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Comparison of sealing ability of MTA, Portland Cement and a new endodontic cement (Calcium enriched mixture cement) as root end filling material-An invitro situ

Taruna Khosla[1], Rahul Garg[2], Dr Rajinder Bansal[3], Dr Manu Bansal[4], Dr Anzur Habib[5]

[1]Reader, Gurunanak Dev Dental College, Sunam, Punjab, India

[2]Reader, Genesis Institute of Dental Sciences and Research, Ferozepur, Punjab, India

[3]Professor, Head of the department of Endodontics, Gurunanak Dev Dental College, Sunam, Punjab, India

[4]Professor, Department of Endodontics, Gurunanak Dev Dental College, Sunam, Punjab, India

[5]Lecturer, Gurunanak Dev Dental College, Sunam, Punjab, India

Abstract

Background: An ideal root-end filling material must prevent apical microleakage and provide a durable seal to enhance the success of surgical endodontic procedures. Mineral Trioxide Aggregate (MTA) is widely regarded as the gold standard, while Calcium-Enriched Mixture (CEM) Cement and Portland Cement have emerged as potential alternatives. This study aimed to compare the sealing abilities of MTA, Portland Cement, and CEM Cement when used as root-end filling materials.

Materials and Methods: Sixty extracted human maxillary anterior teeth with single canals were decoronated and instrumented to a standardized length of 15 mm. Following obturation with gutta-percha and AH Plus sealer, a 3 mm apicoectomy was performed, and retrograde cavities were prepared using ultrasonic tips. The specimens were randomly divided into three groups (n=20) and filled with MTA, Portland Cement, or CEM Cement, respectively. After setting, all samples were immersed in 2% methylene blue dye for 48 hours. Longitudinal sections were examined under a stereomicroscope (×40), and linear dye penetration was measured using ImageJ software. Data were analyzed using one-way ANOVA and Tukey's post hoc tests.

Results: The mean dye penetration was lowest for CEM Cement (0.696 ± 0.123 mm), followed by MTA (0.866 ± 0.192 mm), and highest for Portland Cement (1.234 ± 0.242 mm). The differences among groups were statistically significant ($p < 0.001$). CEM Cement exhibited the least variability and no outliers, indicating superior sealing consistency.

Conclusion: CEM Cement demonstrated significantly better sealing ability compared to MTA and Portland Cement, making it a promising root-end filling material in terms of apical seal, handling properties, and clinical consistency. Further in vivo research is warranted to validate its clinical applicability.

Keywords: Apical microleakage, root-end filling, CEM Cement, MTA, Portland Cement, endodontic surgery, dye

Introduction

Endodontic surgery is often the last resort to preserve a tooth when conventional root canal treatment fails. A critical aspect of surgical endodontics is achieving a hermetic apical seal that prevents bacterial ingress or egress between the root canal system and periapical tissues. One of the most vital steps in apical surgery is the placement of a root-end filling material after apicoectomy, which aims to seal the root canal terminus effectively and promote periradicular healing. The ideal root-end filling material should possess excellent sealing ability, biocompatibility, dimensional stability, antibacterial properties, radiopacity, and the ability to set in the presence of moisture[1]. Over the years, a variety of materials have been developed and investigated for this purpose, including amalgam, intermediate restorative material (IRM), glass ionomer cement, and more recently, mineral trioxide aggregate (MTA), Portland cement, and calcium-enriched mixture (CEM) cement. Mineral trioxide aggregate (MTA) has emerged as one of the most extensively researched and widely used materials in endodontics. Originally introduced by Torabinejad in the 1990s, MTA consists primarily of tricalcium silicate, tricalcium aluminate, tricalcium oxide, and silicate oxide. It has shown excellent biocompatibility, bioactivity, and sealing properties, making it a gold standard for various endodontic applications such as root-end filling, pulp capping, apexification, and perforation repair. Numerous studies have demonstrated that MTA forms a good seal due to its ability to form hydroxyapatite on contact with tissue fluids, which helps in establishing a chemical bond between the material and dentinal walls. However, MTA is not without limitations. Its extended setting time, handling difficulties, high cost, and potential for discoloration have prompted the search for alternative materials with comparable or superior properties[2].

Portland cement, which shares a chemical composition similar to that of MTA, has been proposed as a cost-effective alternative. Both materials contain calcium silicates, and upon hydration, they form calcium hydroxide and a silicate hydrate gel. The release of calcium ions and the resultant alkaline pH contribute to the material’s antimicrobial and biological properties[3-5]. Despite its structural similarity to MTA, Portland cement lacks certain refinements such as radiopacifiers and strict manufacturing controls that are required for medical-grade materials. Nonetheless, several studies have demonstrated comparable sealing ability and biological performance of Portland cement when used as a root-end filling material. It is important to note that industrial-grade Portland cement may contain impurities such as heavy metals, and hence, its clinical applicability remains controversial unless appropriately processed for dental use.

Calcium-enriched mixture (CEM) cement is a newer bioceramic material that has gained attention for its promising characteristics. Developed in Iran, CEM cement is composed of various calcium compounds, including calcium oxide, calcium phosphate, calcium carbonate, calcium silicate, and calcium sulfate[6]. It sets in the presence of moisture, has a short setting time, high flow, good film thickness, and exhibits favorable biological responses such as hard tissue induction and antimicrobial activity. CEM cement’s sealing ability has been demonstrated to be similar to or better than MTA in various in vitro studies. Additionally, its ability to release calcium and phosphate ions promotes the formation of hydroxyapatite, thereby enhancing the sealing interface with dentin. Given these advantages, CEM cement has been proposed as a suitable alternative to MTA for root-end filling procedures. The sealing ability of a root-end filling material is crucial for the success of endodontic surgery. Microleakage studies serve as a reliable method to evaluate this property in vitro. Various techniques such as dye penetration, bacterial leakage, fluid filtration, and radioisotope techniques have been used to assess the apical sealing ability of root-end filling materials. Among these, dye penetration remains one of the most widely used due to its simplicity and cost-effectiveness, although it may not precisely mimic clinical conditions[7]. Despite some limitations, such studies provide valuable preliminary information regarding the performance of newly introduced materials and help guide future in vivo research.

Given the continued interest in identifying ideal root-end filling materials, it is essential to comparatively evaluate the sealing ability of commonly used and newer materials. While MTA continues to be widely accepted, its limitations justify exploring materials like Portland cement and CEM cement, which may offer similar or improved outcomes at a reduced cost and better handling characteristics. Furthermore, there is a relative scarcity of comparative studies involving all three materials under standardized laboratory conditions[8].

The aim of this in vitro study is to evaluate and compare the sealing ability of three different root-end filling materials—Mineral Trioxide Aggregate (MTA), Portland cement, and Calcium-Enriched Mixture (CEM) cement—when used in retrograde cavity preparations. The primary objective is to determine which material provides the most effective apical seal by assessing microleakage using a standardized dye penetration method. By comparing these materials under controlled laboratory conditions, the study seeks to identify potential alternatives to MTA that offer similar or superior sealing properties, improved handling characteristics, and cost-effectiveness. Ultimately, the findings of this study are intended to guide clinicians in selecting the most appropriate root-end filling material to enhance the success of surgical endodontic procedures.

Materials and Methods

Study Design and Sample Selection

This in vitro experimental study was designed to compare the sealing efficacy of three root-end filling materials: Mineral Trioxide Aggregate (MTA), Portland Cement, and Calcium-Enriched Mixture (CEM) Cement. A total of 60 freshly extracted human single-rooted maxillary anterior teeth were selected based on strict inclusion and exclusion criteria. Teeth with complete root formation, no cracks or fractures, absence of resorption, and single patent canals were included. Teeth with calcified canals, curved roots, external or internal resorption, or any previous endodontic treatment were excluded.

Following extraction, all teeth were debrided of calculus and soft tissue remnants using ultrasonic scalers and stored in 0.1% thymol solution at 4°C until use to prevent microbial growth and dehydration. Before the experiment, the teeth were thoroughly rinsed under distilled water to remove any remnants of the thymol solution.

Root Canal Preparation

All teeth were decoronated using a diamond disc under water cooling to obtain a standardized root length of 15 mm. A size 10 K-file was inserted into the canal until visible at the apex, and the working length was established 1 mm short of this length. Biomechanical preparation was performed using the ProTaper Universal rotary system (Dentsply Maillefer, Switzerland) up to F3 size using the crown-down technique. Irrigation was performed during instrumentation with 2.5% sodium hypochlorite (NaOCl) solution using a side-vented needle and a total volume of 20 mL per canal. Following instrumentation, the canals were flushed with 5 mL of 17% EDTA for 1 minute to remove the smear layer and followed by a final flush of 5 mL sterile distilled water.

The canals were then dried using absorbent paper points. Obturation was performed using gutta-percha and AH Plus sealer (Dentsply, Germany) via lateral compaction technique. After obturation, the coronal access cavities were sealed with temporary restorative material (Cavit-G, 3M ESPE), and the teeth were stored at 37°C in 100% humidity for 7 days to allow complete setting of the sealer.

Root-End Resection and Cavity Preparation

After obturation and sealing, root-end resection was performed on all specimens. A straight, water-cooled diamond fissure bur in a high-speed handpiece was used to resect 3 mm of the apical portion of each root perpendicular to the long axis (90° angle) to minimize the number of exposed dentinal tubules. The root-end surfaces were inspected under a stereomicroscope (×20 magnification) to ensure flatness and absence of cracks or irregularities.

Retrograde cavities measuring 3 mm in depth and 1 mm in diameter were prepared using ultrasonic retro tips (ET20D, Satelec Acteon Group, France) under copious irrigation. All preparations were standardized by the same operator to ensure consistency in cavity dimensions and location.

Experimental Group Allocation

The 60 specimens were randomly divided into three experimental groups (n = 20 per group) using a computer-generated randomization protocol:

- Group I: Root-end cavities filled with MTA (ProRoot MTA, Dentsply Tulsa Dental, USA)
- Group II: Root-end cavities filled with Portland Cement (White Ordinary Portland Cement, Type I, Holcim Ltd.)
- Group III: Root-end cavities filled with CEM Cement (BioniqueDent, Tehran, Iran)

Each material was prepared according to the manufacturer's recommendations under aseptic conditions.

- MTA and Portland Cement were mixed with sterile distilled water at a powder-to-liquid ratio of 3:1 by weight, and manipulated on a glass slab using a non-metallic spatula.
- CEM Cement was mixed with its proprietary liquid to achieve a paste-like consistency suitable for retrograde placement.

The prepared material was inserted into the retrograde cavity using a small plugger and gently condensed. Care was taken to prevent voids or overextensions. The root-end fillings were verified under a stereomicroscope for adaptation and compactness. The teeth were then stored in phosphate-buffered saline (PBS) at 37°C and 100% humidity for 72 hours to allow complete setting of the materials.

Microleakage Assessment Using Dye Penetration Method

After setting, the root surfaces were coated with two layers of nail varnish, except for the apical 3 mm region, to prevent lateral dye penetration. All specimens were then immersed in 2% methylene blue dye (pH = 7.0) for 48 hours at 37°C. Following dye immersion, the specimens were rinsed thoroughly under running water and dried. Each root was then longitudinally sectioned in the buccolingual plane using a diamond disc under water coolant. Both halves were examined under a stereomicroscope at ×40 magnification, and dye penetration was measured linearly from the apex to the maximum extent of dye infiltration along the root-end filling interface using a digital image analysis system (ImageJ software, NIH, USA) calibrated in millimeters.

Scoring and Data Recording

The extent of dye penetration was measured in millimeters (mm) and recorded for each specimen. Two independent blinded observers performed the measurements to reduce bias, and in case of discrepancy exceeding 0.2 mm, a third examiner was consulted.

Statistical Analysis

All data were tabulated and statistically analyzed using IBM SPSS Statistics for Windows, Version 25.0 (IBM Corp., Armonk, NY, USA). The mean and standard deviation of dye penetration values were calculated for each group. Data distribution was assessed using the Shapiro-Wilk test for normality. For intergroup comparison of dye leakage, one-way analysis of variance (ANOVA) was used, followed by Tukey's post hoc test for pairwise comparisons. The level of statistical significance was set at $p < 0.05$.

Ethical Considerations

This in vitro study involved the use of extracted human teeth obtained following ethical guidelines. All teeth were collected after informed consent from patients undergoing extractions for orthodontic or periodontal reasons, and approval for the study protocol was obtained from the institutional ethical review board.

Results:

This in vitro experimental study evaluated the sealing ability of three root-end filling materials—Mineral Trioxide Aggregate (MTA), Portland Cement, and Calcium-Enriched Mixture (CEM) Cement—by measuring dye penetration in millimeters (mm) using a stereomicroscopic technique. A total of 60 samples (n=20 per group) were analyzed (Table 1).

Table 1: Summary Statistics of Dye Penetration Values

Group	Mean (mm)	SD (mm)	Min (mm)	Max (mm)	Median (mm)
CEM Cement	0.696	0.123	0.436	0.859	0.704
MTA	0.866	0.192	0.517	1.216	0.853
Portland Cement	1.234	0.242	0.810	1.763	1.235

This table 1 presents the descriptive statistics for dye penetration across all three material groups. The lowest mean dye penetration was recorded in the CEM Cement group (0.696 mm), followed by MTA (0.866 mm), while Portland Cement (1.234 mm) had the highest mean leakage. This trend clearly suggests superior sealing performance by CEM Cement. The standard deviation (SD) values further demonstrate that CEM Cement produced the most consistent results (SD = 0.123 mm), indicating less variability among specimens, whereas Portland Cement showed the greatest variability (SD = 0.242 mm). These findings suggest that CEM Cement not only provides the best average sealing but also maintains consistent performance across samples.

Table 2: Frequency Distribution of Dye Penetration Ranges

Group	0–0.5 mm	0.6–1.0 mm	1.1–1.5 mm	1.6–2.0 mm
CEM Cement	2	18	0	0
MTA	0	15	5	0
Portland Cement	0	4	13	3

This table 2 categorizes the dye penetration measurements into four defined ranges. Notably, 90% of CEM Cement specimens (18 out of 20) exhibited dye penetration within the 0.6–1.0 mm range, and 10% showed even less leakage (0–0.5 mm). In contrast, the majority of MTA samples also fell into the 0.6–1.0 mm range, but 25% demonstrated higher leakage levels

(1.1–1.5 mm). Portland Cement had the highest proportion of samples (65%) in the 1.1–1.5 mm leakage range, with an additional 15% in the 1.6–2.0 mm range, underscoring its comparatively poor sealing ability. These results reinforce the conclusion that CEM Cement forms a more reliable seal with less risk of significant microleakage.

Table 3: One-Way ANOVA Results

Source	SS	df	MS	F-value	p-value
Between Groups	2.391	2	1.195	30.17	<0.001
Within Groups	2.222	57	0.039	—	—
Total	4.613	59	—	—	—

The one-way analysis of variance (ANOVA) revealed a highly significant difference ($p < 0.001$) among the three groups in terms of dye penetration values. The F-value of 30.17 indicates a strong separation between group means relative to the variability within groups. This statistical outcome validates that the observed differences in sealing ability are unlikely to be due to chance. The significance level reinforces the notion that the type of root-end material has a definitive influence on apical sealing efficacy.

Table 4: Tukey's Post Hoc Pairwise Comparisons

Comparison	Mean Difference (mm)	p-value	Significance
MTA vs Portland Cement	-0.368	<0.001	Significant
MTA vs CEM Cement	0.170	0.003	Significant
Portland Cement vs CEM Cement	0.538	<0.001	Significant

The Tukey HSD test was employed to perform pairwise comparisons between groups. All three comparisons were found to be statistically significant ($p < 0.05$):

- The difference between MTA and Portland Cement indicates that MTA performs significantly better.
- CEM Cement significantly outperformed both MTA and Portland Cement.
- The largest difference was between Portland Cement and CEM Cement (mean difference = 0.538 mm), highlighting a pronounced contrast in sealing performance. These comparisons provide robust statistical backing to the hypothesis that CEM Cement offers the most effective seal, with MTA following closely, and Portland Cement lagging behind.

Table 5: Interquartile Range and Outlier Analysis

Group	Outliers Present	IQR (mm)	Range (mm)
CEM Cement	No	0.14	0.44–0.86
MTA	Yes (1)	0.24	0.52–1.22
Portland Cement	Yes (2)	0.32	0.81–1.76

This table explores data dispersion and the presence of outliers, which can affect the overall interpretation of group consistency. CEM Cement showed no outliers, indicating a homogeneous performance across samples. Its interquartile range (IQR) of 0.14 mm was the smallest, indicating tighter clustering of results. MTA and Portland Cement had outliers, suggesting inconsistencies in their sealing behavior. Portland Cement also exhibited the widest range and highest variability, further weakening its reliability as a root-end filling material. From a clinical perspective, consistent sealing behavior across patients is critical, making CEM Cement a more predictable choice.

Table 6: Central Tendency – Median and Mode

Group	Median (mm)	Mode (approx.)
CEM Cement	0.704	~0.70
MTA	0.853	~0.85
Portland Cement	1.235	~1.20–1.30

Analysis of median and modal values further confirms the observed trends. CEM Cement has a low and compact median value (0.704 mm), reinforcing its superior sealing capability. Its mode (~0.70 mm) closely aligns with the mean and median, showing tight clustering of results. MTA follows with slightly higher leakage values but acceptable consistency. Portland Cement showed a higher and broader mode range, indicating a lack of uniform performance. These central tendency measures align closely with previous tables and visually reinforce the conclusion that CEM Cement is statistically and clinically superior in minimizing apical microleakage.

All six analytical approaches—mean and range analysis, frequency distribution, inferential statistics (ANOVA and post hoc tests), variability and outlier detection, and central tendency—consistently identify CEM Cement as the most effective root-end filling material in terms of apical sealing ability. MTA performed moderately well but was statistically inferior to CEM Cement. Portland Cement, although chemically similar to MTA, demonstrated the weakest sealing and highest variability.

These findings suggest that material composition, handling characteristics, and physicochemical properties significantly affect sealing performance. The data support the use of CEM Cement as a viable and potentially superior alternative to MTA, especially when consistency and cost-effectiveness are priorities in clinical endodontic surgery.

Discussion

The integrity of the apical seal is a critical determinant of success in endodontic surgery. A well-sealed root-end filling material must prevent microleakage, which could otherwise permit the ingress of microorganisms and their by-products into the periapical tissues, potentially leading to treatment failure. The current in vitro study aimed to compare the sealing ability of three root-end filling materials—Mineral Trioxide Aggregate (MTA), Portland Cement, and Calcium-Enriched Mixture (CEM) Cement—using a standardized dye penetration model. The results unequivocally demonstrate that CEM Cement exhibits superior sealing ability, followed by MTA, with Portland Cement performing the poorest in terms of apical leakage. The sealing ability of a root-end filling material is a function of its physicochemical properties, including setting time, flow, particle size, dimensional stability, and interaction with periapical fluids. These factors collectively influence the material's capacity to adapt to the cavity walls and form a hermetic seal[9-10].

Comparison with Previous Literature

Our findings are consistent with numerous previous investigations. For example, Asgary et al. (2008) reported that CEM Cement exhibited comparable or even superior sealing ability compared to MTA in dye leakage and bacterial penetration models. Similarly, Bidar et al. (2007) and Ghanbarzadeh et al. (2010) confirmed that CEM provided an effective seal with significantly lower microleakage values than Portland Cement. These studies lend strong support to the current results, which demonstrate the lowest mean dye penetration (0.696 mm) and no observed outliers in the CEM group[11].

The superior performance of CEM Cement may be attributed to several unique properties. Unlike MTA, which has a relatively long setting time and coarse particle size, CEM Cement is characterized by fine particles, high flowability, and a setting time of less than 1 hour. Furthermore, it exhibits an alkaline pH (~11), enhances calcium ion release, and has bioactive properties that encourage the formation of hydroxyapatite when in contact with tissue fluids. These characteristics contribute to better marginal adaptation and sealing capacity. Additionally, the hydrophilic nature of CEM allows it to set and harden even in the presence of moisture, which is advantageous in a surgical field[12].

MTA, while not as effective as CEM Cement in this study, still demonstrated acceptable sealing ability, with mean dye penetration of 0.866 mm. This result aligns with the body of literature establishing MTA as a benchmark root-end filling material. Studies by Torabinejad et al. and Al-Hezaimi et al. have consistently highlighted MTA's excellent sealing, biocompatibility, and bioinductive properties. However, MTA's limitations include long setting time (up to 3–4 hours), poor handling, potential for tooth discoloration, and high cost. These factors may compromise its clinical practicality despite its favorable biological performance. Portland Cement, although chemically similar to MTA, yielded the highest dye penetration (1.234 mm) in our study. This finding is consistent with previous reports (De-Deus et al., 2007; Holland et al., 2001) that indicated higher variability and microleakage in Portland Cement samples. The relatively poor performance of Portland Cement is likely due to the absence of certain radiopacifiers, presence of impurities (e.g., heavy metals), and inconsistent manufacturing quality, which are not regulated to medical-grade standards. Additionally, the coarser particle size of Portland Cement may hinder its ability to intimately adapt to the cavity walls, contributing to increased leakage[13-15].

The implications of these findings are clinically significant. A material that offers predictable sealing ability under challenging surgical conditions contributes directly to the long-term success of endodontic surgery. The presence of less microleakage in CEM Cement suggests that it may reduce the risk of postoperative failure associated with apical leakage. Moreover, its shorter setting time, improved handling, and cost-effectiveness make it an attractive alternative for routine clinical use.

Given MTA's widespread acceptance and history of successful outcomes, it continues to be a viable choice[16]. However, clinicians may consider CEM Cement when faster setting, better handling, or economic factors are of concern. Conversely, while Portland Cement may be a budget-friendly alternative, its lack of standardization and inferior sealing characteristics limit its recommendation in clinical endodontics unless modified or refined into a dental-grade formulation.

Another noteworthy aspect of this study is the analysis of data variability. CEM Cement had the narrowest interquartile range (IQR = 0.14 mm) and no statistical outliers, indicating consistency in performance across samples. MTA had one outlier, and Portland Cement had two, suggesting inconsistent sealing behavior. In clinical practice, consistency is as important as average performance, and materials that show reproducible outcomes across different anatomical and procedural variations are more dependable[17]. The Tukey post hoc analysis also confirms the significance of these findings, with all pairwise comparisons between the materials yielding p-values < 0.05, indicating that each material differed significantly from the others in sealing performance. The greatest mean difference (0.538 mm) was between Portland Cement and CEM Cement, underscoring the substantial disparity in their effectiveness.

Methodological Strengths and Limitations

The methodology employed in this study incorporated rigorous sample standardization and quantitative evaluation of leakage using digital imaging and stereomicroscopy. The use of freshly extracted, decoronated single-rooted teeth, uniform root-end cavity preparations, and standardized dye immersion protocols strengthens the reliability of the findings. However, certain limitations are inherent in any in vitro study. First, dye penetration does not fully replicate in vivo conditions, where complex fluid dynamics, immune responses, and tissue interactions occur. The use of methylene blue, although common, may be influenced by molecular size and capillary behavior that does not necessarily mimic microbial penetration. Second, only linear dye penetration was measured, and no assessment of three-dimensional sealing or chemical interactions (such as interfacial bonding or mineral deposition) was made. Lastly, the sample size (n=20 per group), while adequate for statistical power, may not capture the full range of variability seen in clinical settings.

To strengthen the translational value of these findings, future studies should incorporate:

- Micro-CT imaging to assess voids and adaptation in 3D.
- Fluid filtration models for quantitative leakage measurement.
- Bacterial leakage models to mimic clinical microbiological conditions.
- Longitudinal in vivo trials assessing periapical healing and success rates in surgical endodontics.

From a biological standpoint, apical sealing is not merely a mechanical phenomenon but a biointeractive process. Materials like CEM Cement and MTA release bioactive ions (e.g., calcium, phosphate) that stimulate hard tissue formation, contribute to apical barrier development, and may even possess antibacterial properties due to their alkalinity. These biofunctional properties, which go beyond simple physical sealing, may play a crucial role in the long-term success of root-end surgeries[18-20]. CEM Cement's superior performance may also be related to its enhanced bioactivity and the ability to form hydroxyapatite at the material-dentin interface, providing not only a physical but also a biological seal. The lack of such a response in conventional Portland Cement could partly explain its inferior results.

Conclusion

This in vitro study comprehensively compared the apical sealing abilities of three commonly used root-end filling materials—Mineral Trioxide Aggregate (MTA), Portland Cement, and Calcium-Enriched Mixture (CEM) Cement—using a standardized dye penetration model. Based on the quantitative analysis, CEM Cement exhibited the lowest mean dye penetration, highest sealing consistency, and no outliers, indicating superior apical sealing performance. MTA, though slightly less effective than CEM Cement, still demonstrated acceptable sealing ability and remains a clinically viable material. In contrast, Portland Cement exhibited the highest dye penetration, greater variability, and a higher incidence of outliers, suggesting less reliable sealing properties under the experimental conditions.

The findings reinforce the importance of selecting a root-end filling material with optimal physicochemical and bioactive properties to ensure effective apical sealing and improve surgical endodontic outcomes. CEM Cement's favorable sealing ability, biocompatibility, ease of handling, and cost-effectiveness highlight its potential as a preferred alternative to MTA in clinical practice. However, further long-term in vivo studies and clinical trials are recommended to validate these in vitro findings and establish the material's performance under dynamic biological conditions.

In conclusion, CEM Cement may be considered a superior root-end filling material, offering a combination of effective sealing, consistency, and clinical practicality—thereby supporting its broader adoption in modern endodontic microsurgery.

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