is more related to the area of solid dentin than the density of dentinal tubules. However, it should be mentioned that both studies by Bitter[26] and Gaston[56] used different types of self-etch resin cements as comparable groups, unlike the present study, which compared the multi-step cement with the one-step cement from the same manufacturer. Mazzoni and collaborators,[27] suggested using fiber-post system components (fiber-post, adhesives, and resin cements) from the same manufacturer as it might prevent the incompatibilities between the materials and to evaluate and assess the potential of each system under the *in vitro* testing.

4.3 Different Failure Modes:

The analysis of the failure modes were also investigated, using the stereomicroscope (Olympus, Tokyo, Japan) at 40x magnification, followed by SEM analysis of selected samples of each failure mode category. There was a significant difference between the tested groups in regards to the failure types. The adhesive failures were significantly higher than the cohesive failures, which is in agreement with some previous studies.[26, 36, 50] Goracci and colleagues,[31] stated that the consistent occurrence of adhesive failures is more desirable than the cohesive failures, as it allows evaluating the true interfacial bond strength between resin cement and the dentin. The first type of failure modes (adhesive failure between the post and the resin cement) was significantly higher in the total-etch groups (group 1,2 and 3). The second type of failure modes (adhesive failure between the dentin and the resin cement) was more obvious in the self-etch groups (group 3,4 and 5). A possible explanation of this finding might be that the phosphoric acid used in the total-etch cement is much more effective than the methacrylated phosphoric esters found in the self-etch cements in dissolving the smear layer created on the canal wall during the canal and post preparation, which will lead to a better adhesion of the total-etch cement to the dentinal wall. Another explanation by Mumco and researchers,[25] was that the absence of the chemical union between the epoxy resin-based posts and the methacrylated-based resin will lead to the higher adhesive failure between the posts and the resin cements. This might be improved by pretreating the fiber posts with saline before cementation. However, in the present study, alcohol was only applied as post pretreatment, following the manufacturer instructions. On the other hand, Mazzitelli and collaborators,[50] evaluated the bond strength of different self-etch resin cements to fiber posts after thermocycling, and found that the self-etch cement-dentin joint represents the weakest point in the self-etch resin cement.

The cohesive failures were also seen among the groups, but were much less prevalent. They are usually more related to the specimens with a high bond strength values. The 4th failure mode category is when the fiber post shows failure without any adhesive failures. In the present study, it was noticed as a penetration of the push-out plunger inside the fiber posts (Fig. 20). Therefore, the adhesive bond of the resin cement was stronger, in that specific section, than the fiber post, explaining the failure within the fibers inside the post.

4.4 Limitations of the Study:

It is important to note the limitations of this study, which can be summarized into:

- This is an *in vitro* study that will not replicate the *in vivo* conditions, or replace well-designed clinical trials.
- The coronal restorations (build-ups and crowns) should be fabricated in the future studies, to better resemble the clinical condition. Also, when available, a thermomechanical loading test could be applied on future studies, which will provide a closer resembling to the oral environment.
- Operator error might have been contributed to differences in the specimen thickness during root sectioning, and differences in the position of the post during the post cementation. However, precautions were taken to minimize all of these limitations.

Chapter 5

Conclusions

Within the limitation of this *in vitro* study, it can be concluded that:

- The bond strength to the root canal dentin did not vary with the type of resin cement (total etch vs self-etch).
- The push-out bond strength values of FRC posts were significantly affected by the thermocycling procedure.
- For both types of resin cements (total etch and self-etch), the push-out bond strength values at the coronal region of the root were significantly lower than the middle and the apical thirds.
- Adhesive failures are more commonly noticed among the groups, where the adhesive failure between the post and the cement is more related to the total etch groups, and the adhesive failure between the dentin and the resin cement is more related to the self-etch groups.

Table 1: Components of Resin Cements

Resin Cements	*Manufacturer*	*Composition of the base paste*	*Composition of the catalyst paste*	*Polymerization mode*	*Conditioned Method*
Rely-X Unicem	3 M ESPE, Seefeld, Germany	Methacrylate monomers containing phosphoric acid groups, Silanated fillers, Initiator components, Stabilizers	Methacrylate monomers, Alkaline (basic) fillers, Silanated fillers, Initiator components, Stabilizers, Pigments	Dual	Self-etch resin cement
Rely-X Ultimate	3 M ESPE, Seefeld, Germany	Methacrylate monomers, Radiopaque, silanated fillers, Initiator components, Stabilizers, Rheological additives	Methacrylate monomers, Radiopaque alkaline (basic) fillers, Initiator components, Stabilizers, Pigments, Rheological additives, Fluorescence dye, Dark cure activator for Scotchbond Universal adhesive	Dual	Total etch resin cement

Table 2: Manufacturer’s Instructions for The Handling The Resin Cements

RELY-X ULTIMATE
• Dry the canal with paper points and gentle blow of air. • Attach an Endo Tip to the mixing tip “Wide” for application in the root canal (Do not use Lentulo spirals to insert the cement in the root canal as this can excessively accelerate setting) • Insert the Endo Tip as deeply as possible in the root canal and apply RelyX Ultimate, beginning apically. Keep the tip of the Endo Tip immersed in the cement and slowly move the Endo Tip upwards as the level of the paste rises. • Do not remove the Endo Tip from the cement until the root canal has been completely filled. • Place the post in the root canal filled with cement; apply moderate pressure to hold it in position. We recommend rotating the post slightly during insertion to avoid the inclusion of air bubbles. • Light cure for 20 seconds through the post, or wait for 6 minutes.
RELY-X UNICEM
• Dry the canal with paper points and gentle blow of air. • Mix powder and liquid by triturating the activated capsule. • Apply the cement onto the post surface

- Insert the post and let the cement initially without any interference, followed by light curing for 20 seconds through the post.

Table 3: Study Groups

Cement *Aging*	*Total etch resin cement system*	*Self etch resin cement system*
No thermocycling	Group 1: total etch system/ no thermocycling	Group 4: Self etch system/ no thermocycling
20,000 thermocycles	Group 2: total etch system/ 20,000 thermocycles	Group 5: Self etch system/ 20,000 thermocycles
40,000 thermocycles	Group 3: total etch system/ 40,000 thermocycles	Group 6: Self etch system/ 40,000 thermocycles

Table 4: Descriptive Statistical Analysis for Microtensile Bond Strength (Apical):

		No Thermocycling	20,000 Thermocycles	40,000 Thermocycles
Total Etch System	N	19	16	15
	M	7.81	10.26	9.37
	SD	4.01	3.16	2.62
	Min	0.34	4.77	5.53
	Max	15.49	16.11	16.48
Self Etch System	N	18	14	19
	M	10.30	9.36	7.37
	SD	5.19	2.58	4.49
	Min	3.62	4.67	0.32
	Max	21.51	13.87	17.71

Table 5: Descriptive Statistical Analysis for Microtensile Bond Strength (Middle):

		No Thermocycling	20,000 Thermocycles	40,000 Thermocycles
Total Etch System	N	20	18	19
	M	7.49	9.35	8.86
	SD	3.43	3.64	2.19
	Min	1.01	5.56	5.62
	Max	15.70	19.14	14.18
Self Etch System	N	15	20	18
	M	8.74	9.16	6.89
	SD	4.31	2.88	4.78
	Min	2.30	4.56	0.32
	Max	16.75	17.07	20.81

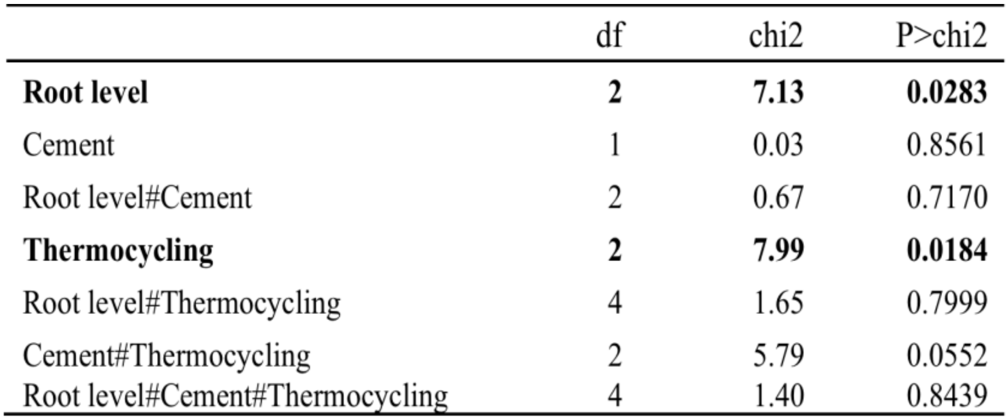
Table 6: Descriptive Statistical Analysis for Microtensile Bond Strength (Coronal):

		No Thermocycling	20,000 Thermocycles	40,000 Thermocycles
Total Etch System	N	18	20	17
	M	6.85	9.27	7.81
	SD	3.66	3.30	2.24
	Min	0.95	5.34	3.88
	Max	15.94	17.31	11.36
Self Etch System	N	16	20	19
	M	8.83	9.26	6.42
	SD	4.10	3.63	4.29
	Min	1.68	1.42	0.34
	Max	14.31	15.35	20.51

Table 7: Coronal Linear Contrast:

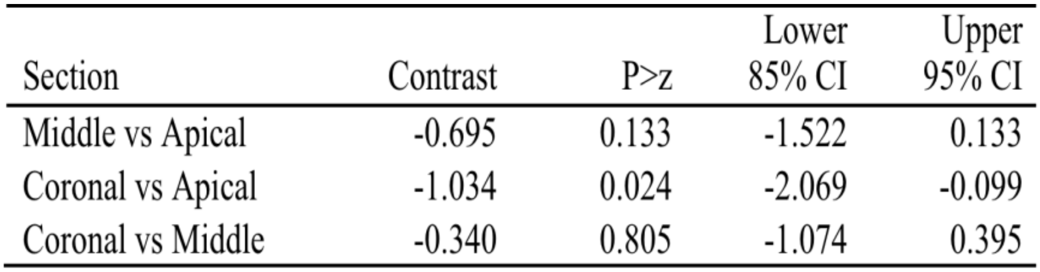
	df	F	P>F
Cement	1	0.08	0.779
Thermocycling	2	3.85	0.024
Cement by Thermocycling	2	1.86	0.161

Table 8: Linear Contrast between All Groups:



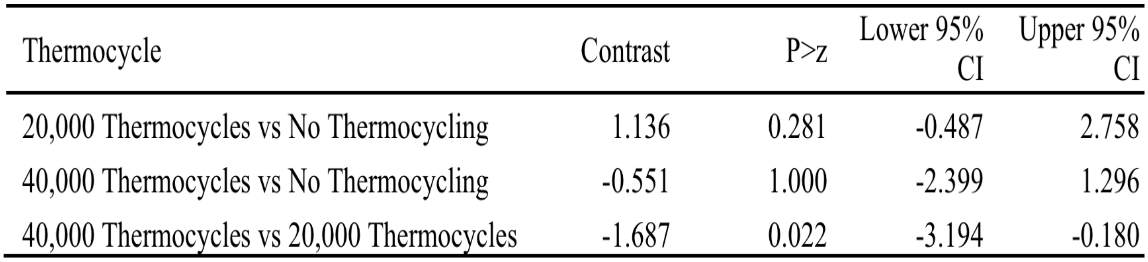
	df	chi2	P>chi2
Root level	**2**	**7.13**	**0.0283**
Cement	1	0.03	0.8561
Root level#Cement	2	0.67	0.7170
Thermocycling	**2**	**7.99**	**0.0184**
Root level#Thermocycling	4	1.65	0.7999
Cement#Thermocycling	2	5.79	0.0552
Root level#Cement#Thermocycling	4	1.40	0.8439

Table 9: Pairwise Comparisons by Sections:



Section	Contrast	P>z	Lower 85% CI	Upper 95% CI
Middle vs Apical	-0.695	0.133	-1.522	0.133
Coronal vs Apical	-1.034	0.024	-2.069	-0.099
Coronal vs Middle	-0.340	0.805	-1.074	0.395

Table 10: Pairwise Comparisons by Thermocycling:



Thermocycle	Contrast	P>z	Lower 95% CI	Upper 95% CI
20,000 Thermocycles vs No Thermocycling	1.136	0.281	-0.487	2.758
40,000 Thermocycles vs No Thermocycling	-0.551	1.000	-2.399	1.296
40,000 Thermocycles vs 20,000 Thermocycles	-1.687	0.022	-3.194	-0.180

Table 11: Failure Type by Group (Apical):

	Failure Type					
Group	1	2	3	4	5	Total
1	13	2	1	0	4	20
	65%	10%	5%	0%	20%	100%
2	9	1	0	5	5	20
	45%	5%	0%	25%	25%	100%
3	11	0	0	5	4	20
	55%	0%	0%	25%	20%	100%
4	10	4	1	1	4	20
	50%	20%	5%	5%	20%	100%
5	7	3	3	3	3	19
	37%	16%	16%	16%	16%	100%
6	3	12	0	1	4	20
	15%	60%	0%	5%	20%	100%
	53	22	5	15	24	119
Total	45%	18%	4%	13%	20%	100%

1 = Total etch system/no thermocycling
2 = Total etch system/20,000 thermocycles
3 = Total etch system/40,000 thermocycles
4 = Self-etch system/no thermocycling
5 = Self-etch system/20,000 thermocycles
6 =Self-etch system/40,000 thermocycles

Table 12: Failure Type by Group (Middle):

	Failure Type					
Group	1	2	3	4	5	Total
1	9	0	0	0	11	20
	45%	0%	0%	0%	55%	100%
2	8	7	1	1	3	20
	40%	35%	5%	5%	15%	100%
3	14	0	0	1	5	20
	70%	0%	0%	5%	25%	100%
4	4	5	2	2	6	19
	21%	26%	11%	11%	32%	100%
5	4	6	0	0	10	20
	20%	30%	0%	0%	50%	100%
6	5	5	2	0	8	20
	25%	25%	10%	0%	40%	100%
Total	44	23	5	4	43	119
	37%	19%	4%	3%	36%	100%

1 = Total etch system/no thermocycling
2 = Total etch system/20,000 thermocycles
3 = Total etch system/40,000 thermocycles
4 = Self-etch system/no thermocycling
5 = Self-etch system/20,000 thermocycles
6 =Self-etch system/40,000 thermocycles

Table 13: Failure Type by Group (Coronal):

	Failure Type					
Group	1	2	3	4	5	Total
1	5	2	1	1	11	20
	25%	10%	5%	5%	55%	100%
2	5	4	0	0	11	20
	25%	20%	0%	0%	55%	100%
3	7	2	1	2	8	20
	35%	10%	5%	10%	40%	100%
4	3	8	2	2	5	20
	15%	40%	10%	10%	25%	100%
5	2	7	0	0	9	18
	11%	39%	0%	0%	50%	100%
6	4	9	1	0	6	20
	20%	45%	5%	0%	30%	100%
Total	26	32	5	5	50	118
	22%	27%	4%	4%	42%	100%

1 = Total etch system/no thermocycling
2 = Total etch system/20,000 thermocycles
3 = Total etch system/40,000 thermocycles
4 = Self-etch system/no thermocycling
5 = Self-etch system/20,000 thermocycles
6 =Self-etch system/40,000 thermocycles

Figure 1: Slow speed diamond saw (Isomet, Bueher, Lake Buff, IL, USA)

Figure 2: A mark placed on the apical aspect of the root before sectioning each slice

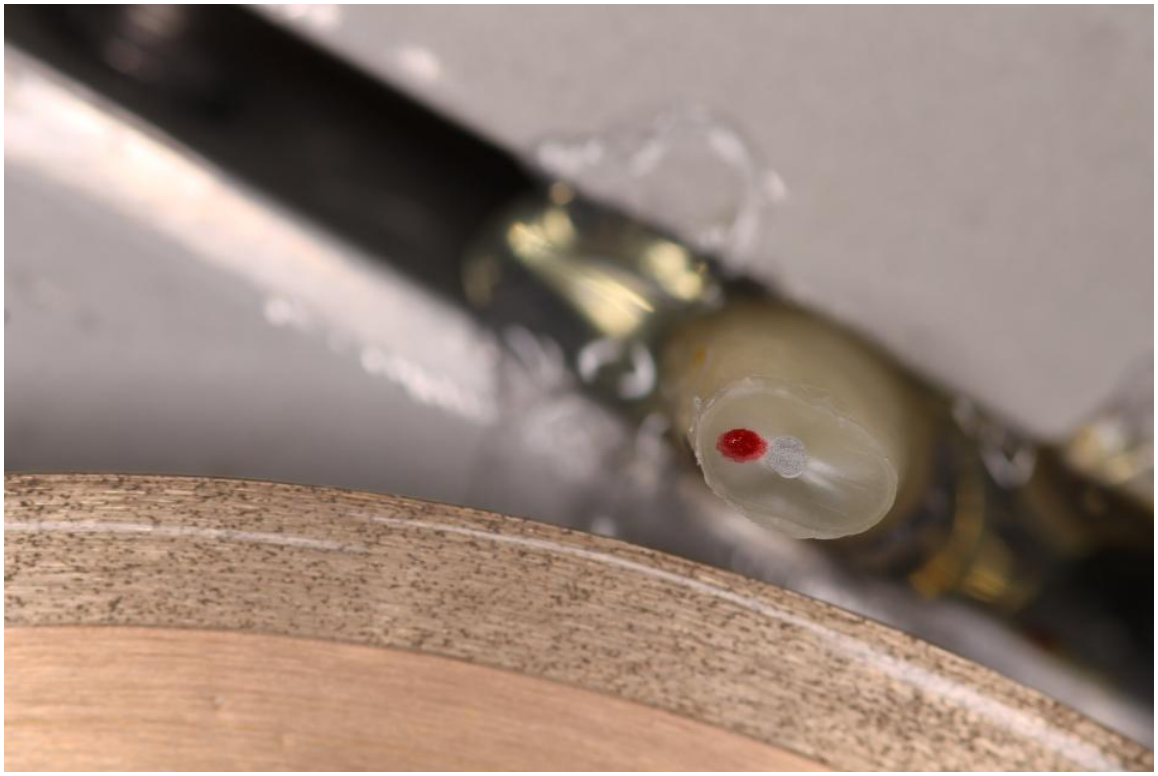


Figure 3: A mark placed on the apical aspect of the root before sectioning each slice

Figure 4: Specimen sectioning into six 1-mm thick post-dentin sections (coronal, middle, and apical)

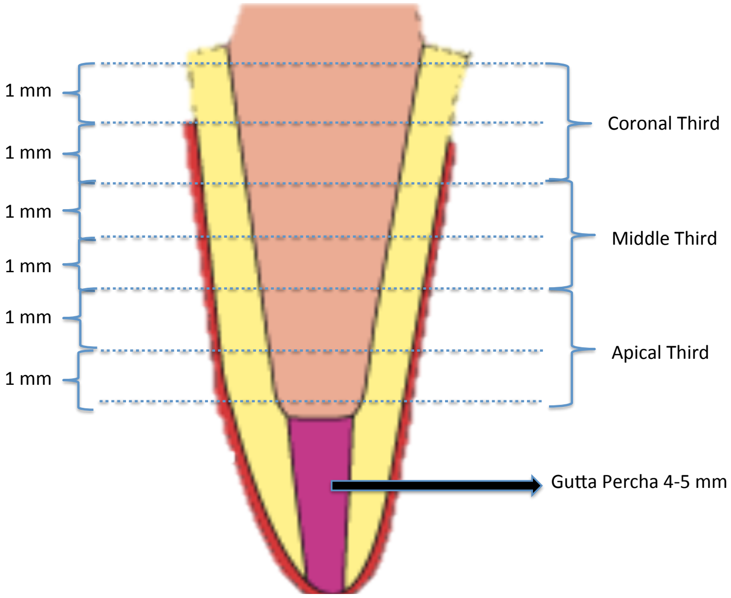


Figure 5: Digital caliper used to measure the thickness of each slice

Figure 6: Universal testing machine (MTS)

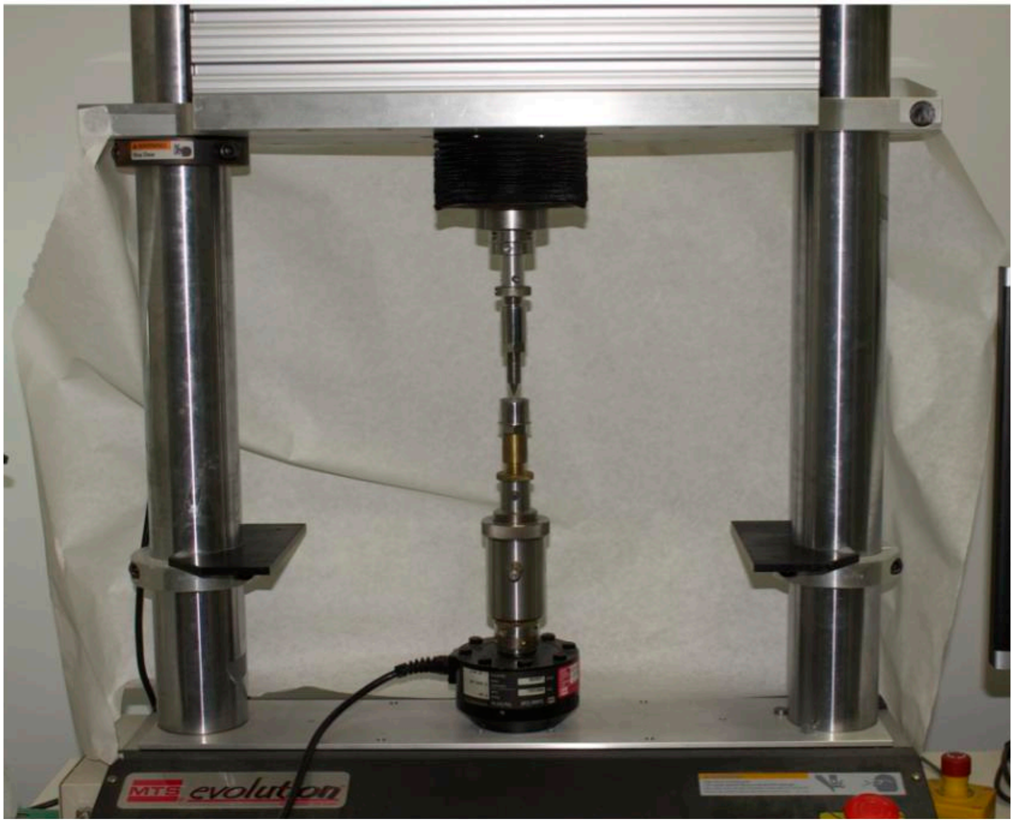


Figure 7: Loading each slice with the MTS plunger. Each slice was positioned so as to contact only the apical aspect of the post on the loading

Figure 8: A shear stress was applied on the slice from its apical aspect to avoid any movement of the post due to the taper of the canal

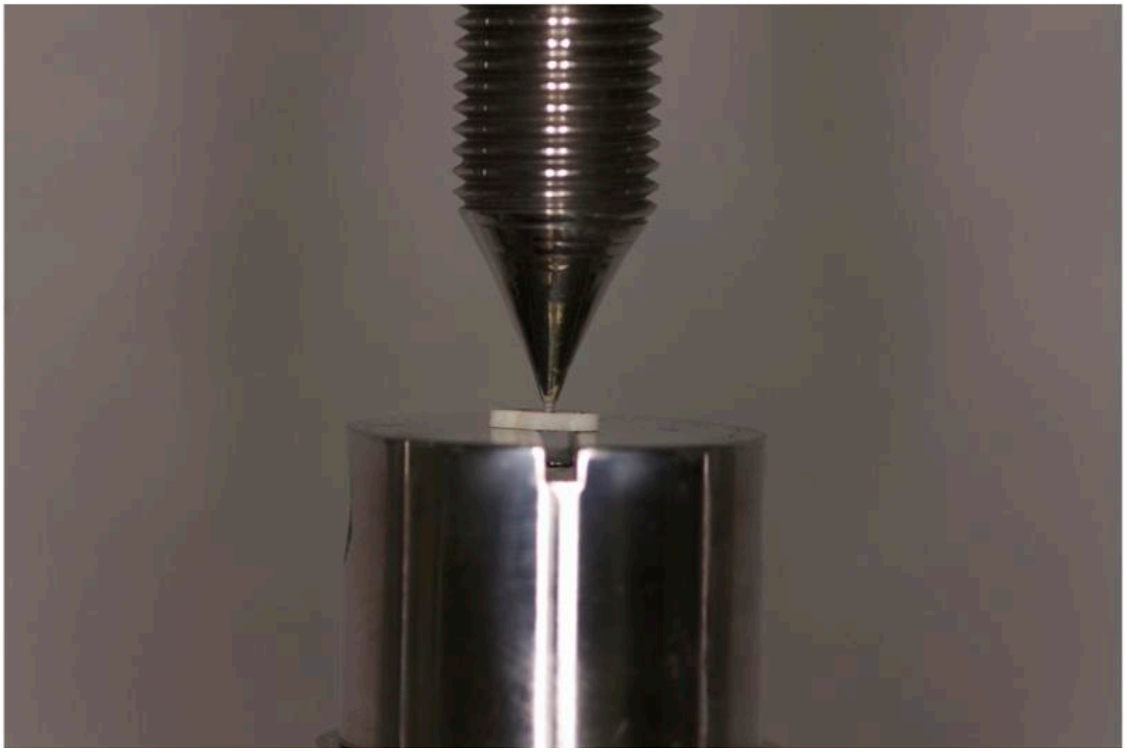


Figure 9: The push-out load was applied in an apical-coronal direction until bond failure occurs at a crosshead speed of 0.5mm/min until failure

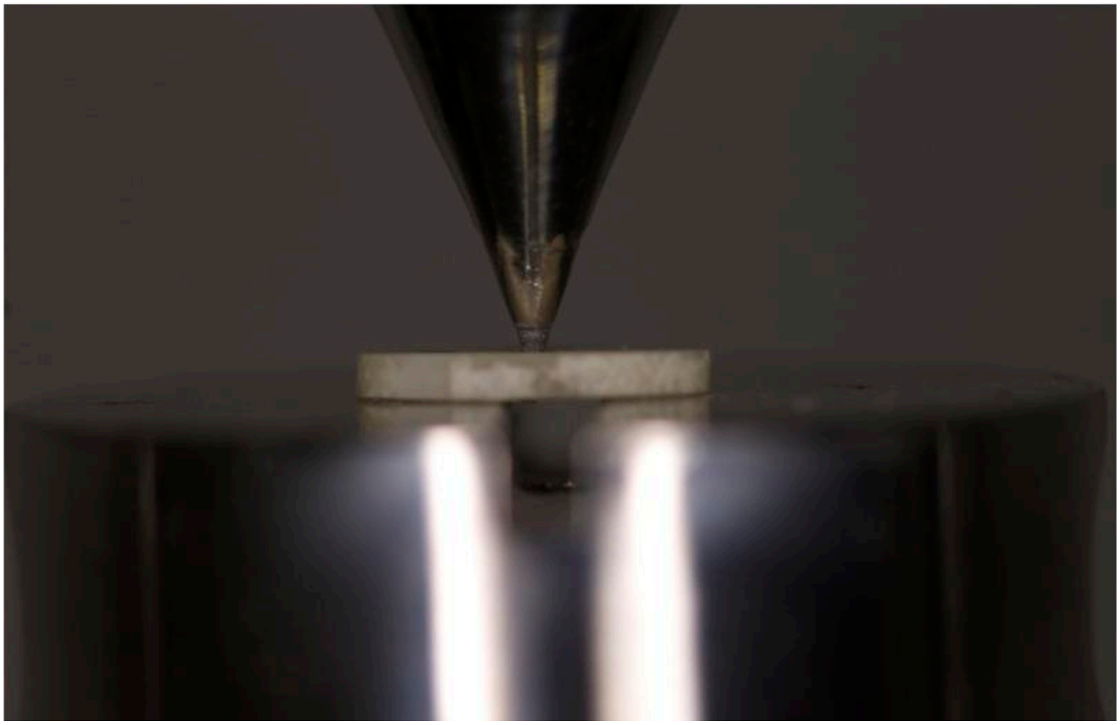
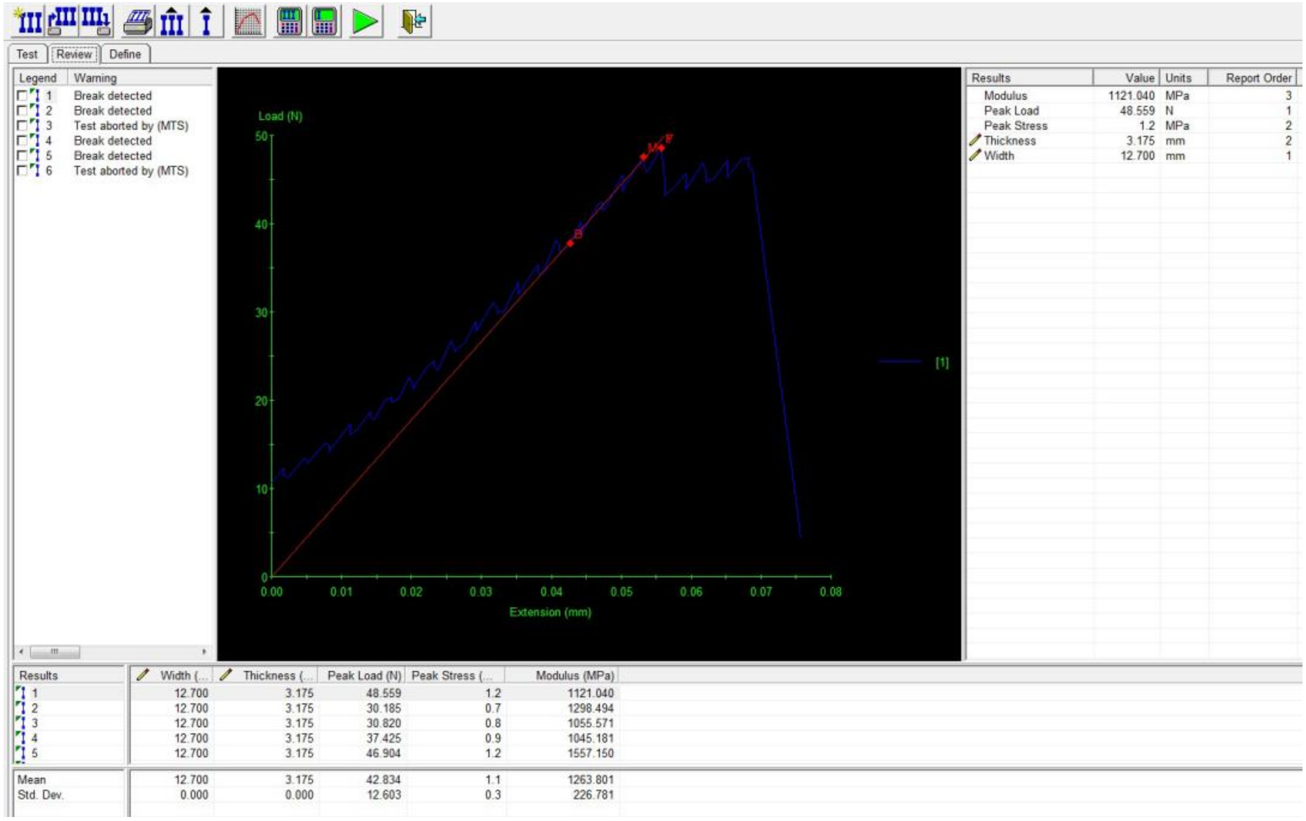


Figure 10: The push-out load was applied in an apical-coronal direction until bond failure occurs at a crosshead speed of 0.5mm/min



Legend	Warning
☐ 1	Break detected
☐ 2	Break detected
☐ 3	Test aborted by (MTS)
☐ 4	Break detected
☐ 5	Break detected
☐ 6	Test aborted by (MTS)

Results	Value	Units	Report Order
Modulus	1121.040	MPa	3
Peak Load	48.559	N	1
Peak Stress	1.2	MPa	2
Thickness	3.175	mm	2
Width	12.700	mm	1

Results	Width (...	Thickness (...	Peak Load (N)	Peak Stress (...	Modulus (MPa)
1	12.700	3.175	48.559	1.2	1121.040
2	12.700	3.175	30.185	0.7	1298.494
3	12.700	3.175	30.820	0.8	1055.571
4	12.700	3.175	37.425	0.9	1045.181
5	12.700	3.175	46.904	1.2	1557.150
Mean	12.700	3.175	42.834	1.1	1263.801
Std. Dev.	0.000	0.000	12.603	0.3	226.781

Figure 11: Failure mode category 1 (Adhesive failure between post and resin cement)

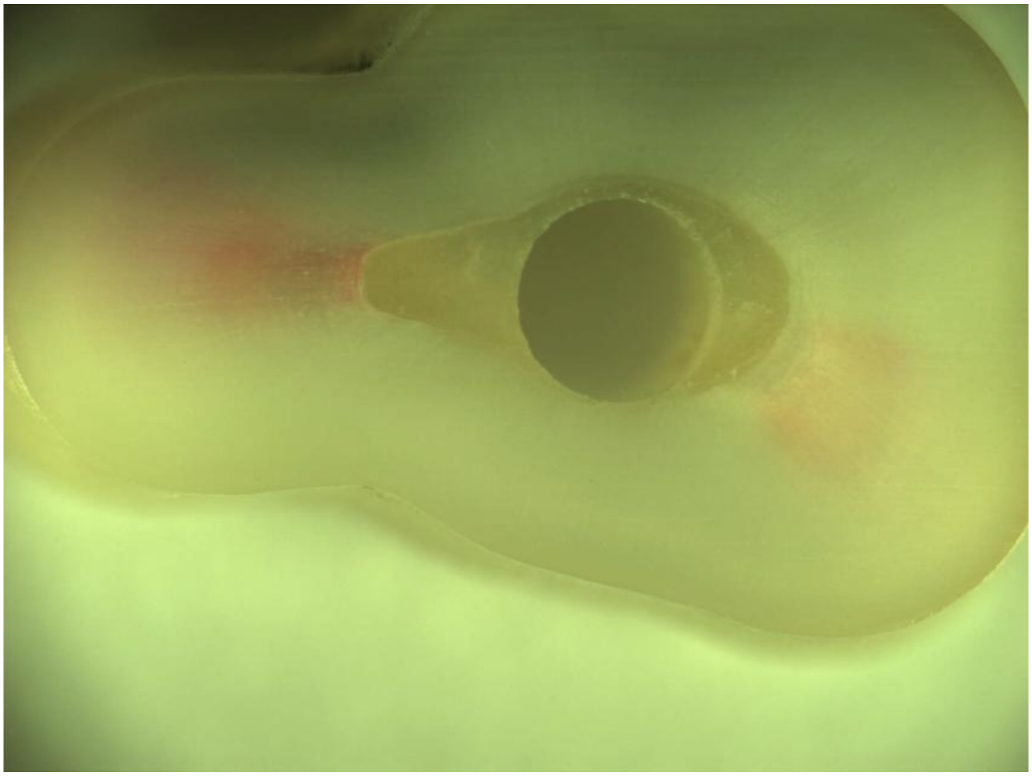


Figure 12: Failure mode category 2 (Adhesive failure between dentin and resin cement)

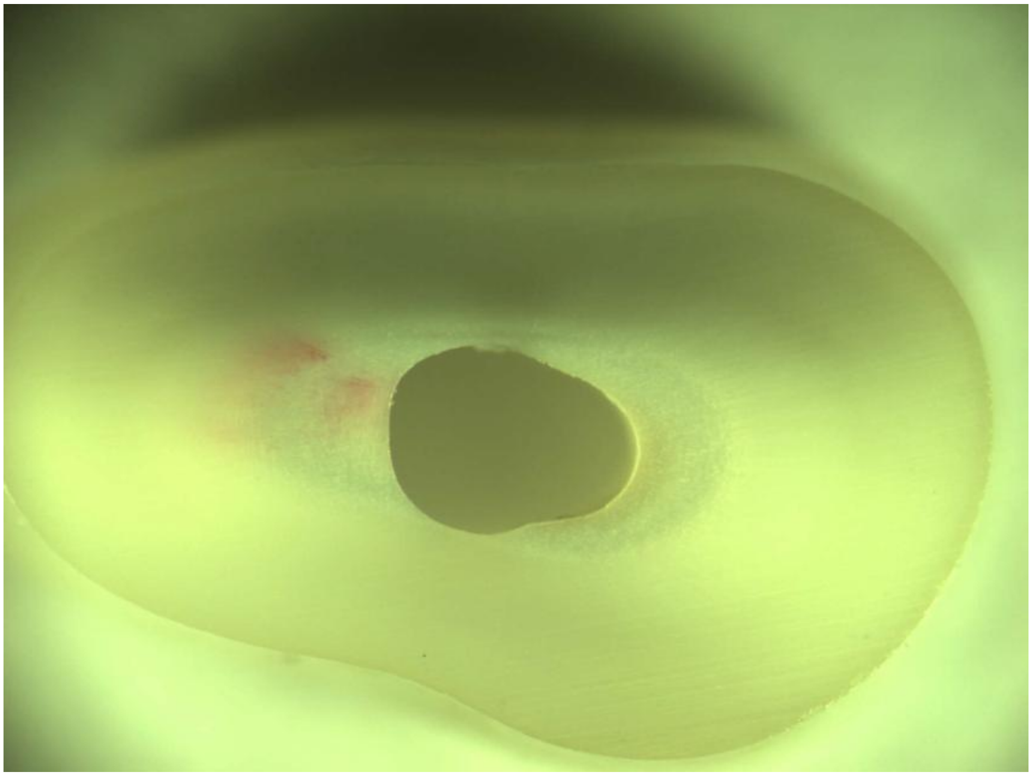


Figure 13: Failure mode category 3 (cohesive failure within dentin)

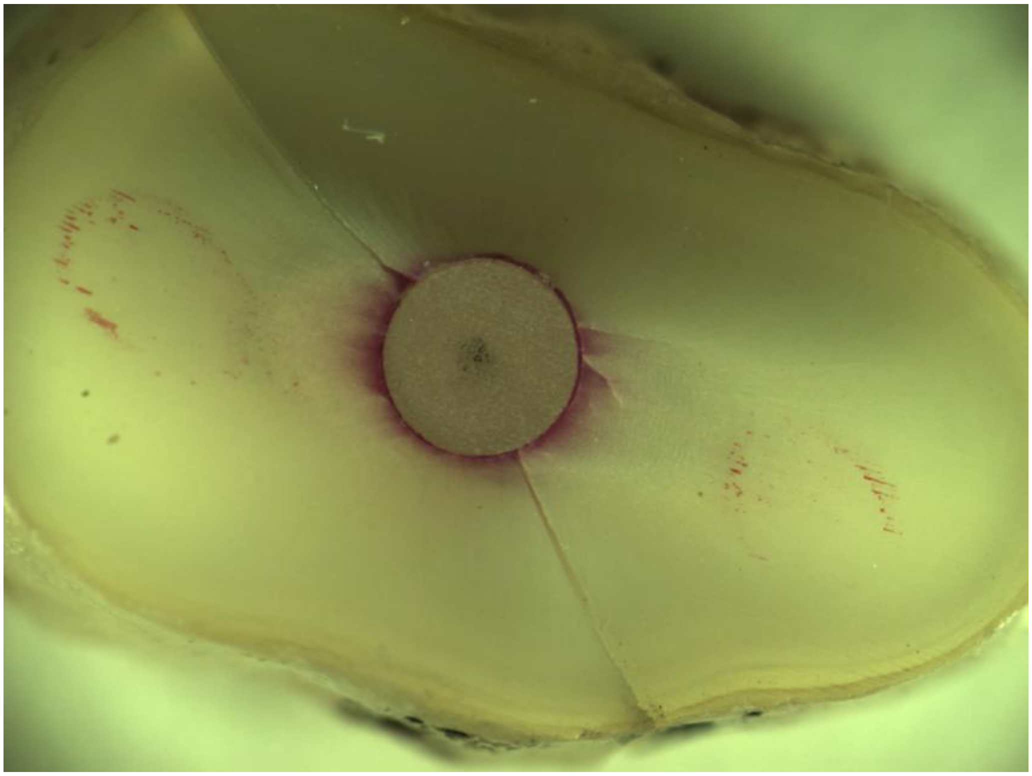


Figure 14: Failure mode category 4 (cohesive failure within post)

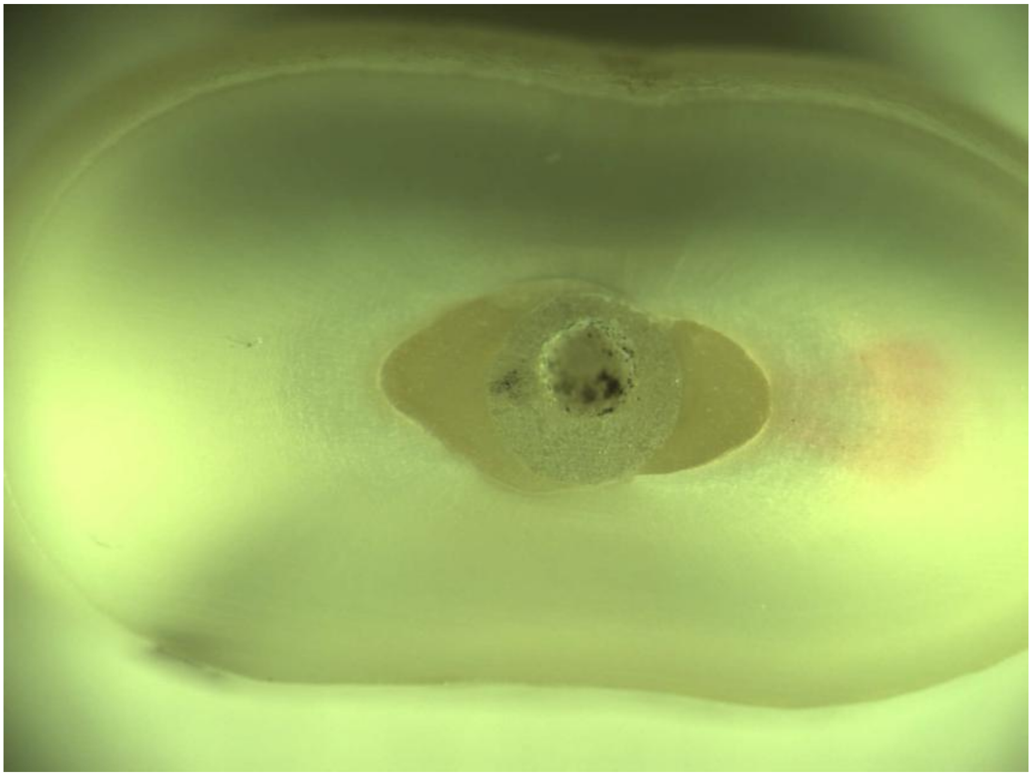


Figure 15: Failure mode category 5 (Mixed failure - combination of failure that occurred both at the interface between dentin/resin cement and post/resin cement)

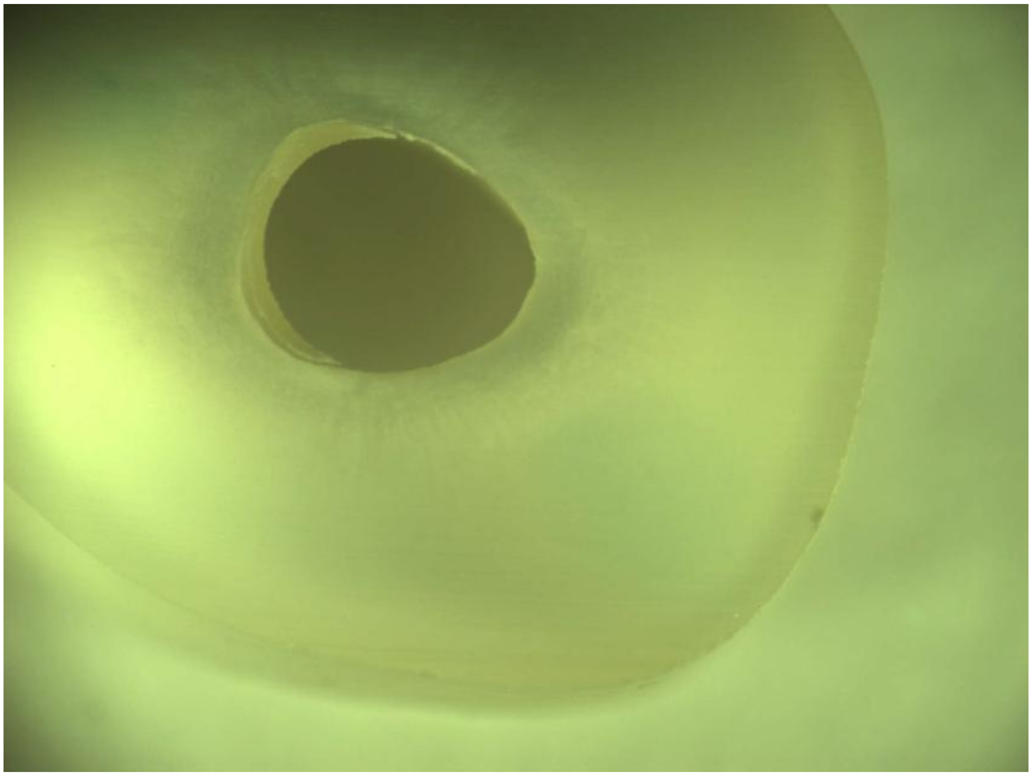


Figure 16: Failure mode category 5 (Mixed failure - combination of failure that occurred both at the interface between dentin/resin cement and post/resin cement)

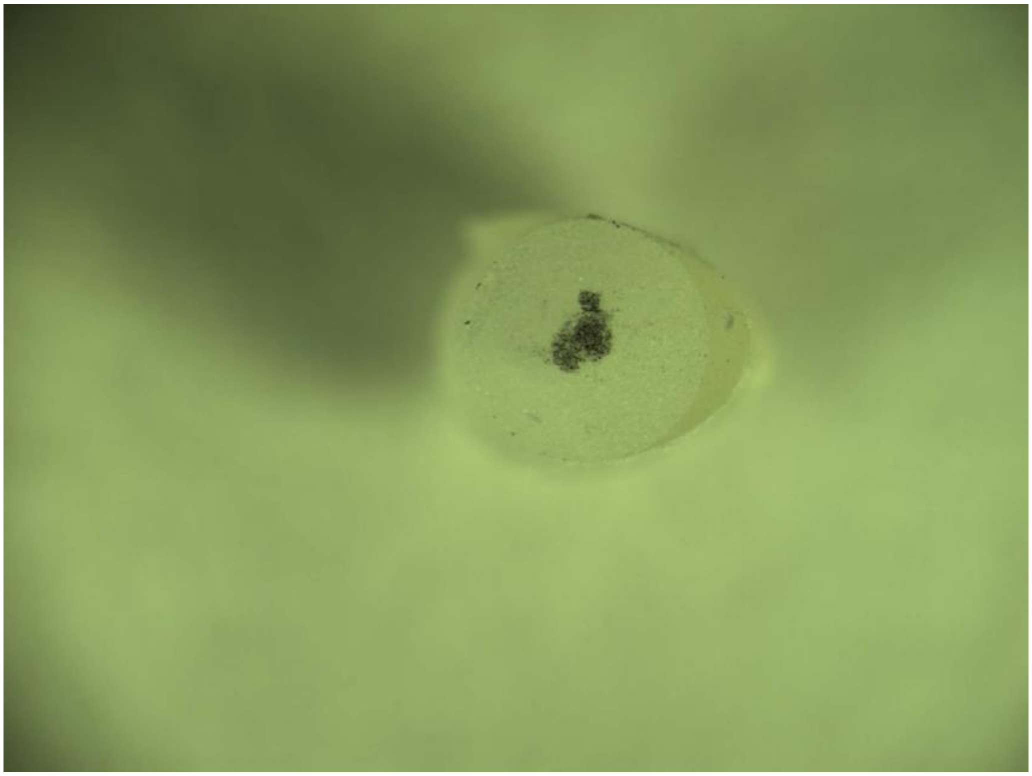


Figure 17: SEM image showing failure mode category 1 (Adhesive failure between post and resin cement)

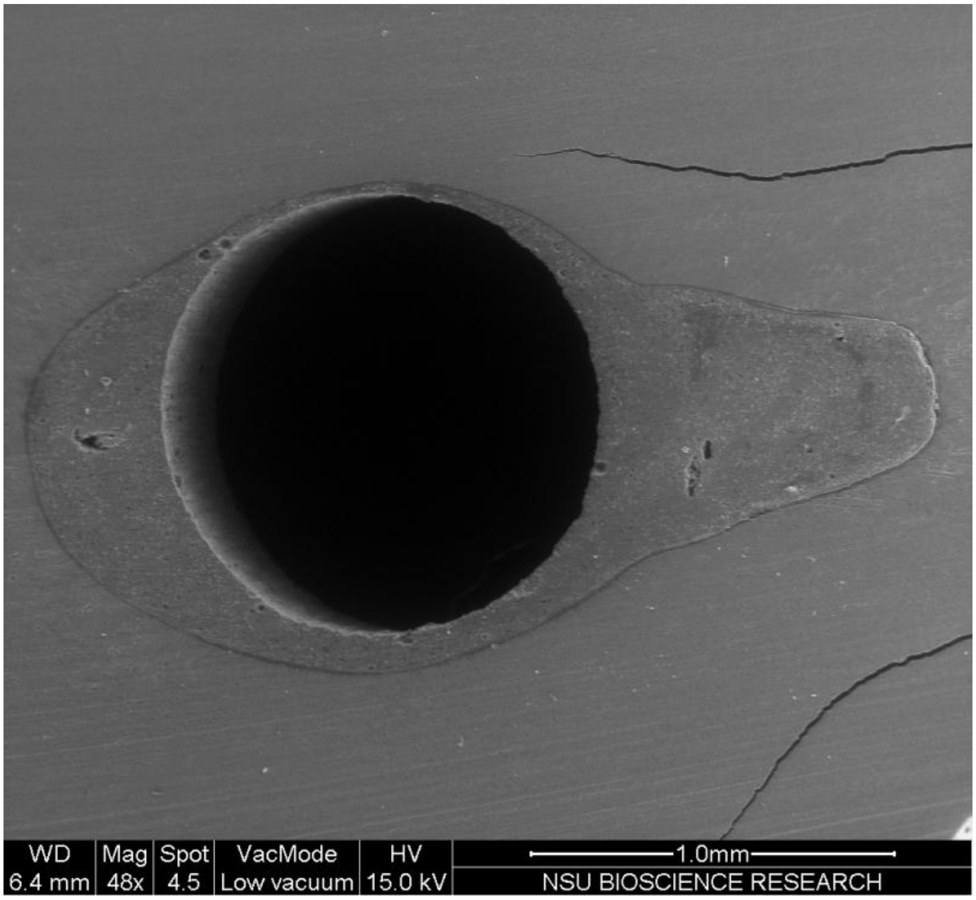


Figure 18 a: SEM image showing failure mode category 2 (Adhesive failure between dentin and resin cement)

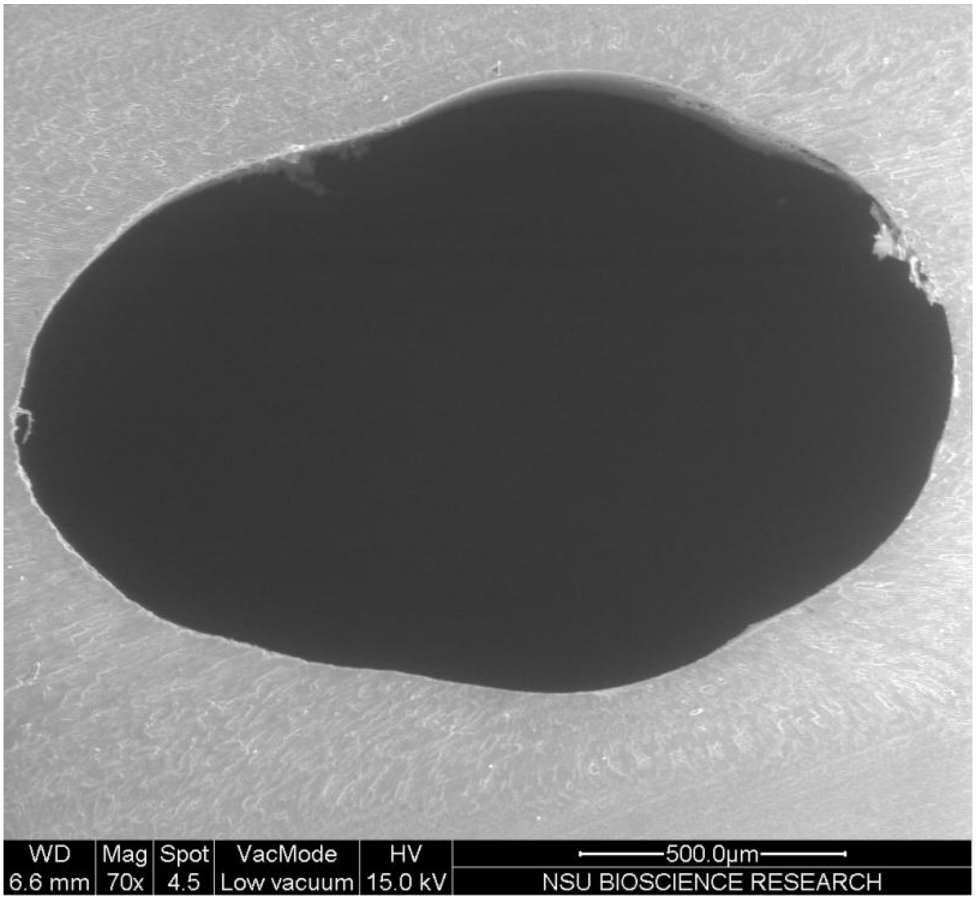


Figure 18 b: SEM image showing failure mode category 2 (Adhesive failure between dentin and resin cement)

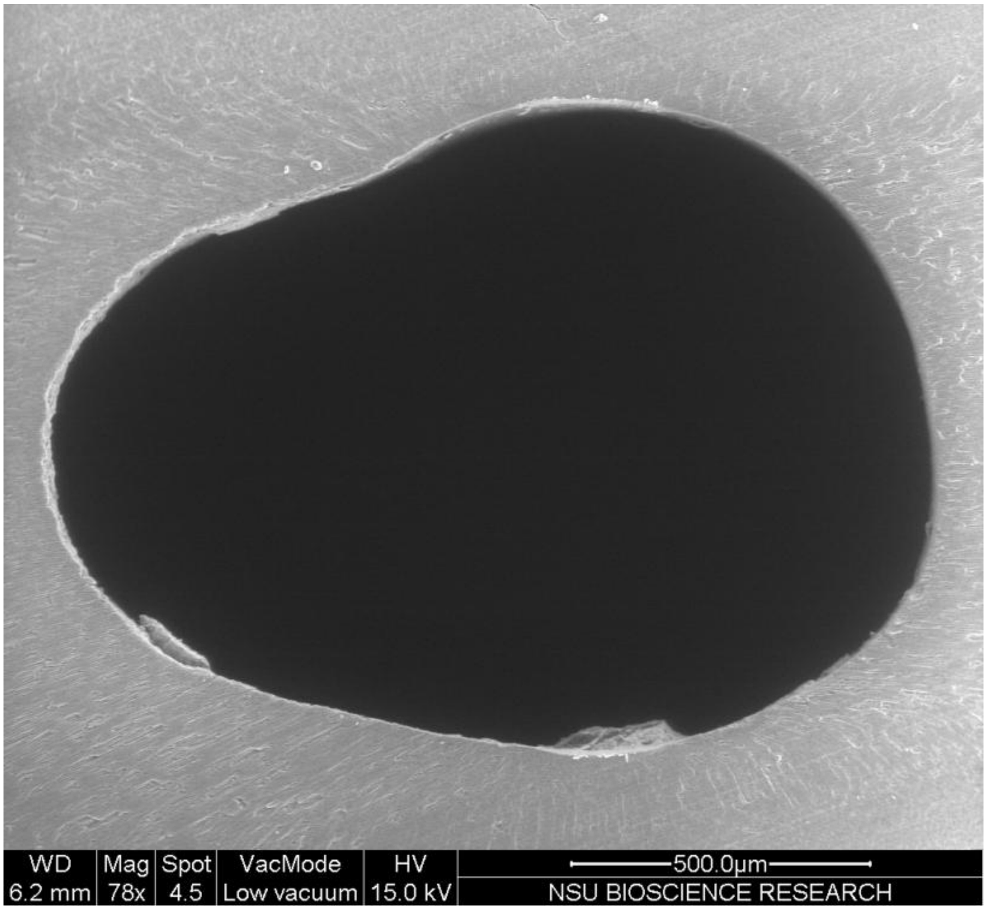


Figure 19 a: SEM image showing failure mode category 3 (cohesive failure within dentin)

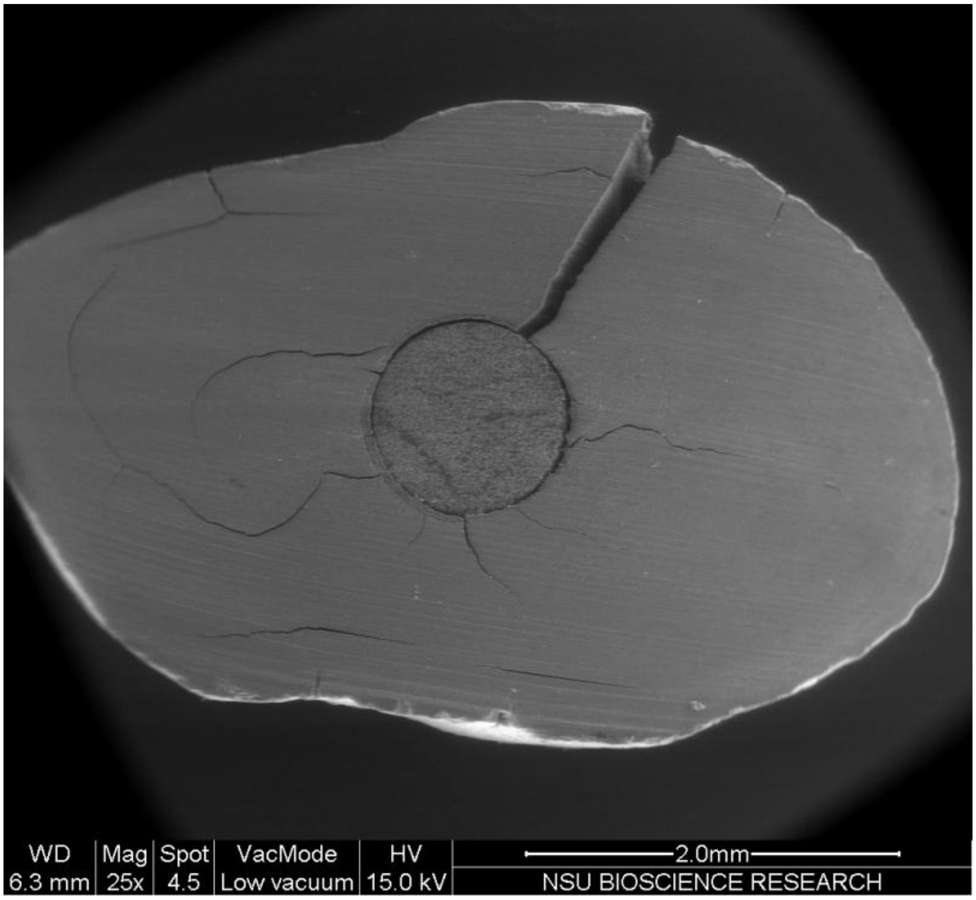


Figure 19 b: SEM image showing failure mode category 3 (cohesive failure within dentin)

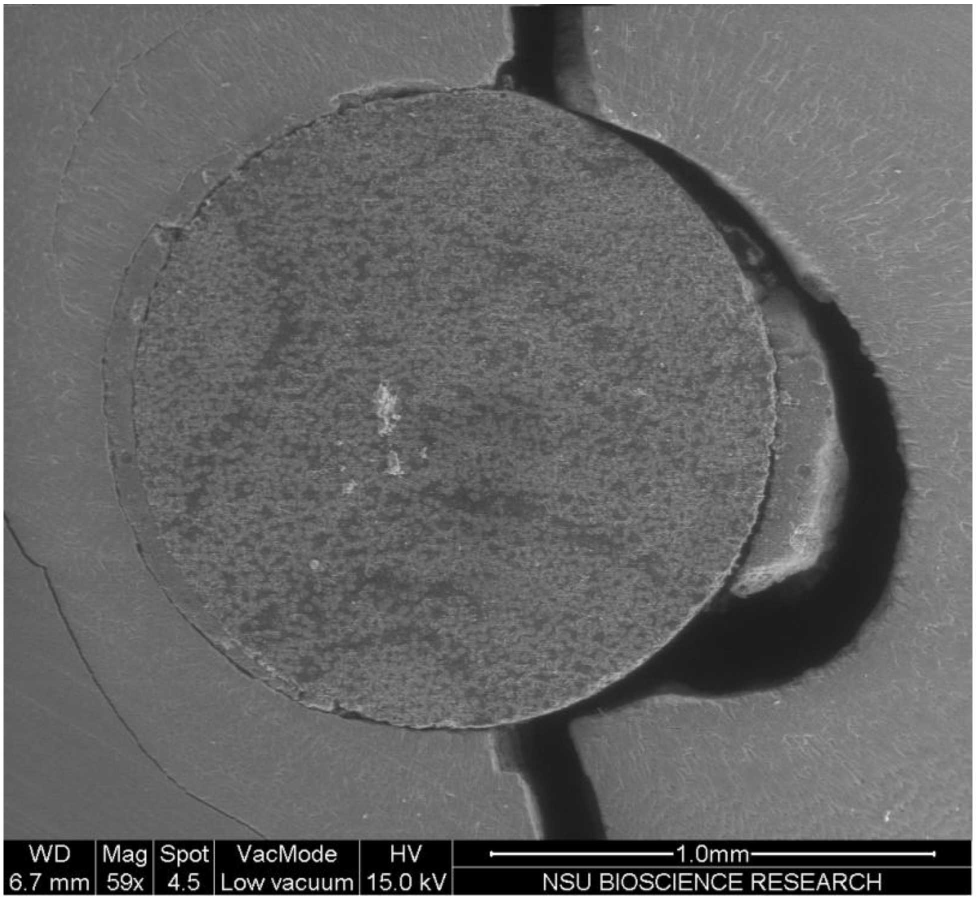


Figure 20 a: SEM image showing failure mode category 4 (cohesive failure within post)

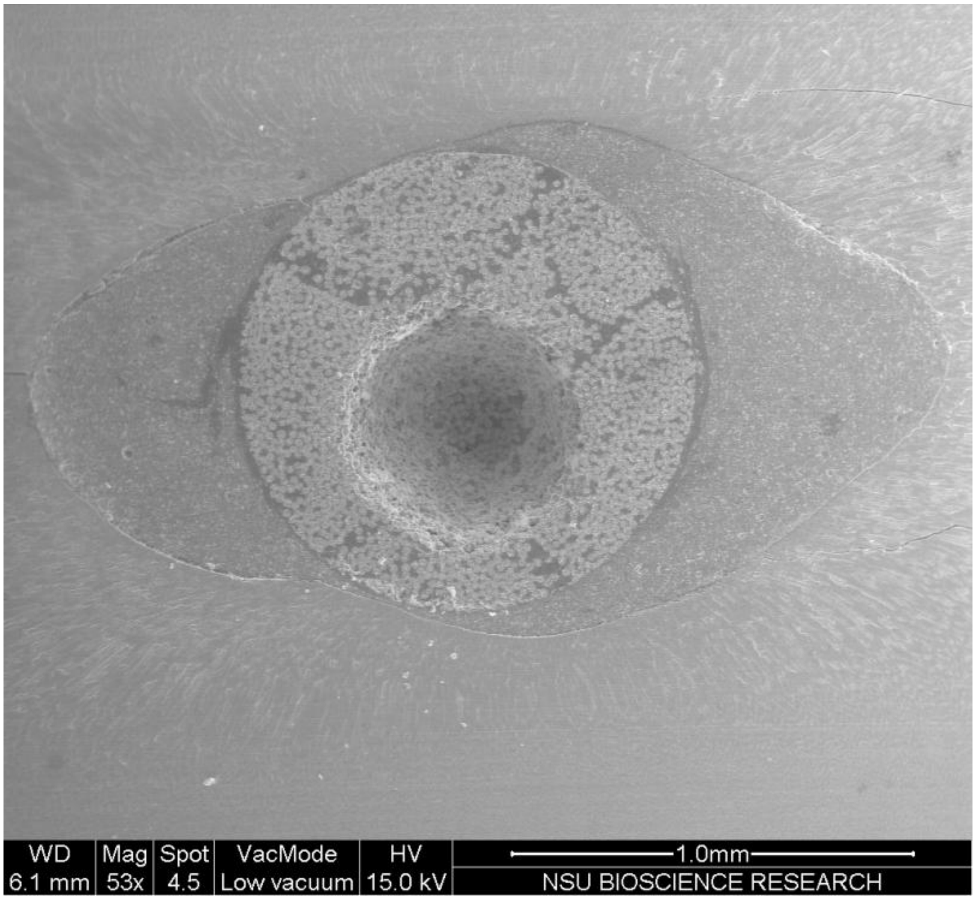


Figure 20 b: SEM image showing failure mode category 4 (cohesive failure within post)

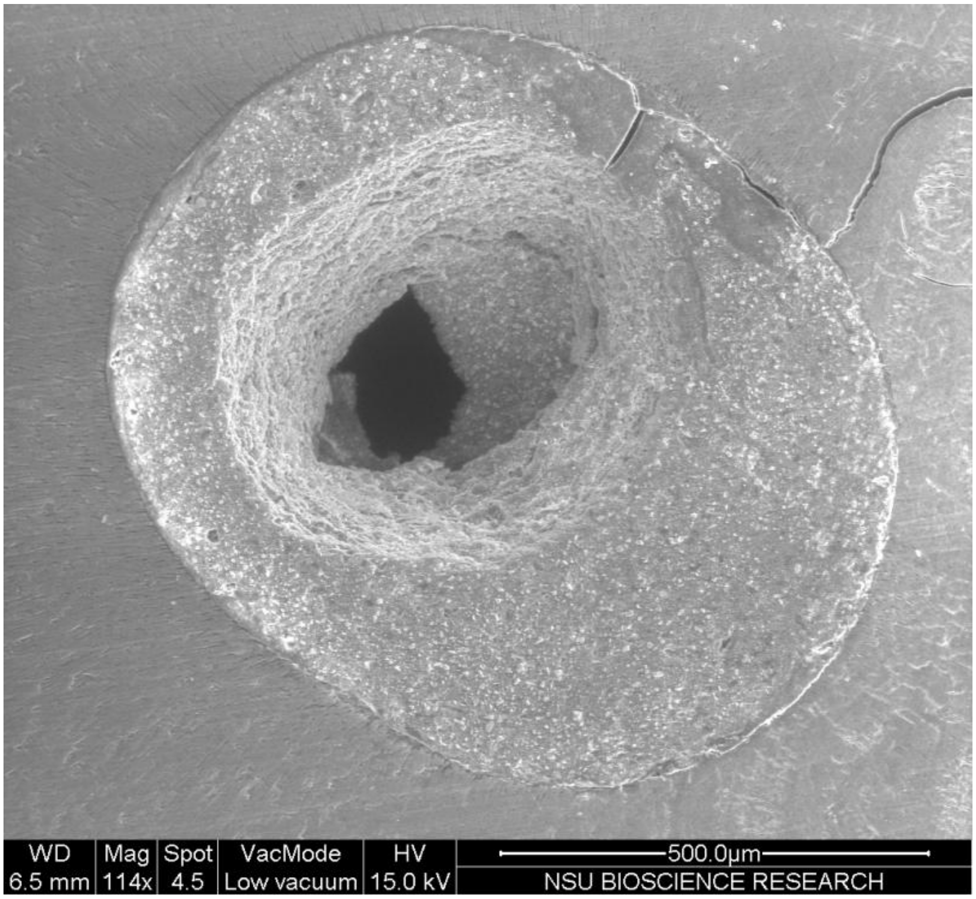


Figure 21 a: SEM image showing failure mode category 5 (Mixed failure - combination of failure that occurred both at the interface between dentin/resin cement and post/resin cement)

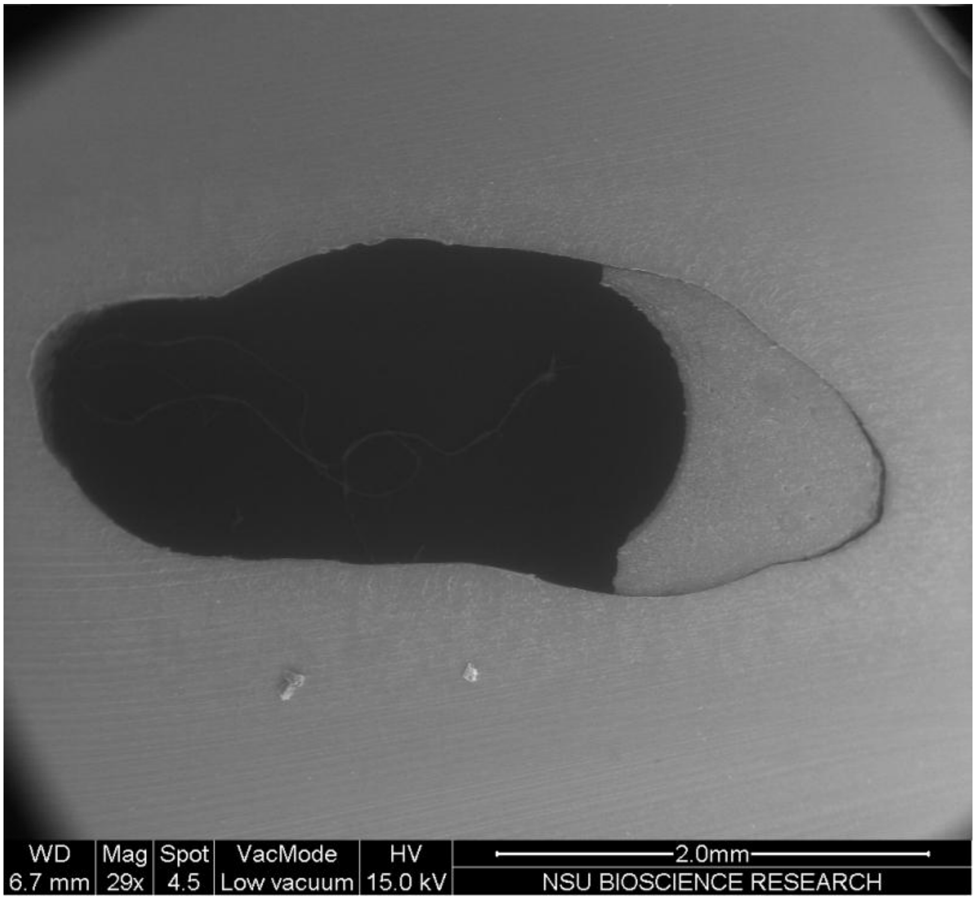
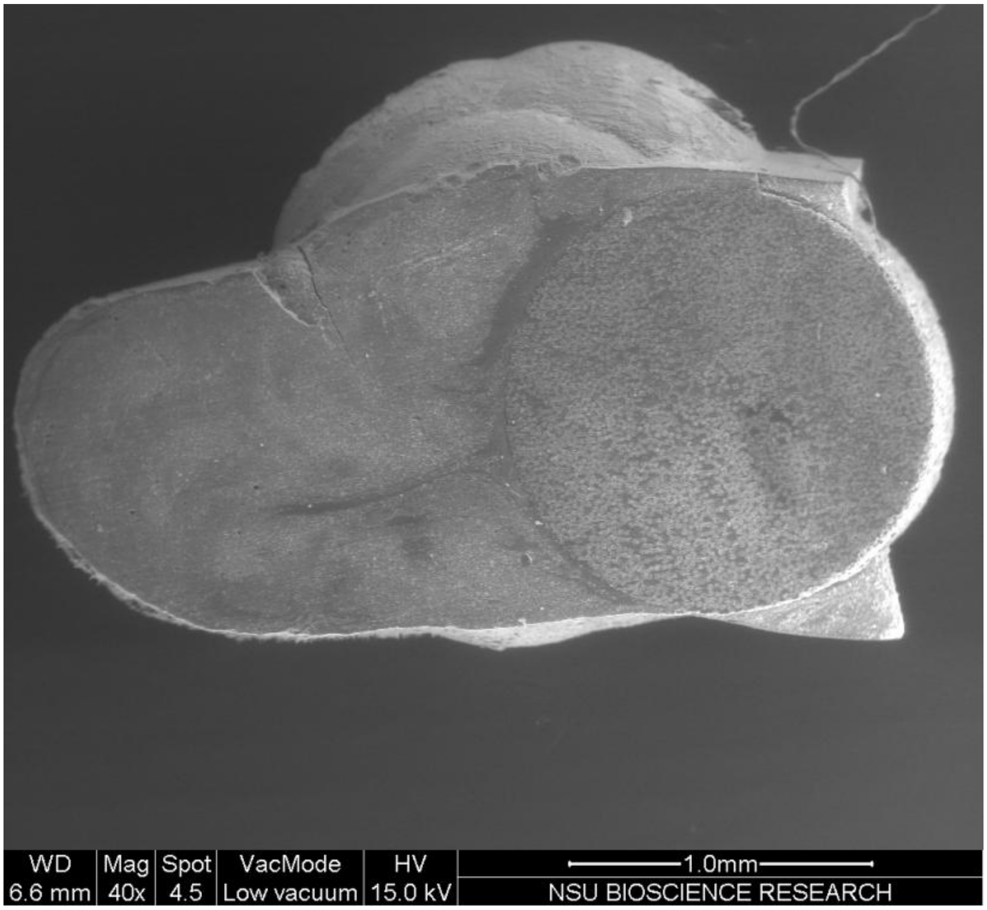


Figure 21 b: SEM image showing failure mode category 5 (Mixed failure - combination of failure that occurred both at the interface between dentin/resin cement and post/resin cement)



Appendix A: Raw Data for Group 1

Tooth #	Root Level	Sample #	Coronal Radius	Apical Radius	Sample Thickness	Area (A)	Debonding Force (N)	Debonding Stress (Mpa)	Mode of Failure
#1	Apical	1	0.45	0.45	1	2.83	14.49	5.13	1
		2	0.5	0.5	1.1	3.29	24.80	7.53	1
	Middle	3	0.6	0.5	1.1	3.64	49.80	13.69	5
		4	0.65	0.65	0.8	3.65	27.55	7.55	1
	Coronal	5	0.75	0.7	1	4.56	39.80	8.73	5
		6	1	0.9	1.1	6.29	37.56	5.98	5
#2	Apical	1	0.45	0.45	1.1	2.96	45.90	15.49	1
		2	0.55	0.55	1.2	3.78	59.40	15.70	5
	Middle	3	0.65	0.6	1	3.93	54.00	13.74	3
		4	0.75	0.7	1	4.56	48.29	10.59	1
	Coronal	5	0.75	0.75	1.1	4.94	64.08	12.97	1
		6	0.9	0.9	1.1	5.93	94.50	15.94	5
#3	Apical	1	0.55	0.55	1.2	3.78	52.60	13.90	1
		2	0.75	0.65	1	4.42	15.40	3.49	5
	Middle	3	0.8	0.8	1	5.02	56.31	11.21	4
		4	0.95	0.9	1	5.82	22.86	3.93	1
	Coronal	5	1	1	1	6.28	42.00	6.69	5
		6	1.1	1.1	1.2	7.57	7.21	0.95	5
#4	Apical	1	0.55	0.5	1.2	3.62	1.23	0.34	2
		2	0.6	0.6	1	3.77	3.80	1.01	5
	Middle	3	0.65	0.65	1	4.08	17.80	4.36	1
		4	0.7	0.7	0.9	4.17	30.47	7.31	1
	Coronal	5	0.8	0.8	1	5.02	47.58	9.47	1
		6	1	1	1	6.28	40.43	6.44	5
#5	Apical	1	0.75	0.7	1	4.56	36.70	8.05	1
		2	0.85	0.85	0.9	5.06	34.80	6.87	1
	Middle	3	0.95	0.95	1	5.97	39.89	6.69	1
		4	1.15	1.1	0.9	6.71	32.39	4.83	1
	Coronal	5	1.15	1.1	1	7.07	48.07	6.80	1
		6	1.3	1.2	1	7.89	39.29	4.98	5
#6	Apical	1	0.45	0.45	1	2.83	40.68	14.39	1
		2	0.55	0.55	1	3.45	39.98	11.58	1
	Middle	3	0.65	0.6	0.9	3.73	45.18	12.12	1
		4	0.7	0.65	0.9	4.03	43.37	10.77	5
	Coronal	5	0.9	0.8	1	5.36	33.64	6.27	5
		6	1.15	1.1	0.9	6.71	44.79	6.67	1
#7	Apical	1	0.75	0.65	1	4.42	32.56	7.37	5
		2	0.9	0.75	1	5.24	31.97	6.10	5
	Middle	3	1.05	0.95	0.9	5.99	26.20	4.37	5
		4	1.15	1.1	1	7.07	25.65	3.63	5
	Coronal	5	1.3	1.25	0.8	7.17	26.80	3.74	5
		6	1.3	1.25	1	8.02	42.97	5.36	5

#8	**Apical**	**1**	**0.5**	**0.45**	**1**	**2.99**	**57.51**	**19.25**	**3**
		2	**0.7**	**0.6**	**1**	**4.10**	**42.73**	**10.42**	**1**
	Middle	**3**	**0.9**	**0.75**	**1**	**5.24**	**46.30**	**8.84**	**1**
		4	**1.15**	**1**	**1**	**6.83**	**52.85**	**7.74**	**1**
	Coronal	**5**	**1.3**	**1.2**	**1.3**	**8.98**	**59.82**	**6.66**	**1**
		6	**1.5**	**1.45**	**1.3**	**10.57**	**56.79**	**5.37**	**5**
#9	**Apical**	**1**	**0.65**	**0.6**	**1.2**	**4.30**	**43.74**	**10.16**	**5**
		2	**0.75**	**0.7**	**1.1**	**4.78**	**45.51**	**9.52**	**5**
	Middle	**3**	**0.9**	**0.9**	**1**	**5.65**	**33.90**	**6.00**	**5**
		4	**1.1**	**1**	**0.9**	**6.29**	**36.63**	**5.82**	**2**
	Coronal	**5**	**1.2**	**1.1**	**1**	**7.26**	**45.46**	**6.26**	**5**
		6	**1.3**	**1.2**	**1**	**7.89**	**48.47**	**6.14**	**2**
#10	**Apical**	**1**	**0.55**	**0.5**	**1.1**	**3.46**	**28.02**	**8.09**	**1**
		2	**0.7**	**0.6**	**1.1**	**4.30**	**23.05**	**5.36**	**5**
	Middle	**3**	**0.9**	**0.65**	**1**	**5.02**	**22.97**	**4.58**	**2**
		4	**0.9**	**0.9**	**1.1**	**5.93**	**19.97**	**3.37**	**1**
	Coronal	**5**	**1.15**	**1.1**	**1**	**7.07**	**33.17**	**4.69**	**1**
		6	**1.3**	**1.2**	**1**	**7.89**	**38.37**	**4.86**	**5**

Appendix B: Raw Data for Group 2

Tooth #	**Root Level**	**Sample #**	**Coronal Radius**	**Apical Radius**	**Sample Thickness**	**Area (A)**	**Debonding Force (N)**	**Debonding Stress (Mpa)**	**Mode of Failure**
#11	**Apical**	**1**	**0.45**	**0.4**	**0.8**	**2.39**	**18.34**	**7.67**	**1**
		2	**0.5**	**0.5**	**0.8**	**2.81**	**18.53**	**6.60**	**1**
	Middle	**3**	**0.65**	**0.6**	**0.9**	**3.73**	**44.18**	**11.85**	**1**
		4	**0.75**	**0.7**	**1**	**4.56**	**46.16**	**10.13**	**1**
	Coronal	**5**	**0.95**	**0.8**	**0.85**	**5.13**	**41.95**	**8.17**	**1**
		6	**1**	**0.95**	**1**	**6.13**	**63.15**	**10.30**	**1**
#12	**Apical**	**1**	**0.45**	**0.4**	**1**	**2.67**	**29.29**	**10.96**	**1**
		2	**0.5**	**0.45**	**1**	**2.99**	**35.23**	**11.80**	**1**
	Middle	**3**	**0.55**	**0.55**	**1**	**3.45**	**44.08**	**12.76**	**5**
		4	**0.6**	**0.55**	**1.1**	**3.79**	**42.77**	**11.28**	**5**
	Coronal	**5**	**0.7**	**0.65**	**0.9**	**4.03**	**60.68**	**15.07**	**3**
		6	**0.9**	**0.8**	**0.9**	**5.09**	**49.84**	**9.79**	**5**
#13	**Apical**	**1**	**0.5**	**0.4**	**1**	**2.84**	**45.75**	**16.11**	**1**
		2	**0.7**	**0.65**	**1**	**4.24**	**31.39**	**7.40**	**5**
	Middle	**3**	**0.8**	**0.75**	**0.8**	**4.36**	**27.38**	**6.28**	**1**
		4	**1.1**	**1**	**0.8**	**5.93**	**47.82**	**8.06**	**1**
	Coronal	**5**	**1.3**	**1.25**	**1**	**8.02**	**47.65**	**5.94**	**1**
		6	**1.4**	**1.35**	**1**	**8.65**	**52.36**	**6.06**	**5**
#14	**Apical**	**1**	**0.35**	**0.4**	**0.8**	**2.11**	**11.63**	**5.51**	**1**

		2	**0.6**	**0.55**	**0.9**	**3.43**	**20.41**	**5.95**	**5**
	Middle	**3**	**0.75**	**0.7**	**0.8**	**4.08**	**27.63**	**6.77**	**5**
		4	**0.75**	**0.7**	**0.9**	**4.33**	**54.64**	**12.63**	**4**
	Coronal	**5**	**0.9**	**0.8**	**0.9**	**5.09**	**55.09**	**10.82**	**1**
		6	**1**	**1**	**1**	**6.28**	**49.72**	**7.92**	**5**
#15	**Apical**	**1**	**0.55**	**0.5**	**0.9**	**3.13**	**46.11**	**14.72**	**4**
		2	**0.55**	**0.5**	**1**	**3.30**	**63.18**	**19.14**	**1**
	Middle	**3**	**0.65**	**0.6**	**0.95**	**3.83**	**66.32**	**17.31**	**5**
		4	**0.7**	**0.65**	**0.9**	**4.03**	**58.87**	**14.62**	**4**
	Coronal	**5**	**0.75**	**0.75**	**1**	**4.71**	**51.84**	**11.01**	**2**
		6	**0.85**	**0.8**	**1**	**5.19**	**77.77**	**14.99**	**1**
#16	**Apical**	**1**	**0.55**	**0.5**	**0.9**	**3.13**	**43.37**	**13.85**	**1**
		2	**0.7**	**0.6**	**1**	**4.10**	**45.93**	**11.20**	**1**
	Middle	**3**	**0.9**	**0.9**	**1**	**5.65**	**50.38**	**8.91**	**1**
		4	**1.1**	**1**	**1.1**	**6.95**	**72.12**	**10.38**	**1**
	Coronal	**5**	**1.3**	**1.2**	**1.1**	**8.27**	**45.97**	**5.56**	**2**
		6	**1.35**	**1.35**	**1.1**	**8.89**	**47.49**	**5.34**	**2**
#17	**Apical**	**1**	**0.8**	**0.7**	**0.9**	**4.49**	**50.77**	**11.30**	**5**
		2	**1**	**1**	**0.8**	**5.62**	**42.92**	**7.64**	**5**
	Middle	**3**	**1.2**	**1.1**	**0.9**	**6.89**	**53.97**	**7.83**	**5**
		4	**1.2**	**1.25**	**1**	**7.70**	**57.85**	**7.51**	**4**
	Coronal	**5**	**1.25**	**1.2**	**0.9**	**7.31**	**55.36**	**7.58**	**4**
		6	**1.3**	**1.3**	**1.1**	**8.56**	**66.33**	**7.75**	**2**
#18	**Apical**	**1**	**0.75**	**0.7**	**0.9**	**4.33**	**33.35**	**7.71**	**1**
		2	**0.9**	**0.8**	**0.8**	**4.80**	**47.79**	**9.95**	**2**
	Middle	**3**	**0.9**	**0.85**	**0.9**	**5.22**	**34.41**	**6.59**	**5**
		4	**1**	**0.9**	**0.8**	**5.37**	**25.63**	**4.77**	**5**
	Coronal	**5**	**1.2**	**1.1**	**1.1**	**7.61**	**70.58**	**9.28**	**2**
		6	**1.3**	**1.2**	**1.2**	**8.64**	**80.79**	**9.36**	**2**
#19	**Apical**	**1**	**0.45**	**0.45**	**0.9**	**2.68**	**33.30**	**12.42**	**2**
		2	**0.5**	**0.5**	**0.8**	**2.81**	**44.24**	**15.75**	**1**
	Middle	**3**	**0.7**	**0.6**	**1**	**4.10**	**54.92**	**13.39**	**5**
		4	**0.75**	**0.7**	**0.9**	**4.33**	**60.41**	**13.97**	**4**
	Coronal	**5**	**1**	**0.95**	**0.9**	**5.82**	**33.59**	**5.78**	**2**
		6	**1.25**	**1.1**	**1.1**	**7.82**	**51.93**	**6.64**	**5**
#20	**Apical**	**1**	**0.5**	**0.45**	**1.2**	**3.27**	**44.83**	**13.71**	**5**
		2	**0.6**	**0.55**	**0.8**	**3.23**	**21.17**	**6.54**	**2**
	Middle	**3**	**0.8**	**0.7**	**0.8**	**4.24**	**40.16**	**9.47**	**2**
		4	**0.9**	**0.85**	**0.9**	**5.22**	**66.27**	**12.69**	**5**
	Coronal	**5**	**1**	**0.95**	**0.85**	**5.65**	**55.17**	**9.76**	**2**
		6	**1.2**	**1.1**	**1.1**	**7.61**	**45.69**	**6.00**	**5**

Appendix C: Raw Data for Group 3

Tooth #	Root Level	Sample #	Coronal Radius	Apical Radius	Sample Thickness	Area (A)	Debonding Force (N)	Debonding Stress (Mpa)	Mode of Failure
#21	Apical	1	0.5	0.4	0.9	2.70	43.40	16.10	4
		2	0.5	0.5	1.1	3.29	30.43	9.24	1
	Middle	3	0.55	0.55	0.9	3.28	45.90	14.01	4
		4	0.6	0.55	0.9	3.43	35.90	10.47	1
	Coronal	5	0.8	0.7	1	4.73	34.75	7.34	1
		6	1	0.8	0.85	5.33	35.81	6.72	2
#22	Apical	1	0.45	0.4	0.8	2.39	23.22	9.71	1
		2	0.55	0.5	1	3.30	36.44	11.04	5
	Middle	3	0.7	0.65	0.9	4.03	38.58	9.58	5
		4	0.8	0.75	0.9	4.62	39.48	8.54	5
	Coronal	5	1	0.9	0.8	5.37	43.71	8.14	1
		6	1.2	1.1	0.9	6.89	40.41	5.86	1
#23	Apical	1	0.5	0.45	1.1	3.13	39.83	12.72	1
		2	0.5	0.5	0.7	2.63	20.61	7.85	1
	Middle	3	0.6	0.55	0.85	3.33	31.20	9.36	5
		4	0.65	0.65	1	4.08	32.90	8.06	1
	Coronal	5	0.8	0.7	1	4.73	36.22	7.65	1
		6	0.85	0.8	0.85	4.78	18.57	3.88	5
#24	Apical	1	0.5	0.45	1.1	3.13	51.61	16.48	1
		2	0.6	0.5	1.1	3.64	51.61	14.18	1
	Middle	3	0.7	0.7	1	4.40	49.95	11.36	1
		4	0.75	0.75	1.1	4.94	82.36	16.67	4
	Coronal	5	0.8	0.8	1	5.02	50.61	10.07	1
		6	0.9	0.85	1.05	5.64	49.75	8.82	5
#25	Apical	1	0.4	0.4	0.9	2.38	21.79	9.14	1
		2	0.5	0.5	1.05	3.22	25.72	7.99	1
	Middle	3	0.55	0.55	1.1	3.62	24.44	6.75	3
		4	0.7	0.65	1.1	4.45	64.44	14.48	4
	Coronal	5	0.75	0.7	1.1	4.78	63.71	13.33	4
		6	0.85	0.8	1.1	5.44	54.50	10.02	1
#26	Apical	1	0.45	0.45	1.2	3.10	17.12	5.53	1
		2	0.5	0.5	1	3.14	19.52	6.22	1
	Middle	3	0.55	0.55	1	3.45	21.70	6.28	1
		4	0.65	0.6	1.1	4.12	38.67	9.38	5
	Coronal	5	0.8	0.75	1.15	5.22	32.70	6.26	5
		6	0.9	0.85	1.2	6.03	34.73	5.76	5
#27	Apical	1	0.5	0.4	1.1	2.98	27.04	9.08	1
		2	0.75	0.7	1.3	5.20	60.22	11.59	5

	Middle	**3**	**0.8**	**0.85**	**0.9**	**4.92**	**49.93**	**10.14**	**1**
		4	**1.1**	**1**	**1**	**6.63**	**60.70**	**9.16**	**1**
	Coronal	**5**	**1.3**	**1.25**	**1**	**8.02**	**45.09**	**5.62**	**1**
		6	**1.5**	**1.5**	**1.05**	**9.65**	**59.87**	**6.20**	**2**
#28	**Apical**	**1**	**0.55**	**0.5**	**0.9**	**3.13**	**22.87**	**7.30**	**5**
		2	**0.75**	**0.7**	**1.2**	**4.99**	**43.73**	**8.76**	**1**
	Middle	**3**	**0.9**	**0.8**	**0.8**	**4.80**	**45.18**	**9.40**	**5**
		4	**1.2**	**1.1**	**1.2**	**7.94**	**62.43**	**7.86**	**1**
	Coronal	**5**	**1.4**	**1.35**	**1.35**	**10.04**	**96.56**	**9.61**	**1**
		6	**1.5**	**1.4**	**0.9**	**8.69**	**42.83**	**4.93**	**5**
#29	**Apical**	**1**	**0.5**	**0.45**	**1**	**2.99**	**31.62**	**10.59**	**1**
		2	**0.5**	**0.5**	**0.9**	**2.98**	**35.67**	**11.97**	**5**
	Middle	**3**	**0.9**	**0.8**	**1.1**	**5.62**	**34.56**	**6.14**	**1**
		4	**1**	**0.95**	**1.1**	**6.43**	**77.72**	**12.09**	**4**
	Coronal	**5**	**1.25**	**1.2**	**1**	**7.70**	**68.63**	**8.91**	**1**
		6	**1.3**	**1.25**	**1**	**8.02**	**63.05**	**7.86**	**5**
#30	**Apical**	**1**	**0.45**	**0.4**	**0.7**	**2.24**	**9.97**	**4.46**	**4**
		2	**0.5**	**0.5**	**0.8**	**2.81**	**19.70**	**7.01**	**5**
	Middle	**3**	**0.6**	**0.55**	**1**	**3.62**	**38.11**	**10.54**	**1**
		4	**0.75**	**0.7**	**0.8**	**4.08**	**26.81**	**6.57**	**5**
	Coronal	**5**	**0.75**	**0.75**	**1.1**	**4.94**	**43.51**	**8.81**	**1**
		6	**0.8**	**0.8**	**1.2**	**5.50**	**102.25**	**18.58**	**4**

Appendix D: Raw Data for Group 4

Tooth #	**Root Level**	**Sample #**	**Coronal Radius**	**Apical Radius**	**Sample Thickness**	**Area (A)**	**Debonding Force (N)**	**Debonding Stress (Mpa)**	**Mode of Failure**
#31	**Apical**	**1**	**0.6**	**0.5**	**0.8**	**3.11**	**17.34**	**5.58**	**2**
		2	**0.6**	**0.55**	**0.9**	**3.43**	**23.21**	**6.76**	**2**
	Middle	**3**	**0.75**	**0.65**	**0.9**	**4.19**	**53.89**	**12.85**	**5**
		4	**0.75**	**0.65**	**1.1**	**4.63**	**41.89**	**9.04**	**5**
	Coronal	**5**	**0.8**	**0.75**	**1**	**4.87**	**93.64**	**19.21**	**4**
		6	**1.1**	**1**	**1.1**	**6.95**	**80.71**	**11.62**	**2**
#32	**Apical**	**1**	**0.4**	**0.35**	**0.9**	**2.24**	**24.25**	**10.84**	**1**
		2	**0.45**	**0.4**	**1**	**2.67**	**25.48**	**9.53**	**Missing**
	Middle	**3**	**0.5**	**0.4**	**1**	**2.84**	**24.31**	**8.56**	**3**
		4	**0.65**	**0.5**	**1.1**	**3.83**	**5.30**	**1.39**	**3**
	Coronal	**5**	**0.85**	**0.7**	**1.2**	**5.38**	**82.60**	**15.35**	**1**

		6	**1**	**0.95**	**0.9**	**5.82**	**39.89**	**6.86**	**1**
#33	**Apical**	**1**	**0.5**	**0.45**	**1**	**2.99**	**16.42**	**5.50**	**1**
		2	**0.55**	**0.5**	**0.7**	**2.76**	**13.06**	**4.73**	**2**
	Middle	**3**	**0.65**	**0.55**	**1**	**3.79**	**10.72**	**2.83**	**2**
		4	**0.65**	**0.65**	**1**	**4.08**	**14.76**	**3.62**	**2**
	Coronal	**5**	**0.95**	**0.9**	**1.1**	**6.10**	**38.61**	**6.33**	**5**
		6	**1.1**	**1**	**0.8**	**5.93**	**69.69**	**11.74**	**4**
#34	**Apical**	**1**	**0.5**	**0.4**	**1.2**	**3.11**	**34.06**	**10.96**	**1**
		2	**0.55**	**0.5**	**1**	**3.30**	**46.26**	**14.01**	**3**
	Middle	**3**	**0.65**	**0.6**	**0.9**	**3.73**	**49.75**	**13.34**	**5**
		4	**0.7**	**0.6**	**1**	**4.10**	**69.88**	**17.03**	**1**
	Coronal	**5**	**0.75**	**0.7**	**1**	**4.56**	**23.87**	**5.24**	**2**
		6	**1**	**0.9**	**1**	**6.00**	**62.98**	**10.50**	**5**
#35	**Apical**	**1**	**0.5**	**0.5**	**1**	**3.14**	**22.80**	**7.26**	**1**
		2	**0.7**	**0.5**	**1.2**	**4.20**	**24.09**	**5.74**	**1**
	Middle	**3**	**0.65**	**0.6**	**1**	**3.93**	**23.08**	**5.87**	**1**
		4	**0.8**	**0.75**	**1**	**4.87**	**31.81**	**6.53**	**1**
	Coronal	**5**	**0.9**	**0.85**	**1**	**5.50**	**12.63**	**2.30**	**1**
		6	**0.95**	**0.95**	**1**	**5.97**	**10.00**	**1.68**	**1**
#36	**Apical**	**1**	**0.6**	**0.5**	**1**	**3.47**	**38.18**	**11.00**	**5**
		2	**0.9**	**0.8**	**1.1**	**5.62**	**49.98**	**8.89**	**5**
	Middle	**3**	**0.95**	**0.85**	**1.1**	**5.95**	**51.42**	**8.63**	**2**
		4	**1.05**	**0.9**	**1.1**	**6.49**	**39.12**	**6.03**	**5**
	Coronal	**5**	**1.15**	**1.1**	**1.1**	**7.42**	**54.65**	**7.37**	**2**
		6	**1.2**	**1.2**	**0.8**	**6.74**	**25.09**	**3.72**	**2**
#37	**Apical**	**1**	**0.55**	**0.5**	**1**	**3.30**	**53.47**	**16.20**	**1**
		2	**0.65**	**0.5**	**1.2**	**3.99**	**66.86**	**16.75**	**5**
	Middle	**3**	**0.7**	**0.6**	**0.8**	**3.67**	**49.51**	**13.48**	**5**
		4	**0.95**	**0.85**	**1**	**5.68**	**88.45**	**15.57**	**2**
	Coronal	**5**	**1.05**	**1**	**0.9**	**6.12**	**51.77**	**8.47**	**5**
		6	**1.25**	**1.15**	**0.9**	**7.19**	**71.42**	**9.93**	**2**
#38	**Apical**	**1**	**0.55**	**0.5**	**1**	**3.30**	**71.01**	**21.51**	**1**
		2	**0.6**	**0.55**	**1**	**3.62**	**54.11**	**14.97**	**1**
	Middle	**3**	**0.65**	**0.6**	**0.9**	**3.73**	**53.34**	**14.31**	**5**
		4	**0.65**	**0.6**	**1**	**3.93**	**71.29**	**18.14**	**4**
	Coronal	**5**	**0.85**	**0.8**	**1**	**5.19**	**75.78**	**14.61**	**4**
		6	**0.85**	**0.85**	**0.9**	**5.06**	**63.21**	**12.48**	**4**
#39	**Apical**	**1**	**0.55**	**0.5**	**0.9**	**3.13**	**19.11**	**6.10**	**1**
		2	**0.55**	**0.5**	**0.9**	**3.13**	**18.26**	**5.83**	**2**
	Middle	**3**	**0.6**	**0.55**	**1**	**3.62**	**25.54**	**7.06**	**2**
		4	**0.65**	**0.6**	**1**	**3.93**	**17.15**	**4.36**	**2**
	Coronal	**5**	**0.65**	**0.65**	**1**	**4.08**	**41.17**	**10.09**	**5**
		6	**0.8**	**0.7**	**1**	**4.73**	**27.85**	**5.88**	**2**
#40	**Apical**	**1**	**0.45**	**0.4**	**1**	**2.67**	**42.82**	**16.02**	**5**
		2	**0.55**	**0.5**	**1**	**3.30**	**40.42**	**12.25**	**5**

	Middle	**3**	**0.65**	**0.6**	**0.9**	**3.73**	**41.88**	**11.23**	**3**
		4	**0.7**	**0.7**	**1**	**4.40**	**53.92**	**12.27**	**1**
	Coronal	**5**	**0.75**	**0.7**	**1**	**4.56**	**56.44**	**12.38**	**3**
		6	**0.8**	**0.7**	**0.9**	**4.49**	**56.93**	**12.67**	**2**

Appendix E: Raw Data for Group 5

Tooth #	**Root Level**	**Sample #**	**Coronal Radius**	**Apical Radius**	**Sample Thickness**	**Area (A)**	**Debonding Force (N)**	**Debonding Stress (Mpa)**	**Mode of Failure**
#41	**Apical**	**1**	**0.4**	**0.4**	**1.1**	**2.63**	**48.56**	**18.43**	**3**
		2	**0.5**	**0.45**	**1**	**2.99**	**30.19**	**10.11**	**5**
	Middle	**3**	**0.55**	**0.5**	**0.9**	**3.13**	**30.82**	**9.84**	**5**
		4	**0.6**	**0.5**	**0.9**	**3.29**	**37.43**	**11.36**	**1**
	Coronal	**5**	**0.7**	**0.65**	**0.9**	**4.03**	**46.90**	**11.65**	**5**
		6	**0.75**	**0.7**	**0.9**	**4.33**	**63.11**	**14.59**	**Missing**
#42	**Apical**	**1**	**0.45**	**0.4**	**0.9**	**2.54**	**20.71**	**8.17**	**1**
		2	**0.5**	**0.5**	**0.9**	**2.98**	**13.59**	**4.56**	**1**
	Middle	**3**	**0.6**	**0.55**	**0.9**	**3.43**	**4.87**	**1.42**	**1**
		4	**0.8**	**0.75**	**0.85**	**4.49**	**59.53**	**13.25**	**4**
	Coronal	**5**	**1**	**0.9**	**0.8**	**5.37**	**37.53**	**6.99**	**5**
		6	**1**	**0.95**	**0.9**	**5.82**	**53.23**	**9.15**	**5**
#43	**Apical**	**1**	**0.45**	**0.45**	**0.9**	**2.68**	**24.65**	**9.19**	**1**
		2	**0.55**	**0.5**	**0.9**	**3.13**	**33.32**	**10.64**	**5**
	Middle	**3**	**0.6**	**0.55**	**1**	**3.62**	**36.41**	**10.07**	**5**
		4	**0.65**	**0.65**	**0.85**	**3.76**	**29.75**	**7.91**	**5**
	Coronal	**5**	**0.9**	**0.85**	**0.9**	**5.22**	**38.61**	**7.40**	**2**
		6	**1.1**	**1**	**0.9**	**6.29**	**69.43**	**11.04**	**2**
#44	**Apical**	**1**	**0.4**	**0.35**	**0.9**	**2.24**	**18.43**	**8.24**	**1**
		2	**0.5**	**0.5**	**0.9**	**2.98**	**23.67**	**7.95**	**5**
	Middle	**3**	**0.7**	**0.65**	**1**	**4.24**	**31.47**	**7.41**	**5**
		4	**0.9**	**0.9**	**1**	**5.65**	**43.06**	**7.62**	**5**
	Coronal	**5**	**1**	**0.95**	**0.85**	**5.65**	**31.73**	**5.61**	**5**
		6	**1.2**	**1**	**1**	**7.04**	**63.55**	**9.02**	**5**
#45	**Apical**	**1**	**0.45**	**0.45**	**1**	**2.83**	**35.47**	**12.55**	**Missing**
		2	**0.55**	**0.5**	**1**	**3.30**	**36.58**	**11.08**	**1**
	Middle	**3**	**0.55**	**0.55**	**0.9**	**3.28**	**50.31**	**15.35**	**5**
		4	**0.6**	**0.6**	**0.8**	**3.37**	**62.11**	**18.43**	**4**
	Coronal	**5**	**0.75**	**0.7**	**0.95**	**4.44**	**34.65**	**7.80**	**2**
		6	**0.95**	**0.8**	**1**	**5.56**	**35.93**	**6.47**	**2**

#46	**Apical**	**1**	**0.4**	**0.35**	**0.85**	**2.17**	**15.77**	**7.25**	**1**
		2	**0.45**	**0.45**	**0.9**	**2.68**	**16.65**	**6.21**	**1**
	Middle	**3**	**0.5**	**0.5**	**1.05**	**3.22**	**45.02**	**13.99**	**2**
		4	**0.55**	**0.5**	**0.9**	**3.13**	**43.46**	**13.87**	**2**
	Coronal	**5**	**0.75**	**0.7**	**1**	**4.56**	**37.52**	**8.23**	**1**
		6	**0.8**	**0.75**	**0.8**	**4.36**	**27.88**	**6.40**	**1**
#47	**Apical**	**1**	**0.45**	**0.45**	**0.85**	**2.61**	**12.16**	**4.67**	**1**
		2	**0.5**	**0.45**	**1.1**	**3.13**	**53.47**	**17.07**	**2**
	Middle	**3**	**0.55**	**0.55**	**1.1**	**3.62**	**45.18**	**12.47**	**2**
		4	**0.7**	**0.65**	**0.85**	**3.91**	**43.74**	**11.17**	**2**
	Coronal	**5**	**0.9**	**0.8**	**1.1**	**5.62**	**39.68**	**7.06**	**2**
		6	**1.2**	**1.1**	**1**	**7.26**	**27.95**	**3.85**	**5**
#48	**Apical**	**1**	**0.45**	**0.45**	**1**	**2.83**	**24.54**	**14.22**	**3**
		2	**0.5**	**0.5**	**1**	**3.14**	**27.54**	**8.77**	**5**
	Middle	**3**	**0.6**	**0.55**	**1.1**	**3.79**	**41.88**	**11.05**	**Missing**
		4	**0.6**	**0.6**	**0.9**	**3.57**	**53.92**	**15.08**	**3**
	Coronal	**5**	**0.65**	**0.65**	**1.05**	**4.18**	**34.51**	**8.25**	**5**
		6	**0.75**	**0.7**	**1**	**4.56**	**27.43**	**6.02**	**2**
#49	**Apical**	**1**	**0.45**	**0.4**	**1.1**	**2.80**	**19.11**	**6.82**	**1**
		2	**0.55**	**0.55**	**1.1**	**3.62**	**38.71**	**10.68**	**2**
	Middle	**3**	**0.55**	**0.55**	**0.9**	**3.28**	**43.45**	**13.26**	**2**
		4	**0.6**	**0.55**	**0.95**	**3.52**	**36.15**	**10.26**	**5**
	Coronal	**5**	**0.7**	**0.65**	**0.8**	**3.80**	**35.28**	**9.29**	**5**
		6	**0.9**	**0.85**	**1.1**	**5.77**	**53.48**	**9.27**	**5**
#50	**Apical**	**1**	**0.5**	**0.5**	**1.1**	**3.29**	**40.29**	**12.23**	**4**
		2	**0.8**	**0.7**	**1**	**4.73**	**63.81**	**13.48**	**2**
	Middle	**3**	**0.85**	**0.8**	**1.1**	**5.44**	**40.29**	**7.41**	**5**
		4	**1**	**1**	**1.1**	**6.59**	**78.99**	**11.99**	**2**
	Coronal	**5**	**1.1**	**1.1**	**1.1**	**7.25**	**75.31**	**10.39**	**5**
		6	**1.25**	**1.15**	**1.2**	**8.29**	**59.58**	**7.19**	**2**

Appendix F: Raw Data for Group 6

Tooth #	Root Level	Sample #	Coronal Radius	Apical Radius	Sample Thickness	Area (A)	Debonding Force (N)	Debonding Stress (Mpa)	Mode of Failure
#51	Apical	1	0.45	0.45	0.8	2.53	1.87	0.74	4
		2	0.5	0.45	0.8	2.67	20.54	7.69	5
	Middle	3	0.55	0.5	0.9	3.13	18.89	6.03	2
		4	0.6	0.5	0.9	3.29	12.91	3.92	1
	Coronal	5	0.75	0.7	0.9	4.33	3.83	0.89	2
		6	0.8	0.8	1	5.02	27.35	5.44	1
#52	Apical	1	0.5	0.45	0.8	2.67	2.91	1.09	1
		2	0.5	0.5	1	3.14	1.70	0.54	1
	Middle	3	0.6	0.6	0.9	3.57	1.22	0.34	1
		4	0.8	0.75	0.85	4.49	1.44	0.32	5
	Coronal	5	0.9	0.85	0.9	5.22	1.68	0.32	5
		6	1.1	1	1	6.63	2.23	0.34	5
#53	Apical	1	0.45	0.4	0.7	2.24	8.98	4.01	2
		2	0.55	0.45	0.9	3.00	14.30	4.78	2
	Middle	3	0.65	0.6	1	3.93	16.42	4.18	2
		4	0.85	0.8	1	5.19	15.75	3.04	2
	Coronal	5	0.9	0.9	0.9	5.36	47.50	8.86	5
		6	1	1	0.8	5.62	54.27	9.66	5
#54	Apical	1	0.45	0.35	1	2.52	15.74	6.23	2
		2	0.45	0.4	0.9	2.54	12.07	4.76	5
	Middle	3	0.5	0.5	1	3.14	17.25	5.49	1
		4	0.65	0.6	0.8	3.52	20.92	5.95	5
	Coronal	5	0.8	0.7	0.9	4.49	20.94	4.66	1
		6	0.9	0.8	0.85	4.95	37.26	7.53	5
#55	Apical	1	٠.٤	0.35	0.9	2.24	11.29	5.05	2
		2	0.45	0.4	0.8	2.39	16.29	6.81	1
	Middle	3	0.5	0.45	0.8	2.67	15.09	5.65	2
		4	0.55	0.5	0.8	2.95	22.34	7.56	2
	Coronal	5	0.7	0.65	0.8	3.80	26.34	6.94	3
		6	0.85	0.8	1.1	5.44	47.01	8.64	2
#56	Apical	1	0.45	0.4	0.9	2.54	17.85	7.04	5
		2	0.55	0.5	1	3.30	21.08	6.38	2
	Middle	3	0.6	0.55	1	3.62	16.30	4.51	2
		4	0.75	0.7	0.9	4.33	29.36	6.79	2
	Coronal	5	0.9	0.85	1	5.50	40.49	7.36	2

		6	**1.1**	**1**	**0.8**	**5.93**	**47.21**	**7.95**	**5**
#57	**Apical**	**1**	**0.4**	**0.4**	**0.7**	**2.10**	**19.61**	**9.33**	**5**
		2	**0.5**	**0.45**	**0.9**	**2.83**	**25.33**	**8.94**	**2**
	Middle	**3**	**0.65**	**0.5**	**0.9**	**3.47**	**33.24**	**9.58**	**2**
		4	**0.7**	**0.65**	**0.7**	**3.55**	**36.59**	**10.30**	**2**
	Coronal	**5**	**0.8**	**0.75**	**1**	**4.87**	**34.68**	**7.12**	**5**
		6	**0.9**	**0.9**	**0.9**	**5.36**	**33.74**	**6.29**	**5**
#58	**Apical**	**1**	**0.4**	**0.35**	**0.9**	**2.24**	**39.62**	**17.71**	**2**
		2	**0.4**	**0.4**	**1.2**	**2.75**	**57.26**	**20.81**	**1**
	Middle	**3**	**0.5**	**0.45**	**1**	**2.99**	**61.25**	**20.51**	**1**
		4	**0.55**	**0.55**	**1.1**	**3.62**	**61.03**	**16.85**	**2**
	Coronal	**5**	**0.7**	**0.65**	**1.05**	**4.35**	**57.04**	**13.12**	**5**
		6	**0.9**	**0.8**	**1.05**	**5.50**	**15.53**	**2.83**	**2**
#59	**Apical**	**1**	**0.45**	**0.35**	**0.8**	**2.26**	**22.43**	**9.92**	**1**
		2	**0.45**	**0.45**	**0.9**	**2.68**	**34.98**	**13.05**	**3**
	Middle	**3**	**0.5**	**0.5**	**0.9**	**2.98**	**33.57**	**11.27**	**3**
		4	**0.6**	**0.55**	**1**	**3.62**	**35.26**	**9.75**	**2**
	Coronal	**5**	**0.75**	**0.7**	**0.8**	**4.08**	**21.77**	**5.34**	**1**
		6	**0.9**	**0.85**	**1.1**	**5.77**	**40.59**	**7.03**	**2**
#60	**Apical**	**1**	**0.5**	**0.5**	**1**	**3.14**	**20.65**	**6.58**	**2**
		2	**0.65**	**0.55**	**1.1**	**3.97**	**22.19**	**5.59**	**5**
	Middle	**3**	**0.7**	**0.7**	**1**	**4.40**	**25.60**	**5.82**	**2**
		4	**0.8**	**0.75**	**1.1**	**5.11**	**43.42**	**8.50**	**2**
	Coronal	**5**	**0.85**	**0.8**	**1.1**	**5.44**	**54.30**	**9.98**	**5**
		6	**1.1**	**1**	**0.7**	**5.56**	**23.41**	**4.21**	**5**

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