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ORIGINAL ARTICLE

Physical and mechanical properties of a strontium silicate-based sealer

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Abstract

Introduction This study aimed to evaluate the physical and mechanical properties of an endodontic sealer containing strontium silicates (Sr–Si sealer, C-Root SP, Beijing, China) compared to a calcium silicate-based sealer (Ca–Si sealer, Endosequence BC Sealer, Savannah, USA).

Methods Elemental composition of the sealers was confirmed by energy-dispersive X-ray spectroscopy (EDS). Afterwards, particle size was evaluated with SEM (scanning electron microscopy). Flow ($n = 10$ per group), setting time. ($n = 5$), film thickness ($n = 10$), and radiopacity ($n = 10$) were tested under ISO 6876/2012 standards. To mimic clinical applications, a pressure-flow test ($n = 10$) was designed and carried out to estimate the forces needed to initiate sealer flow into dentin tubules. A direct observation on sealer penetration depth inside dentin tubule was also performed by SEM with 20 extracted single-canaled teeth, obturated with either Sr–Si or Ca–Si sealer ($n = 10$ each) using hydraulic condensation technique, resulting in 1080 per sealer group. The data were analyzed with a *t* test ($\alpha = 0.05$).

Results The Sr–Si sealer contained 10.6 wt% Sr and an average particle size of 1.59 ± 0.97 µm, while the Ca–Si sealer contained 27.0 wt% Ca and a particle size at 8.05 ± 5.66 µm. The Sr–Si sealer also contained 16.2% tantalum which was not found in Ca–Si sealer. In the ISO tests, the Sr–Si sealer showed longer setting time, better flowability, and radiopacity ($p < 0.01$). The force to initiate the flow in simulated tubules for the Sr–Si sealer was 11.00 ± 0.74 N, significantly lower than the Ca–Si sealer's 21.51 ± 2.59 N. The results were also consistent with the observation on extracted teeth that Sr–Si sealer penetrated further than Ca–Si sealer.

Conclusions The properties of the Sr–Si sealer suggest that it possesses desirable characteristics based on current in vitro criteria. While these results provide a strong foundation for its application, conclusions regarding its long-term clinical suitability depend on further clinical trials.

Keywords Root canal filling materials · Strontium silicate · Calcium silicate

Introduction

Obturation of the root canal system is critical for creating a fluid-tight seal after instrumentation, aiming to prevent reinfection by microorganisms and isolate any bacteria that survived the cleaning process [1]]. Given the complex anatomy of the root canal system [2], a sealer is used with gutta-percha to fill voids and accessory canals, ensuring a better seal and embolizing the residual microorganism [3]. Additionally, the sealer acts as a lubricant for the obturation material and possesses antibacterial properties [4]. However, traditional zinc oxide-eugenol (ZOE) sealers are soluble, potentially leading to recurrent infections [5, 6].

Silicate-based bioceramic sealers have emerged as a promising alternative, offering superior volume stability and bioactivity. These materials are biocompatible and reduce leakage, leading to their increasing popularity among dentists and endodontists [7]. Calcium silicate-based (Ca–Si) sealers, in particular, require moisture for setting and release calcium ions, contributing to their bioactivity [1]. However, some Ca–Si sealers have prolonged setting time (up to 168 h) and contain aluminum, which raises concerns in

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dental clinics and general health [8, 9]. A prolonged setting time presents at least two concerns: an increased risk of higher toxicity due to extended leaching of unset material, and the potential for inconsistent performance in clinical settings [10]. Additionally, it increases the vulnerability of the root canal filling to coronal microleakage and contamination before the placement of a definitive restoration, thereby impacting reinfection rates and the overall success of endodontic treatment [11]. Given the considerable heterogeneity among commercial Ca–Si sealers, Endosequence BC Sealer was selected for this study as it is a first-generation product and a widely studied and reported commercial bioceramic sealer [12]**.**

In 2021, a strontium silicate-based (Sr–Si) pre-mixed injectable bioceramic sealer received FDA approval. However, in vitro, in vivo, and clinical studies on the Sr–Si sealer are rare. The chemical composition of the Sr–Si sealer was disclosed by the manufacturer, as well as the Ca–Si manufacturers (Table 1). Strontium is proposed to have osteogenic and biocompatible properties, and the Sr–Si sealer is said to be insoluble, aluminum-free, and free from shrinkage upon setting [13, 14]. Recent publications showed low cytotoxicity and excellent biocompatibility the Sr–Si sealer. However, its physical and mechanical properties, particularly dentin tubule penetration, remain unreported [15].

Despite the lack of high-quality clinical studies, it is generally accepted that sealer penetration correlates with positive clinical outcomes primarily due to the sealer's ability to seal off and entomb residual microorganisms [16]. Although the FDA requires basic physical properties and biosafety disclosures, ISO standards primarily address fundamental physical and mechanical tests. Standardized tests conducted bench-top inadequately replicate clinical complexities. For example, the ability of a sealer to flow and penetrate accessory canals and dentin tubules is critical to insulate and entomb infection. The ISO flow test can only evaluate the flowability of sealers between two glass plates. Alternative models evaluating sealer penetration into dentinal tubules are necessary. Sealer penetration is key for creating a strong, impermeable seal that prevents bacterial infiltration and minimizes reinfection risks. Therefore, evaluating and optimizing sealer penetration are crucial for successful, durable outcomes in endodontic therapy.

Despite the increasing use of Sr–Si sealers, no study has compared their properties to those of Ca–Si sealers. This study aimed to analyze the composition of Sr–Si and Ca–Si sealers using energy-dispersive spectroscopy (EDS) and compare their particle size by SEM (scanning electron microscopy) and flow, setting time, film thickness, and radiopacity per ISO standards. Furthermore, a customized "pressure flow" test and an SEM observation on "dentin tubule penetration" were performed for a comprehensive evaluation on the flowability. The null hypothesis was that there would be no statistically significant differences in the physical and mechanical properties, including flowability and dentin tubule penetration, between the strontium silicate-based sealer and the calcium silicate-based sealer.

Materials and methods

The manuscript of this laboratory study has been written according to Preferred Reporting Items for Laboratory studies in Endodontology (PRILE) 2021 guidelines.

The Sr–Si sealer (C-Root SP, C-Root, Beijing, China, LOT #20220101) and Ca–Si sealer (Endosequence BC Sealer, Brasseler, Savannah, USA, LOT #22001SP) sealers were used in this study.

The sealer was smeared onto an aluminum SEM stub and left in a 37 °C incubator with 100% relative humidity until the sealers were set. The stub was then placed into the SEM (Hitachi SU6600, Japan) and EDS elemental analysis was done for both sealers. For particle-size evaluation, a total of 50 particles were measured from 5 different, randomly selected SEM images per sealer. All visible particles, regardless of elemental composition, were included in the measurement to ensure a non-biased representation of both sealers. The diameter of the particle was measured using ImageJ software.

The flow, setting time, film thickness, and radiopacity were assessed following ISO 6876/2012 standards [17]. However, despite the use of these standardized and well-accepted methods, results are often difficult to compare across various studies. For flow, the weight equivalent of 0.05 mL of each sealer ($n = 10$ per group) was placed onto a glass plate. Another glass plate was put on top of the sealer, followed by a weight with a mass of 100 g. After 10 min, the minimum and maximum diameters were measured using the ImageJ software, and the average of the minimum and maximum diameters was calculated for each specimen. Setting time was evaluated by placing the sealers ($n = 5$ per group) into a gypsum mold and put into an incubator at 37 °C with

Table 1 Manufacturer's chemical composition of tested sealers in weight %

Sealer	Tricalcium silicate	Dicalcium silicate	Zirconium oxide	Calcium hydroxide	Strontium silicate	Calcium phosphate
Sr–Si	0.0	0.0	10.0–30.0	1.0–4.0	20.0–45.0	2.0–20.0
Ca–Si	20.0–35.0	7.0–15.0	35.0–45.0	1.0–4.0	0.0	0.0

100% relative humidity. An Mitutoyo Digimatic Indicator was used to apply 100 g of force to the surface of the sealer using a probe with a 2 mm-diameter flat end. Measurements were repeated every 30 min until the primary surface setting of the sealers was observed. After the observation of the surface setting, the measurements were repeated every 15 min until the probe did not make a visible indentation on the surface of the sealer. Film thickness testing involved compressing the sealers ($n = 10$ each group) between two glass plates. The plates with the sealer were then placed under the Instron 5566A (Instron Corp, Norwood, MA) electromechanical universal testing machine with a load cell of 1kN capacity in compression mode, and a 150 N load was applied until the sealer filled the space between the glass plates. After 10 min, the combined thickness of plates and sealer was measured with a micrometer to obtain sealer film thickness. For radiopacity, specimens ($n = 10$ per group) were incubated at 37 °C and 100% relative humidity until the sealers were set. They were then irradiated along with an aluminum step wedge using the Heliodent Plus X-ray unit, operating at 60 kV and 7 mA with an exposure time of 0.10 s. Using ImageJ, the gray pixel values of 3 areas from each specimen and each aluminum step were measured and converted into millimeters of aluminum using a calibration curve.

The pressure-flow experiment was designed to mimic sealer flow into dentin tubules and determine the force required to initiate the flow (Fig. 1). This test was developed de novo to mechanically simulate the hydraulic condensation technique, where pressure from the master cone is used to push the sealer into the dentin tubules. Sealers ($n = 10$ per group) were injected into a glass syringe and the syringe with the sealer was subjected to a push test through a 32G needle with 0.108 mm inner diameter capillary, using the Instron 5566A electromechanical universal testing machine with a load cell of 1kN capacity at room temperature (21 °C)

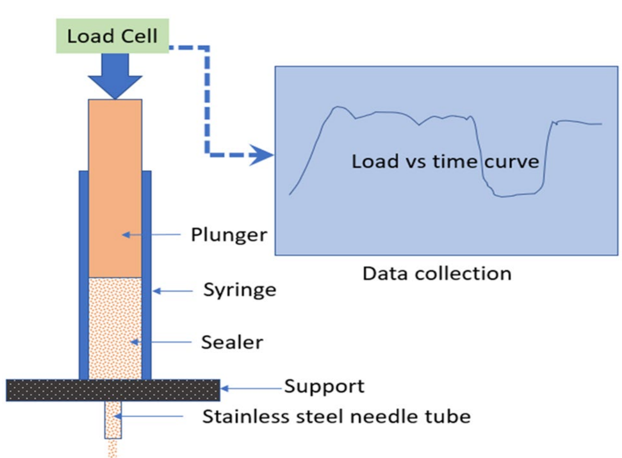

Fig. 1 Diagram of pressure-flow experimental setup

and 55% relative humidity using a 10 mm-diameter plunge with a crosshead speed of 10 mm/min for 5 mm. Force was plotted against time and the force required to get the sealer flowing was obtained from the graph.

For sealer penetration, 20 single-canaled extracted teeth were used. Teeth obtained were free of caries, prior restorations or endodontic treatment. The teeth were from anonymous donors, and the reason for extraction was unknown. The use of unidentified extracted teeth did not meet the regulatory definition of human subjects research; therefore, IRB review was not required (Boston University IRB determination letter H-46261). The extracted teeth were disinfected in a 6% sodium hypochlorite solution for 3 days, and then stored in PBS solution at 4 °C until use. All teeth were accessed and instrumented to a Protaper Gold size F3 rotary file (Dentsply Tulsa Dental Specialties, Tulsa, USA). The canals were irrigated with 1 mL of 6% sodium hypochlorite with the change of each file. The final rinse was performed with 2 mL of 17% EDTA for 1 min followed by 2 mL of 6.0% sodium hypochlorite. Using the hydraulic condensation technique (when a pre-fitted gutta percha cone and sealer is used to create hydraulic pressure and seal a canal), teeth were then obturated with either C-Root (10 root canals) or BC sealer (10 root canals). All specimens were placed in a 37 °C incubator with 100% relative humidity for 1 week to allow the sealers to set. The teeth were then decoronated, fractured in half, and viewed using the SEM. Sealer penetration was measured at the coronal, middle and apical portions of the teeth. At each standardized location, 120 images were taken and a total of 360 measurements were performed per location for each sealer group. Penetration was defined as the distance the sealer travelled starting from the canal wall to the furthest point the sealer went in the dentinal tubule. Distance was measured using the ImageJ software. All measurements were performed by a single investigator. Sealer penetration was compared between the different portions of the tooth as well. Penetration was compared between the different portions of the tooth as well.

Statistical analysis

Statistical analyses were performed using JMP Pro 18.0.2 (SAS, Cary, NC) with the significant level set at 5% for all experiments.

A power analysis was performed to determine sample sizes using the DOE (Design of Experiment) function "power for two independent sample means" with a significant level of $\alpha = 0.05$ and a power of $\beta \geq 0.85$. Preliminary analysis confirmed that the data of film thickness, flow, setting time, and opacity met the assumptions for parametric testing using a Shapiro–Wilk normality test ($\alpha = 0.05$). Data analysis was then done using a Student's t test for all experiments, except for the comparison of sealer penetration of the different locations of the tooth, for which a one-way ANOVA test was used. Pressure-flow data were not confirmed for the normal distribution, and therefore, the nonparametric Kruskal–Wallis test was applied.

Results

EDS analysis showed that the Sr–Si sealer was composed of oxygen (31.4%), tantalum (16.2%), zirconium (18.2%), calcium (11.5%), strontium (10.6%), phosphorus (7.6%), and silicon (4.5%). The Ca–Si sealer was composed of oxygen (30.8%), zirconium (35.6%), calcium (27.0%), and silicon (6.6%). Although the manufacturers claimed to be a calcium or strontium silicate-based sealer, silicon only comprised 6.6% and 4.5% of the composition respectively (Table 2).

The Sr–Si sealer had a mean particle diameter of 1.59 ± 0.97 µm, and the Ca–Si sealer had a mean particle diameter of 8.05 ± 5.66 µm (Table 3 and Fig. 2). The Sr–Si sealer had smaller average particle sizes with statistical differences ($p < 0.05$). In the meantime, the standard

Table 2 Element weight% ± standard deviation of Sr–Si and Ca–Si sealers by EDS

Sealer	O	Ta	Zr	Ca	Sr	P	Si
Sr–Si	31.4 ± 0.5	16.2 ± 0.6	18.2 ± 0.5	11.5 ± 0.2	10.6 ± 0.5	7.6 ± 0.2	4.5 ± 0.2
Ca–Si	30.8 ± 0.3	0.0 ± 0.0	35.6 ± 0.4	27.0 ± 0.3	0.0 ± 0.0	0.0 ± 0.0	6.6 ± 0.1

Table 3 Particle size, flow, setting time, film thickness, radiopacity, and pressure-flow of the sealers.

Sealer	N	Mean particle diameter (µm)	N	Mean flow diameter (mm)	N	Mean setting time (hr)	N	Mean film thickness (µm)	N	Mean radiopacity (mmAl)	N	Mean pressure-flow force (N)
Sr–Si	100	1.59 ± 0.97	10	27.47 ± 1.08	5	66.25 ± 3.50	10	29.30 ± 3.95	10	7.21 ± 0.13	10	11.00 ± 0.75
Ca–Si	100	8.05 ± 5.66	10	24.70 ± 0.98	5	40.55 ± 3.39	10	30.60 ± 3.81	10	6.79 ± 0.10	10	21.51 ± 2.59
p-Value		$p < 0.0001$		$p < 0.0001$		$p < 0.0001$		$p = 0.23$		$p < 0.0001$		$p < 0.0001$

Statistical analysis is done using *t* test or Kruskal–Wallis test. All means are listed with their standard deviations

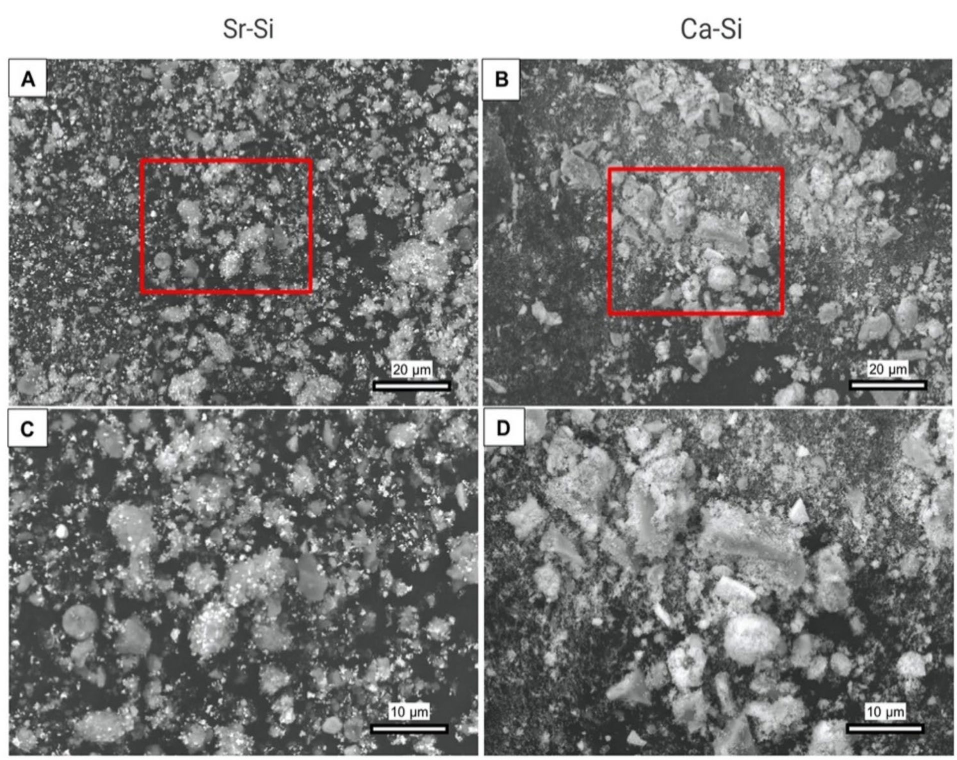

Fig. 2 SEM images of particles from the sealers. **A** and **C** Sr–Si sealer; **B** and **D** Ca–Si sealer. **C** and **D** Higher magnification images under 2000 × magnification at the square on (**A**) and (**B**) under 1000× magnification, respectively. Sr–Si sealer presented homogeneous and smaller particle sizes in low and high magnification images

deviation of particle sizes in Sr–Si sealer group was much less, which represented a higher homogeneity.

The flow, setting time, film thickness, radiopacity, and pressure-flow results are shown in Table 3. Briefly, the Sr–Si sealer had a higher flow, radiopacity, longer setting time, and required less force to initiate flow with statistical differences ($p < 0.05$). Therefore, the null hypotheses on flow, radiopacity, setting time, and force to initiate the flow were rejected. There was no significant difference in film thickness between the two sealers ($p > 0.05$). Therefore, the null hypothesis on film thickness failed to be rejected.

Penetration depth assessed by SEM was significantly greater for the Sr–Si sealer than the Ca–Si sealer in all locations of the tooth (Fig. 3 and Table 4). It is also consistent with the results from "pressure-flow" test. For the Ca–Si sealer, there was no significant difference among the different locations of the tooth, but for the Sr–Si sealer, the middle portion of the tooth had the greatest penetration, followed by the coronal portion, and lastly, the apical section.

The SEM photos (Fig. 3) showed the sealers (both Ca–Si and Sr–Si) moving through the dentin tubules from the main canal space. The Sr–Si sealer penetrates deeper into the tubules compared to the Ca–Si sealer.

Discussion

Elemental analysis confirmed the elements listed in the SDS sheets disclosed by the manufacturers. Tantalum oxides are commonly used as an alternative radiopacifier to bismuth oxide, which has been shown to cause tooth discoloration [18]. Previous studies have also shown that tantalum oxide has a high radiopacity [19] and good biocompatibilty [20]. The presence of tantalum oxide is indicated in the C-Root 510(k) approval document (K212983) [21]. The authors suspect the tantalum detected in the current study served for the radiopacity of the Sr–Si sealer. In the following ISO tests, the Sr–Si sealer showed higher radiopacity than the Ca–Si sealer, likely due to the presence of both tantalum oxide (10.1%) and zirconium oxide (9.4%). In contrast, the Ca–Si sealer only contained zirconium oxide. The combination of high atomic number elements (tantalum, $Z = 72$; zirconium, $Z = 40$) in the Sr–Si sealer provided superior radiopacity. Both sealers met the minimum ISO standard for radiopacity (≥ 3 mm Al). Despite being intended as bioactive components within their respective sealers, Sr, Ca, and Si are present only in small amounts, which is reflected in their low weight percentages. Setting time is another critical factor

Table 4 Depth of sealer penetration in dentin tubules

Sealer	Location	N	Mean length ± std dev (µm)	Significance group*
Sr–Si	Coronal	360	112.77 ± 5.30	B
	Middle	360	159.00 ± 8.36	A
	Apical	360	42.36 ± 4.38	C
Ca–Si	Coronal	360	5.22 ± 0.93	D
	Middle	360	2.72 ± 0.44	D
	Apical	360	2.25 ± 0.70	D

*Levels not connected by same letter have a statistically significant difference ($p < 0.05$)

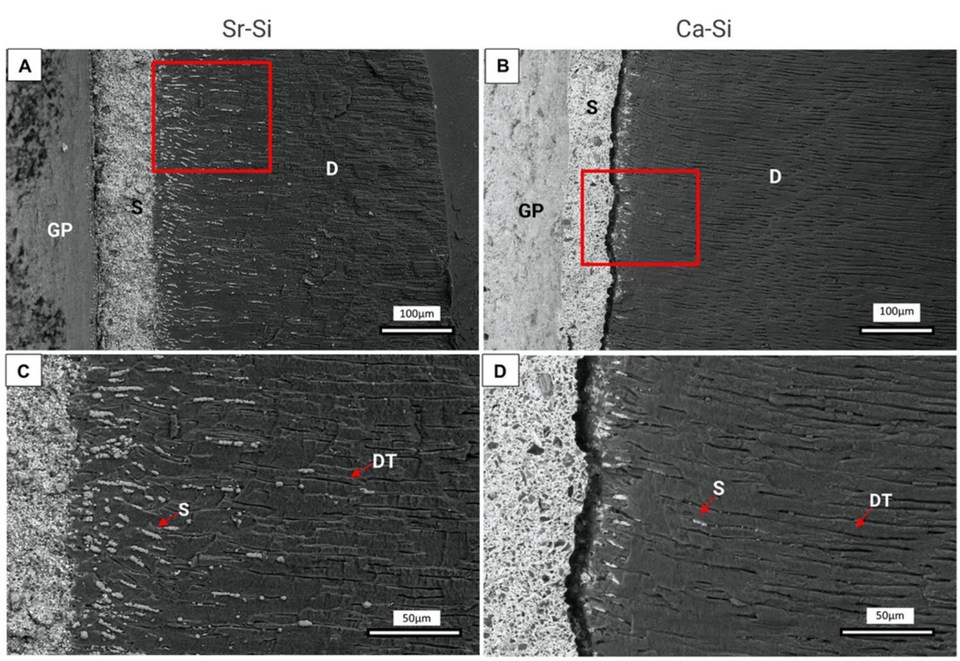

Fig. 3 SEM images of dentin tubule penetration for the sealers. **A** and **C** are from the Sr–Si sealer group; **B** and **D** are from the Ca–Si sealer group. **C** and **D** are the higher magnification images under 500× magnification at the square on (**A**) and (**B**) under 200 × magnification, respectively. Sr–Si sealer penetrated further into dentin tubules in low and high magnification images. *D* dentin, *DT* dentin tubule, *GP* gutta percha, *S* sealer

that influences the practical use of sealers. A sealer should not set too quickly, as it may not provide enough time for the clinician to manipulate and place it into the canal [22]. Conversely, a prolonged setting time (observed in both sealers) poses a clinical risk, primarily by delaying the achievement of the final seal, due to possible washout of the sealer when setting [23]. This delay increases the potential for microleakage and contamination, which is a major factor contributing to treatment failure and reinfection [24]. Furthermore, prolonged setting times can lead to cytotoxicity and tissue irritation [25]. In this experiment, the Sr–Si sealer had a longer setting time than the Ca–Si sealer. According to the manufacturers, the Sr–Si sealer should set in 8 h, while the Ca–Si sealer should set in 4 h. Although the setting time in each group is clinically acceptable, both sealers exceeded the manufacturers' expectations. The setting time measured in our study was tested under in vitro conditions, which may not directly reflect the clinical scenario.

In ISO tests, flow and film thickness are indicators of how well a sealer can penetrate dentinal tubules and fill root canal irregularities [26, 27]. In this study, the Sr–Si sealer exhibited greater flow and smaller thickness than the Ca–Si sealer, with both meeting ISO standards for flow and being under the maximum limit for film thickness. These results indicate that the Sr–Si sealer may perform better in sealing complex canal systems and accessory canals. The above results were verified by non-ISO tests.

The novel "pressure-flow" experiment, using a glass syringe to simulate sealer penetration, showed that the Ca–Si sealer required more force to initiate flow, whereas the Sr–Si sealer flowed more easily with less force. While previous studies have utilized various capillary systems to mimic dentinal tubule environment [28, 29], our custom-developed test was specifically designed to better replicate the in vivo scenario of hydraulic condensation—a clinical technique increasingly favored for use with bioceramic sealers. This difference, along with increased friction and surface tension, may explain why the Ca–Si sealer penetrated less effectively.

Penetration is a critical factor for creating a strong, impermeable seal that prevents bacterial infiltration and minimizes reinfection risks. Effective penetration also improves the bond between the sealer and dentin, enhancing treatment stability and longevity. Previous studies have reported that the Ca–Si sealer can achieve a maximum tubular penetration of approximately 2 mm [30, 31]. The differences between these results and the present study may be attributed to the different microscopy techniques used: SEM in the present study and confocal laser scanning microscopy in the earlier research. SEM provides detailed insights into the surface structures of sealers at high resolution [32], while confocal microscopy may be affected by the autofluorescence properties of dentin, potentially leading to false readings [33]. Additionally, nonspecific binding of fluorescent tags to dentin can result in inaccurate findings when using confocal microscopy [34]. While confocal microscopy is useful for visualizing tubule penetration, it lacks the ability to analyze the composition of sealers, which is crucial for understanding their performance [32].

The significantly greater dentin tubule penetration observed for the Sr–Si sealer compared to the Ca–Si sealer (Table 4) correlates with its greater flowability observed (Table 3). This finding is consistent with the recent literature, as demonstrated by Chew et al. 2023, who showed that sealers with superior flowability achieved greater sealer penetration [35]. This highlights the role of material flow in achieving an effective seal, a factor also emphasized in a review done by La Rosa et al. These authors noted that bioceramic sealers exhibit different physical properties based on their composition [36].

One of the reasons that could explain the differences in flow, film thickness, pressure-flow, and penetration is particle size. In this study, the Ca–Si sealer had a larger average particle diameter (8.05 ± 5.66 µm) compared to the Sr–Si sealer (1.59 ± 0.97 µm). Considering that dentin tubule diameters in the root typically range from approximately 4.32 µm in the coronal third, to 3.74 µm in the middle third and as small as 1.73 µm in the apical third [37], the Sr–Si sealer's small particles are optimally sized to penetrate all three regions. This difference in particle size was also evident in the "pressure-flow" tests, where the Ca–Si sealer, with its larger and more heterogeneous particle size, required more force to initiate flow compared to the Sr–Si sealer, which had a more uniform particle distribution. It is important to note that the finding of smaller and more homogenous particle size is specific only to the tested Sr–Si product and may not be generalizable to other strontium silicate-based sealers.

The study utilized extracted teeth where the specific donor age and reason for extraction were unknown. It is noteworthy that the intra-group results for sealer penetration appeared very consistent, despite the natural variations inherent in human dentin. Within each sealer group, the greatest penetration was observed in the middle section, followed by the coronal, with the least penetration in the apical third. This is likely due to the decreasing size of dentin tubules toward the apex [38]. The middle third showed greater penetration, possibly due to better fitting of the gutta-percha cone during hydraulic condensation. In contrast, the Ca–Si sealer showed no significant location-based differences, likely due to its lower flowability, which resulted in limited penetration throughout the tooth.

Sealers that penetrate dentinal tubules provide micromechanical retention and help entomb residual bacteria to prevent reinfection [39]. Therefore, optimizing sealer penetration is essential for ensuring durable outcomes in endodontic therapy.

However, this in vitro study has several important limitations. First, the evaluation was restricted to a single commercial product from each sealer class, which limits the generalizability of the findings to the entire heterogenous class of bioceramic sealers. Second, the study's in vitro nature does not incorporate dynamic biological factors, such as tissue fluid pressure or a microbial challenge, which are critical components of the clinical environment. Finally, this investigation focused on the immediate physical properties and did not include experiments on long-term stability, solubility, and chronic biocomptability. To comprehensively assess the biological effects and clinical performance, particularly regarding long-term durability and resistance to bacterial penetration, future in vivo and clinical studies are necessary.

Conclusion

The properties of the Sr–Si sealer suggest that it possesses desirable characteristics based on current in vitro criteria. While these results provide a strong foundation for its application, conclusions regarding its long-term clinical suitability depend on further clinical trials.

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Declarations

Conflict of interest All the authors declare that no conflicts of interest are involved in this study.

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