RESEARCH PAPER

A Comparative Evaluation of Microleakage of Cement Retained Implant Copings Luted with Four Commercially Available Luting Cements. An in Vitro Study

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ABSTRACT
Background: The success of cement-retained implant restorations is often compromised by microleakage at the abutment-coping interface, which can lead to peri-implant complications. This study was designed to evaluate and compare the sealing ability of four different luting agents.
Materials and Methods: Forty Nickel-Chromium copings were fabricated and luted to Titanium implant abutments. The specimens were divided into four groups: Group I (Zinc Phosphate), Group II (Zinc Polycarboxylate), Group III (Glass Ionomer Cement), and Group IV (Resin Cement). After thermocycling microleakage was assessed using 0.5% basic fuchsin dye penetration and stereomicroscopic examination.
Results: Resin cement (Group IV) demonstrated the lowest mean microleakage score (0.425 ± 0.265), followed by Glass Ionomer (1.225 ± 0.448), Zinc Polycarboxylate (2.225 ± 0.448), and Zinc Phosphate (3.225 ± 0.448).
Conclusion: Adhesive resin cements provide a significantly superior marginal seal compared to traditional acid-base cements in implant-supported restorations.
Keywords: *Microleakage, Cement-Retained Restorations, Luting Cements, Dental Implants, Marginal Seal, Titanium Abutments, Dye Penetration, Nickel-Chromium Alloy*
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AIMS AND OBJECTIVES

The primary objective of this in vitro study is to comparatively evaluate the microleakage of metallic Nickel-Titanium copings luted to Titanium abutments using four different luting agents:

1. To measure the depth of dye penetration in specimens luted with Zinc Phosphate, Zinc Polycarboxylate, Glass Ionomer, and Resin cements.
2. To determine which luting agent offers the most effective hermetic seal under simulated oral conditions (thermocycling).
3. To provide evidence-based guidelines for clinicians in selecting luting agents that balance sealing capability and clinical utility.

INTRODUCTION

The rehabilitation of edentulous patients has been revolutionized by endosseous dental implants. Since

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Brånemark's discovery of osseointegration, the focus of implant dentistry has shifted from achieving mere bone-implant survival to ensuring long-term prosthetic success through stability, function, and aesthetics. Central to this success is the restorative interface—the junction between the implant abutment and the final prosthesis.

The Shift to Cement-Retained Restorations While early implant restorations were primarily screw-retained for "retrievability," they faced challenges including poor aesthetics due to occlusal access holes and difficulty achieving passive fit. Cement-retained restorations gained popularity by mimicking conventional prosthodontics, offering superior aesthetics, simplified occlusion, and a "passive fit" where the cement layer compensates for minor framework discrepancies. However, this introduced a new vulnerability: **microleakage**.

The Phenomenon of Microleakage Microleakage is the clinically undetectable passage of bacteria and fluids between the abutment surface and the coping. Unlike natural teeth, where leakage affects the pulp, implants are surrounded by a mechanically weaker "permucosal seal." Microleakage creates a bacterial reservoir; under masticatory loading, a "pumping effect" can force endotoxins into the peri-implant sulcus, inciting peri-implant mucositis or irreversible peri-implantitis and bone loss. Thus, the sealing ability of the luting agent is a biological imperative for tissue health.

Substrates: Titanium and Nickel-Chromium The sealing challenge is compounded by the substrates involved. This study evaluates medical-grade **Titanium (Ti-6Al-4V)** abutments and **Nickel-Chromium/Nickel-Titanium** copings. Unlike natural hydroxyapatite, these metallic surfaces rely on surface oxides and mechanical roughening (sandblasting) for adhesion. The luting agent must bridge these dissimilar metals while resisting thermal stresses.

Luting Agents Under Evaluation The choice of cement involves a compromise between retention and retrievability. This study evaluates four distinct classes:

1. **Zinc Phosphate:** A legacy micromechanical cement with high rigidity but significant solubility in oral fluids and no chemical adhesion.
2. **Zinc Polycarboxylate:** The first to offer chemical adhesion (chelation), often favored for "semi-permanent" cementation due to its retrievability, though it may deform under heavy loads.
3. **Glass Ionomer Cement (GIC):** Provides chemical bonding to metal oxides but is brittle and sensitive to moisture contamination during its initial setting phase.
4. **Resin Cement:** Consisting of a polymer matrix (e.g., Bis-GMA), these offer the highest strength and insolubility. Modern formulations (e.g., 10-MDP) bond chemically to titanium, though their high retention makes retrievability difficult.

Rationale for the Study Despite the clinical prevalence of these materials, there is a paucity of data comparing their performance specifically on Nickel-Titanium copings luted to Titanium abutments. Given the differing coefficients of thermal expansion between these alloys, the cement interface is under constant stress. This *in vitro* study aims to provide evidence-based guidelines by evaluating microleakage through standardized thermocycling and dye penetration, helping clinicians balance sealing efficacy with clinical utility.

MATERIALS AND METHODOLOGY

- **IMPLANT ANALOGUE:**

Implant analogue of diameter 4.5 mm (Noris NM-T6004) internal hex is selected. This represents a standard size used for most posterior teeth.

Length of 10 mm is selected as this provides enough surface area for the surrounding plaster to grip the analogue securely without the risk of rotation or displacement during testing.

- **ABUTMENT ANALOGUES**:

A straight type of titanium "cement-retained" abutment (Noris abutment NM-A5909) is used.

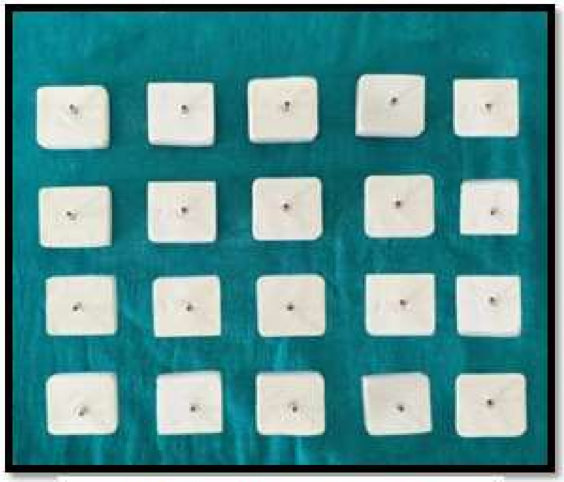
Gingival Height of **2 mm** is used as this height ensures the margin of the future crown sits just above the "gum line" of the plaster model.

Abutment height of **9.5 mm** and diameter **4.5mm** is selected to provide adequate surface area for the luting cement being tested.

The straight titanium abutments were connected to their corresponding mounted implant analogues and tightened to a torque of 20Ncm using a calibrated analogue torque wrench, in accordance with standard prosthetic protocols.

- **MOUNTING OF IMPLANT ANALOGUES:**

The mounting of the implant analogues was performed using a standardized hand- mixing technique with Type II plaster (Kaldent). Distilled water and powder were proportioned ratio. The plaster was spatulated manually against the walls of a rubber bowl for 60 seconds until a homogenous consistency was achieved. To ensure a bubble-free mount, the mixture was placed on a dental vibrator (figure) during the pouring process into molds (30mm x 25mm x 20mm in dimension). Each analogue was held in a vertical orientation and submerged until the implant platform was flush with the plaster surface. The specimens were allowed to bench-set for one hour.

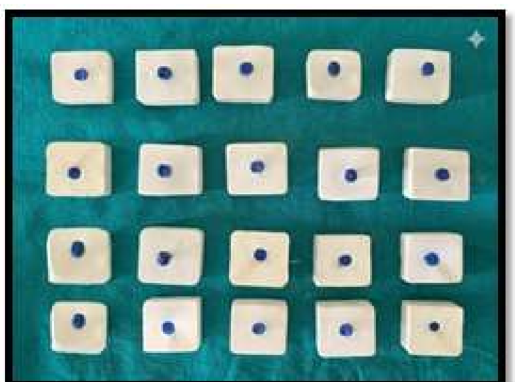


MOUNTED ABUTMENT ANALOG

- **NICKEL-CHROMIUM (NI-CR) ALLOY**: Used for the fabrication of the metallic copings. Nickel-Chromium (Ni-Cr) alloy was selected as the base metal substrate for fabricating the copings due to its exceptional mechanical properties, high modulus of elasticity, and cost-effectiveness. In fixed prosthodontics, this non-precious alloy provides superior rigidity in thin cross-sections, effectively resisting deformation under functional loads.

FABRICATION OF WAX PATTERN

Patterns were prepared using Type II inlay wax with a uniform thickness of 0.5 mm. To maintain this specific thickness across all samples, a putty index was created from a master pattern and used for all subsequent wax-ups



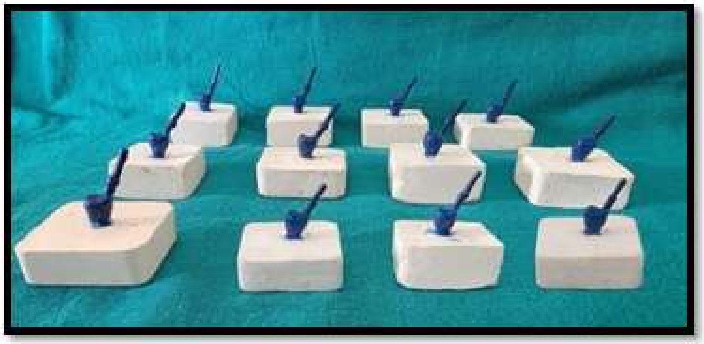
WAX PATTERNS

Investing

The wax pattern was sprued. A sprue former was made of wax, and a reservoir was attached to the sprue. The length of the sprue was adjusted so that the wax pattern was approximately ¼ inch from the casting ring.[42]After spuring, the wax pattern was carefully removed from the dies so as the minimize distortion of the wax pattern.

They were then attached to the crucible former and coated with a surface tension reducing agent. A single layer of ceramic liner was adapted to the casting ring and moistened by dipping a bowl of water, and the excess water was shaken away. They were invested with phosphate – bonded investment material (60 gm of powder to 16 ml of 100% mixing liquid).

The investment powder and liquid were hand spatulated for 15 to 20 seconds to incorporate powder.[43] Then the investment was mechanically vacuum mixed for 60 seconds. After placing the lined casting ring over the pattern, with the aid of vibration, the investment was poured down the side of the ring. The ring was filled slowly. The investment was allowed to set for 2 to 3 hours before proceeding with burnout.[44]



SPRUE AND RESERVOIR ATTACHMENT

Burnout

The casting ring was placed in a burnout furnace at room temperature and the temperature was raised to 250ºC maintained for 60 minutes. Thereafter the temperature was raised to 950ºC and held for 30 minutes.

Casting

- AFTER completion of the burnout the casting procedure was carried out in an induction casting using nickel – chromium (Ni-Cr) alloy. Nickel-chromium (ni-cr) alloy used for the fabrication of the metallic copings. Nickel-Chromium (Ni-Cr) alloy was selected as the base metal substrate for fabricating the copings due to its exceptional mechanical properties, high modulus of elasticity, and cost-effectiveness. In fixed prosthodontics, this non-precious alloy provides superior rigidity in thin cross-sections, effectively resisting deformation under functional loads.

NICKEL-CHROMIUM COPINGS

Recovery of the Casting

The casting were recovered by divesting the investment. Burs were used to remove the investment from the inner surface of the casting such as a thin layer investment left behind. Sandblasting was done to remove the residual investment and oxide layer.

LUTING CEMENTS (TEST GROUPS).

1. Zinc Polycarboxylate Cement
2. Zinc Phosphate Luting Cement.
3. Glass ionomer cement
4. Resin cement

➢ **CEMENTATION PROCEDURE**

a) Zinc Phosphate Cement (Group III)

The article outlines the following specific protocol for this cement:

- **Mixing:** The cement was mixed strictly in accordance with the manufacturer's instructions regarding mixing time, mixing conditions, and powder-to-liquid ratio.
- **Application:** The luting agent was applied completely on all internal walls of the metallic copings.
- **Seating:** The coping was seated onto the abutment analogue with firm finger pressure for **10 seconds**.
- **Loading:** Immediately following seating, a constant **2 kg axial load** was applied for **5 minutes** using a customized holding device to ensure equal load distribution.
- **Finishing:** After the setting time, excess cement was

removed using a Hollenback carver.

- **Setting:** The specimens were allowed to set for 24 hours before further testing.

b) Zinc Polycarboxylate Cement (Group II)
The procedure for this cement followed the exact same standardized protocol as Zinc Phosphate:

- **Mixing:** Mixed according to the manufacturer's specific instructions.
- **Application:** Applied to cover the internal walls of the coping.
- **Seating & Loading:** Seated with finger pressure (10 seconds) followed by the standardized **2 kg load for 5 minutes**.
- **Finishing:** Excess cement removed after the final set.
- **Setting:** Left undisturbed for 24 hours.

c) Glass Ionomer Cement

Mixing: Powder and liquid dispensed in manufacturer-recommended ratio and mixed rapidly (within 45–60 seconds) on a paper pad or glass slab until a glossy, homogenous consistency is achieved.

Application: A thin, uniform layer of cement is applied to the internal walls of the coping and the axial walls of the abutment.

Seating & Loading: Seated with finger pressure (10 seconds) followed by the standardized **2 kg load for 5 minutes** using the customized holding device.

Finishing: Excess cement is removed carefully when the material reaches a rubbery stage, prior to the final set, to avoid damaging the marginal seal.

Setting: Left undisturbed for 24 hours.

d) Resin Cement

Mixing: Base and catalyst pastes are mixed (or dispensed via automix tip) according to the manufacturer's instructions to ensure a void-free, uniform mix.

Application: The cement is applied directly to the internal surface of the coping (and optionally the abutment, depending on the system).

Seating & Loading: Seated with finger pressure (10 seconds) followed by the standardized **2 kg load for 5 minutes** using the customized holding device.

Finishing: Excess cement is removed after a brief "tack cure" (2–5 seconds) or when the cement reaches a gel state. The margins are then light-cured (if dual-cure) or allowed to chemically cure completely.

Setting: Left undisturbed for 24 hours.

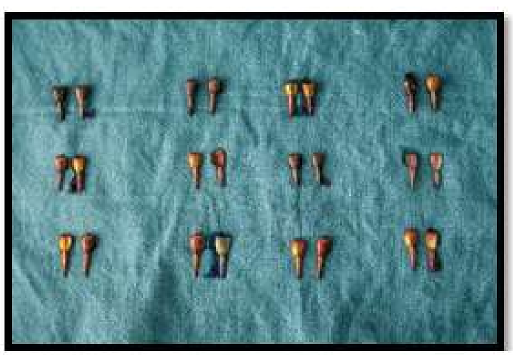
CHEMICALS AND INDICATORS

Dye Penetration
The dye penetration test was the primary method used to evaluate the sealing ability of the luting agents. Following the thermocycling process, the cemented specimens were immersed in a **0.5% aqueous solution of basic fuchsin** for a duration of **24 hours**. Basic fuchsin is an organic dye widely used in microleakage studies because it effectively acts as a tracer, diffusing into micro-spaces created by cement dissolution or poor adaptation.

EVALUATION OF MICROLEAKAGE

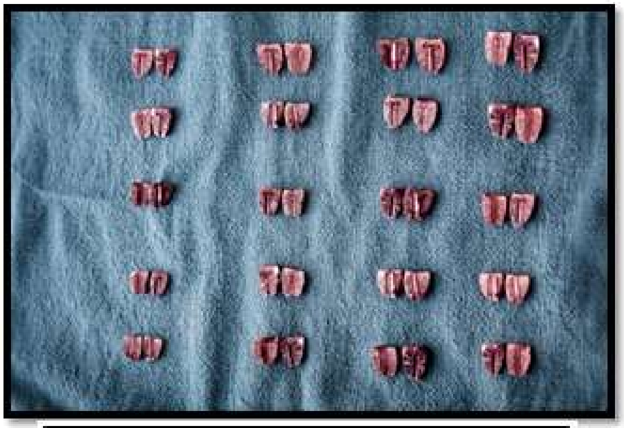
➢ **Thermocycling**
After 24 h, the cemented specimens were removed from plaster blocks and subjected to 5000 cycles of thermocycling, it was done to simulate oral environment.

➢ **Dye Penetration Protocol**
- Following the thermocycling process, the cemented specimens were removed from the water baths.
- They were immediately immersed in a 0.5% aqueous solution of basic fuchsin dye.
- The immersion period lasted for 24 hours to allow sufficient time for the dye to act as a tracer and penetrate any microscopic voids or gaps present at the cement-abutment interface.



CEMENTED SPECIMEN KEPT IN BASIC FUSCHIN DYE

- **Specimen Sectioning**
- After dye exposure, the specimens were cleaned and prepared for internal examination.
- Each coping was sectioned longitudinally along the buccolingual axis.
- A carborundum disc was used for the sectioning procedure to ensure a clean cut through the metal coping and titanium abutment without distorting the cement interface.



SECTIONED SPECIMEN

- **Microscopic Examination**
- The sectioned halves were viewed under a stereomicroscope.
- A magnification of 40x was utilized to clearly visualize the extent of dye penetration along the internal walls.

SECTIONED SPECIMEN UNDER STEREOMICROSCOPE

- **Scoring Methodology**
- To minimize the risk of false-negative results, a multiple surface scoring method was employed.
- Microleakage scores were recorded at two interfaces (buccal and lingual) for each sectioned specimen.
- This resulted in a total of four scores per specimen, ensuring a comprehensive assessment of the marginal seal.

Scoring Criteria (Tjan et al.) The depth of dye penetration was quantified using the following ordinal scale:

- Score 0: No microleakage visible on the axial wall.
- Score 1: Microleakage extending up to 1/3rd of the axial wall length.
- Score 2: Microleakage extending up to 2/3rd of the axial wall length.

- Score 3: Microleakage extending along the full length of the axial wall.
- Score 4: Microleakage extending onto the occlusal surface

STAGE 0 MICROLEAKAGE

STAGE 1 MICROLEAKAGE

STAGE 2 MICROLEAKAGE

STAGE 3 MICROLEAKAGE

STAGE 4 MICROLEAKAGE

RESULTS

A total of 40 implant coping specimens were evaluated in the present in vitro study, with 10 specimens in each of the four study groups based on the type of luting cement used. Microleakage was assessed at four predetermined sites, namely Buccal 1, Buccal 2, Lingual 1, and Lingual 2, and the mean microleakage score was calculated for each group. The results were expressed as mean and standard deviation, and intergroup as well as intragroup comparisons were carried out to determine the effect of different commercially available luting cements on the degree of microleakage.

Table 1: Group-wise descriptive statistics of microleakage scores at all measured sites

Group	Luting cement used	Buccal 1 Mean ± SD	Buccal 2 Mean ± SD	Lingual 1 Mean ± SD	Lingual 2 Mean ± SD	Overall mean microleakage score Mean ± SD
I	Zinc phosphate cement	3.200 ± 0.632	3.200 ± 0.632	3.300 ± 0.675	3.200 ± 0.632	3.225 ± 0.448
II	Zinc polycarboxylate cement	2.200 ± 0.632	2.200 ± 0.632	2.200 ± 0.632	2.300 ± 0.675	2.225 ± 0.448
III	Glass ionomer cement	1.200 ± 0.632	1.200 ± 0.632	1.200 ± 0.632	1.300 ± 0.675	1.225 ± 0.448
IV	Resin cement	0.400 ± 0.516	0.400 ± 0.516	0.400 ± 0.516	0.500 ± 0.527	0.425 ± 0.265

Table 1 shows the group-wise descriptive statistics of microleakage scores recorded at Buccal 1, Buccal 2, Lingual 1, and Lingual 2 for the four luting cement groups. Group I, luted with zinc phosphate cement, showed the highest mean microleakage scores at all measured sites, with an overall mean score of 3.225 ± 0.448, indicating the greatest dye penetration and the poorest marginal seal. Group II, luted with zinc polycarboxylate cement, showed lower mean values than Group I, with an overall mean score of 2.225 ± 0.448, suggesting moderate microleakage. Group III, luted with glass ionomer cement, demonstrated further reduction in microleakage, with an overall mean score of 1.225 ± 0.448. Group IV, luted with resin cement, showed the lowest mean values at all measured sites, with an overall mean score of 0.425 ± 0.265, indicating the least dye penetration and the best sealing ability. Overall, the results of Table 1 suggest that resin cement performed best in minimizing microleakage, whereas zinc phosphate cement performed the worst.

Graph 1: Group-wise descriptive statistics of microleakage scores at all measured sites

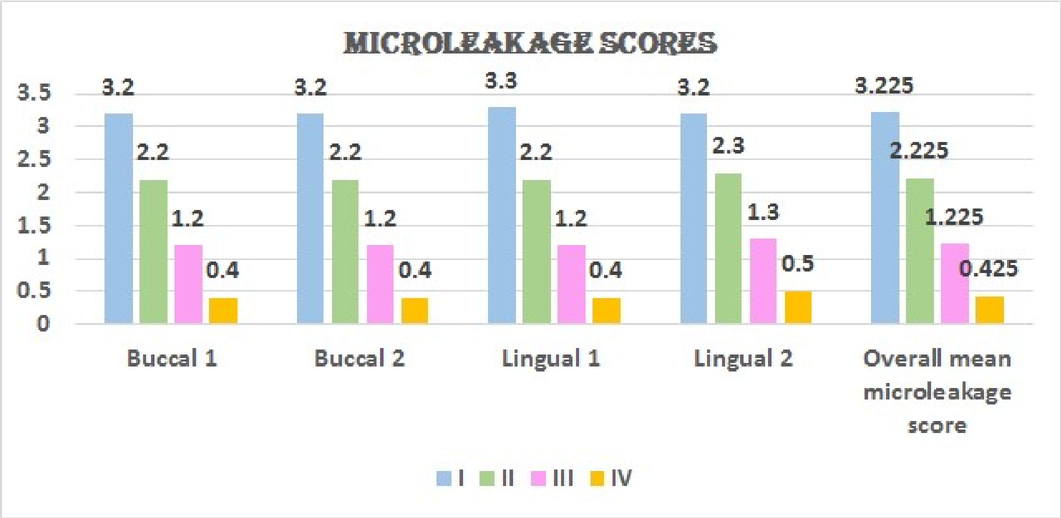


Table 2: Overall comparison of mean microleakage score among the four groups

Group	Luting cement used	n	Mean	SD	95% CI Lower Bound	95% CI Upper Bound	F value	p value
I	Zinc phosphate cement	10	3.225	0.448	2.905	3.545	87.868	<0.001*
II	Zinc polycarboxylate cement	10	2.225	0.448	1.905	2.545		

III	Glass ionomer cement	10	1.225	0.448	0.905	1.545		
IV	Resin cement	10	0.425	0.265	0.236	0.614		

*Significant

Table 2 shows the overall comparison of mean microleakage scores among the four groups. Group I had the highest mean microleakage score, followed by Group II, Group III, and Group IV. The 95% confidence interval for Group I ranged from 2.905 to 3.545, while for Group IV it ranged from 0.236 to 0.614, reflecting a clear difference in leakage levels between the groups. The one-way ANOVA revealed a highly statistically significant difference among the four groups (F = 87.868, p < 0.001). This indicates that the type of luting cement had a significant effect on microleakage, and the difference observed among the cements was not due to chance alone.

Graph 2: Overall comparison of mean microleakage score among the four groups

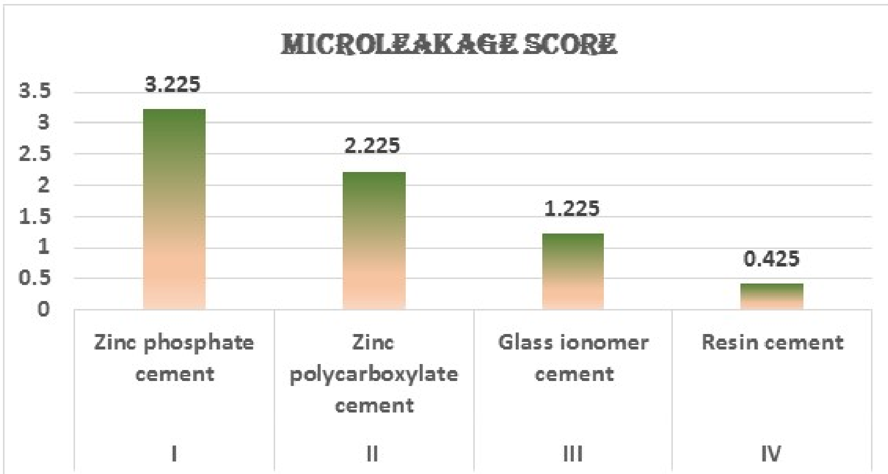


Table 3: Pairwise comparison of overall mean microleakage score between groups

Group 1	Group 2	Mean difference	Std. Error	p value
I (Zinc phosphate)	II (Zinc polycarboxylate)	1.000	0.130	<0.001*
I (Zinc phosphate)	III (Glass ionomer)	2.000	0.130	<0.001*
I (Zinc phosphate)	IV (Resin cement)	2.800	0.130	<0.001*
II (Zinc polycarboxylate)	III (Glass ionomer)	1.000	0.130	<0.001*
II (Zinc polycarboxylate)	IV (Resin cement)	1.800	0.130	<0.001*
III (Glass ionomer)	IV (Resin cement)	0.800	0.130	<0.001*

*Significant

Table 3 shows the pairwise comparison of the overall mean microleakage scores between the study groups. All intergroup comparisons were statistically highly significant (p < 0.001). Group I showed significantly higher microleakage than Group II, Group III, and Group IV, with the largest mean difference seen between Group I and Group IV (2.800). Group II also showed significantly greater microleakage than Group III and Group IV. Similarly, Group III demonstrated significantly higher microleakage than Group IV. These pairwise comparisons confirm that each cement group differed significantly from the others, with resin cement providing the most favorable marginal seal and zinc phosphate cement showing the highest leakage.

Table 4: Site-wise intergroup comparison of microleakage scores

Site	F value	p value
Buccal 1	40.273	<0.001*
Buccal 2	40.273	<0.001*
Lingual 1	41.409	<0.001*
Lingual 2	34.804	<0.001*
Overall mean score	87.868	<0.001*

*Significant

Table 4 shows the site-wise intergroup comparison of microleakage scores. A statistically highly significant difference was observed among the four groups at all measurement sites, namely Buccal 1 (F = 40.273, p < 0.001), Buccal 2 (F = 40.273, p < 0.001), Lingual 1 (F = 41.409, p < 0.001), and Lingual 2 (F = 34.804, p < 0.001). The overall mean score was also significantly different among the groups (F = 87.868, p < 0.001). These findings indicate that the effect of luting cement on microleakage was consistent at all observed sites and was not confined to only one surface or location

Table 5: Distribution of microleakage grades across all evaluated surfaces in each group

Group	Score 0 n (%)	Score 1 n (%)	Score 2 n (%)	Score 3 n (%)	Score 4 n (%)
I – Zinc phosphate cement	0 (0.0)	0 (0.0)	4 (10.0)	23 (57.5)	13 (32.5)
II – Zinc polycarboxylate cement	0 (0.0)	4 (10.0)	23 (57.5)	13 (32.5)	0 (0.0)
III – Glass ionomer cement	4 (10.0)	23 (57.5)	13 (32.5)	0 (0.0)	0 (0.0)
IV – Resin cement	23 (57.5)	17 (42.5)	0 (0.0)	0 (0.0)	0 (0.0)

Table 5 shows the distribution of microleakage grades across all evaluated surfaces in each group. In Group I, most of the observations were concentrated in score 3 (57.5%) and score 4 (32.5%), indicating severe microleakage. In Group II, the majority of observations were seen in score 2 (57.5%) and score 3 (32.5%), which suggests moderate leakage. Group III mainly showed score 1 (57.5%) and score 2 (32.5%), indicating mild to moderate leakage. In contrast, Group IV showed only score 0 (57.5%) and score 1 (42.5%), with no higher leakage scores observed. This pattern clearly demonstrates that resin cement had the most favourable sealing property, while zinc phosphate cement had the least favourable performance.

Graph 3: Distribution of microleakage grades across all evaluated surfaces in each group

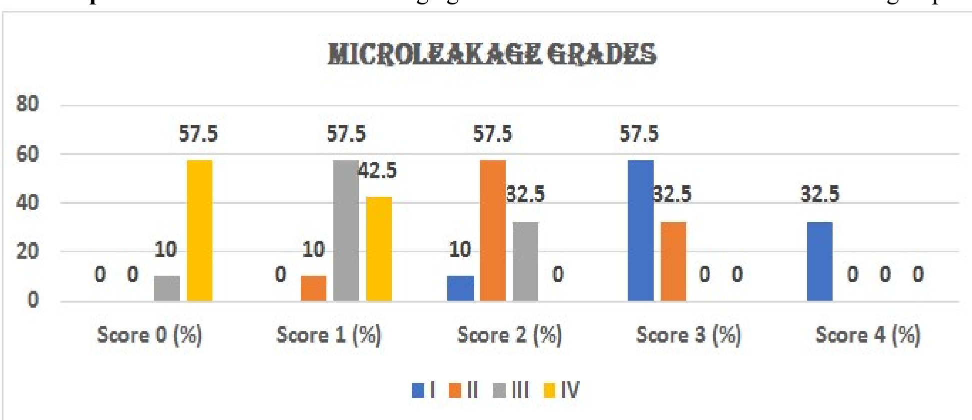


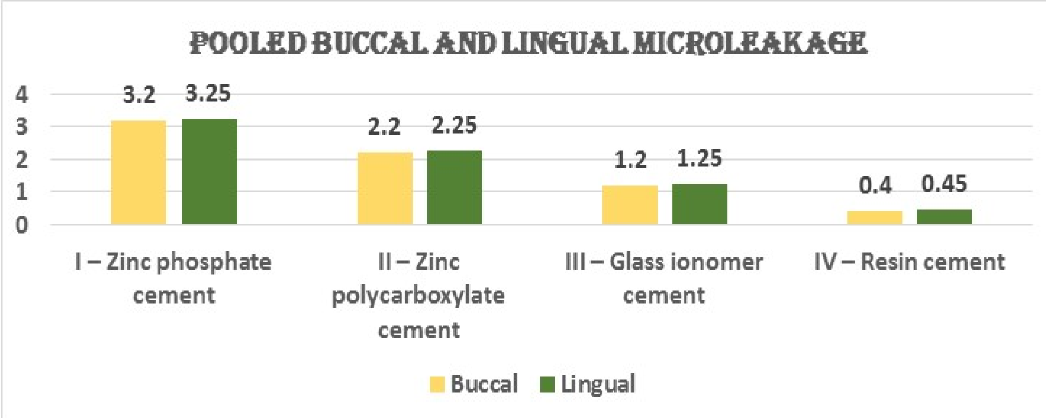
Table 6: Comparison of pooled buccal and lingual microleakage scores within each group

Group	Buccal pooled mean ± SD	Lingual pooled mean ± SD	t value	p value
I – Zinc phosphate cement	3.200 ± 0.537	3.250 ± 0.486	-0.318	0.758 (NS)
II – Zinc polycarboxylate cement	2.200 ± 0.537	2.250 ± 0.486	-0.318	0.758 (NS)
III – Glass ionomer cement	1.200 ± 0.537	1.250 ± 0.486	-0.318	0.758 (NS)
IV – Resin cement	0.400 ± 0.394	0.450 ± 0.284	-0.361	0.726 (NS)

NS = Not significant

Table 6 shows the comparison of pooled buccal and lingual microleakage scores within each group. In Group I, the buccal pooled mean was 3.200 ± 0.537 and the lingual pooled mean was 3.250 ± 0.486. In Group II, the buccal and lingual pooled means were 2.200 ± 0.537 and 2.250 ± 0.486, respectively. In Group III, the values were 1.200 ± 0.537 and 1.250 ± 0.486, while in Group IV they were 0.400 ± 0.394 and 0.450 ± 0.284. In all groups, the difference between buccal and lingual pooled scores was statistically not significant (p > 0.05). This indicates that within each luting cement group, microleakage was distributed similarly on buccal and lingual surfaces, and there was no site-specific predominance of leakage.

Graph 4: Comparison of pooled buccal and lingual microleakage scores within each group



Overall Interpretation

Overall, the present study showed a clear gradation in microleakage among the four commercially available luting cements. Zinc phosphate cement demonstrated the highest microleakage and the poorest marginal seal, followed by zinc polycarboxylate cement and glass ionomer cement. Resin cement showed the lowest microleakage scores at all measured sites and the best sealing ability. The intergroup differences were statistically highly significant, while the intragroup comparison between buccal and lingual surfaces was not significant. These findings suggest that the type of luting cement plays a major role in controlling microleakage at the coping-abutment interface, and resin cement appears to be the most effective among the cements evaluated in this study

Statistical Analysis

The collected data were entered in Microsoft Excel and analyzed using Statistical Package for Social Sciences 26.0 version. Descriptive statistics were calculated in the form of mean, standard deviation, frequency, percentage, and 95% confidence interval. Intergroup comparison of mean microleakage scores was performed using one-way analysis of variance (ANOVA). Post hoc pairwise comparison between the groups was carried out to identify the specific groups showing statistically significant differences. Site-wise comparison of Buccal 1, Buccal 2, Lingual 1, and Lingual 2 scores among the groups was also done using one-way ANOVA. Comparison of pooled buccal and lingual scores within each group was performed using paired t-test. A p value of less than 0.05 was considered statistically significant.

Consolidated Table: Overall summary of microleakage scores among the four luting cement groups

Group	Luting cement used	Buccal 1 Mean ± SD	Buccal 2 Mean ± SD	Lingual 1 Mean ± SD	Lingual 2 Mean ± SD	Overall mean microleakage score Mean ± SD	95% CI	Rank
I	Zinc phosphate cement	3.200 ± 0.632	3.200 ± 0.632	3.300 ± 0.675	3.200 ± 0.632	3.225 ± 0.448	2.905–3.545	4
II	Zinc polycarboxylate cement	2.200 ± 0.632	2.200 ± 0.632	2.200 ± 0.632	2.300 ± 0.675	2.225 ± 0.448	1.905–2.545	3
III	Glass ionomer cement	1.200 ± 0.632	1.200 ± 0.632	1.200 ± 0.632	1.300 ± 0.675	1.225 ± 0.448	0.905–1.545	2
IV	Resin cement	0.400 ± 0.516	0.400 ± 0.516	0.400 ± 0.516	0.500 ± 0.527	0.425 ± 0.265	0.236–0.614	1

DISCUSSION

The primary objective of this investigation was to evaluate microleakage at the interface of implant copings luted with four distinct agents: Zinc Phosphate, Zinc Polycarboxylate, Glass Ionomer Cement (GIC), and Resin Cement. To simulate the oral environment, thermal stresses were applied, and 2% basic fuchsin dye was used to quantify fluid ingress. The study demonstrated a statistically significant hierarchy in sealing efficacy: **Resin Cement > GIC > Zinc Polycarboxylate > Zinc Phosphate.**

Group I (Zinc Phosphate) yielded the highest microleakage (3.225 ± 0.448). This is justified by its lack of chemical adhesion and high solubility. As noted by Black (1895) and Rosenstiel (1998), the material relies purely on mechanical friction. Under thermocycling, hydrolytic dissolution occurs, creating microscopic voids for bacterial and fluid ingress.

Group II (Zinc Polycarboxylate) showed moderate leakage (2.225 ± 0.448). While it offers chemical adhesion to metal oxides via calcium ion chelation, its low compressive strength and high elasticity lead to plastic deformation under thermal loads, eventually severing the adhesive bond.

Group III (GIC) performed as the second-most effective sealer (1.225 ± 0.448). GICs achieve true chemical adhesion and possess a favourable coefficient of thermal expansion. However, sensitivity to moisture contamination during the initial 24-hour maturation phase explains the observed dye penetration compared to resin-based alternatives.

Group IV (Resin Cement) demonstrated the best performance (0.425 ± 0.265). Its organic dimethacrylate matrix creates a cross-linked, hydrophobic polymer network that is hydrolytically stable. Unlike acid-base cements, resin cements are non-porous and achieve a hermetic seal through micromechanical interlocking. The minimal leakage observed is likely a result of polymerization shrinkage rather than material dissolution.

Methodological Correlation: While CAD/CAM milling ensured marginal gaps were within the 30–50µm clinical threshold, leakage still occurred in traditional cement groups. This confirms the hypothesis by Rossetti et al. (2008) that even precise restorations require a dimensionally stable, insoluble luting agent to prevent capillary action. The dye penetration method remains a reliable gold standard for visualizing potential pathways for peri-implant bacterial colonization.

CONCLUSION

The choice of luting agent is a primary determinant of marginal integrity in cement-retained restorations. Under simulated thermal stresses, **Resin Cement** proved superior, providing the most effective biological hermetic seal due to its hydrophobic matrix and high flexural strength.

Conversely, **Zinc Phosphate** exhibited the poorest performance, posing the highest risk for marginal "wash-out" and subsequent peri-implant complications. While GIC and Polycarboxylate offer intermediate sealing, they lack the volumetric stability of resin. Clinically, while resin cements maximize biological protection against peri-implantitis, clinicians must balance this against the need for future retrievability. Ultimately, for long-term success, a dimensionally stable and insoluble luting agent is mandatory to supplement high-precision prosthetic fabrication.

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