

Research Article

Comparison of the compressive strength of a nanoparticle-indonesian white portland cement-resin mixture and resin-modified calcium silicate: study experimental

Armybet Itaq Fitri Sabila¹, Indra Primathena^{2*}, Denny Nurdin³, Arief Cahyanto^{3,4}

*Correspondence:

indra.primathena@unpad.ac.id

¹Undergraduate Study Program, Faculty of Dentistry, Universitas Padjadjaran, Indonesia

²Department Conservative Dentistry, Faculty of Dentistry, Universitas Padjadjaran, Indonesia

³Department of Clinical Sciences, College of Dentistry, Ajman University, Ajman, United Arab Emirates

⁴Centre of Medical and Bio-allied Health Sciences Research, Ajman University, Ajman, United Arab Emirates

Submission: 06 April 2026

Revised : 30 Mei 2026

Accepted: 27 June 2026

Published: 30 June 2026

DOI: [10.24198/pjdrs.v10i2.69743](https://doi.org/10.24198/pjdrs.v10i2.69743)

ABSTRACT

Introduction: Dental caries has a high prevalence in Indonesia and requires restorative treatment to maintain pulp vitality. Pulp capping is one treatment option, and its success is influenced by the material used. Indonesian White Portland Cement (IWPC) has potential as an alternative pulp-capping material, particularly in nanoparticle form combined with resin; however, its mechanical strength requires evaluation. This study aimed to formulate a nano-IWPC-resin mixture and evaluate its compressive strength compared with that of resin-modified calcium silicate (TheraCal LC), with and without incubation in Ringer's lactate. **Methods:** This true experimental study used 32 samples divided into four groups: Group 1, incubated nano-IWPC-resin; Group 2, non-incubated nano-IWPC-resin; Group 3, incubated resin-modified calcium silicate (TheraCal LC); and Group 4, non-incubated TheraCal LC. Samples were irradiated using a light-curing unit and tested for compressive strength using a universal testing machine with a 5 kN load cell at 1.0 mm/min until failure. Data were analyzed using tests for normality and homogeneity, followed by One-Way ANOVA, and the Games-Howell post hoc test. **Results:** The incubated nano-IWPC-resin mixture showed the highest compressive strength value (104.46 ± 8.55 MPa), followed by the non-incubated TheraCal LC (83.85 ± 16.57 MPa), non-incubated nano-IWPC-resin (67.21 ± 6.60 MPa), and incubated TheraCal LC (39.04 ± 7.37 MPa). Statistical analysis showed a significant difference among the four groups ($p < 0.001$). **Conclusion:** The incubated nano-IWPC-resin mixture exhibited higher compressive strength than TheraCal LC after incubation in Ringer's lactate, supporting its potential as an alternative pulp-capping material.

KEYWORDS: Indonesian white portland cement, nanoparticle, compressive strength, resin-modified calcium silicate.

Perbedaan compressive strength antara campuran resin - nanopartikel - semen portland putih indonesia dan resin-modified calcium silicate : studi eksperimental

ABSTRAK

Pendahuluan: Karies gigi memiliki prevalensi tinggi di Indonesia dan memerlukan perawatan restoratif untuk mempertahankan vitalitas pulpa. Salah satu pilihan perawatan adalah pulp capping dan keberhasilannya dipengaruhi oleh bahan yang digunakan. Semen Portland putih Indonesia (SPPI) memiliki potensi sebagai bahan alternatif pulp capping, terutama dalam bentuk nanopartikel yang dikombinasikan dengan resin; namun, kekuatan mekanisnya perlu dievaluasi. Tujuan penelitian ini bertujuan memformulasikan campuran nanopartikel-SPPI-resin dan menganalisis kekuatan tekannya dibandingkan dengan resin-modified calcium silicate (TheraCal LC), dengan dan tanpa inkubasi dalam larutan Ringer laktat. **Metode:** Penelitian eksperimental murni ini menggunakan 32 sampel yang dibagi menjadi empat kelompok: Kelompok 1, campuran nanopartikel-SPPI-resin yang diinkubasi; Kelompok 2, nanopartikel-SPPI-resin tanpa inkubasi; Kelompok 3, resin-modified calcium silicate (TheraCal LC) yang diinkubasi; dan Kelompok 4, TheraCal LC tanpa inkubasi. Sampel disinari menggunakan light-curing unit dan diuji kekuatan tekannya menggunakan universal testing machine dengan load cell 5 kN pada kecepatan 1,0 mm/menit hingga terjadi kegagalan. Data dianalisis menggunakan uji normalitas, homogenitas, One-Way ANOVA, dan uji post hoc Games-Howell. **Hasil:** Campuran nanopartikel-SPPI-resin yang diinkubasi menunjukkan nilai kekuatan tekan tertinggi ($104,46 \pm 8,55$ MPa), diikuti oleh kelompok kontrol tanpa inkubasi ($83,85 \pm 16,57$ MPa), nanopartikel-SPPI-resin tanpa inkubasi ($67,21 \pm 6,60$ MPa), dan kelompok kontrol dengan inkubasi ($39,04 \pm 7,37$ MPa). Analisis statistik menunjukkan adanya perbedaan signifikan antar kelompok ($p < 0,001$). **Simpulan:** Campuran nanopartikel-SPPI-resin yang diinkubasi menunjukkan kekuatan tekan lebih tinggi dibandingkan TheraCal LC setelah inkubasi dalam larutan Ringer laktat, sehingga berpotensi menjadi bahan alternatif pulp capping.

KATA KUNCI: Semen portland putih indonesia, nanopartikel, compressive strength, resin modified calcium silicate

INTRODUCTION

Caries remains one of the most prevalent oral diseases and can progress to deep lesions that increase the risk of pulpal involvement if not managed appropriately.¹⁻³ Maintaining pulp vitality is clinically desirable because vital pulp therapy is designed to preserve the dentin–pulp complex and avoid more invasive treatment when indicated.¹⁻³ Accordingly, contemporary management of deep caries increasingly considers vital pulp therapy as a biologically based approach when the clinical conditions are favorable.²

Pulp capping is one of the vital pulp therapy strategies aimed at preserving or restoring pulp health after caries excavation or accidental exposure.¹ The success of pulp capping is influenced by case selection and procedural factors, including control of bleeding, aseptic technique, and the quality of coronal sealing.¹ In addition, the biological and mechanical performance of the capping material plays a major role in treatment outcomes.³ An ideal pulp capping material should be biocompatible and bioactive to support hard-tissue barrier formation while maintaining adequate sealing ability.³

Mineral Trioxide Aggregate (MTA) is a cement-based material that is commonly used in dental procedures for pulp capping and root canal treatment. MTA materials consist of a mixture of tricalcium silicate (58.3%), dicalcium silicate, and tricalcium aluminate.⁴⁻⁶ The addition of Bismuth oxide (Bi_2O_3) in MTA serves as a radiopaque material to allow visualization of the material on radiographs. The main function of MTA is to stimulate dentin formation and protect vital pulp tissue. Mineral Trioxide Aggregate has disadvantages, including high cost, prolonged setting time, difficulty in handling, and reduced stability in a humid environment.⁴⁻⁶

Mineral trioxide aggregate (MTA) has long been considered a reference material for pulp capping due to its documented clinical applications and favorable biological performance.⁴ However, MTA presents several practical and clinical limitations, including handling difficulties due to its granular consistency, high material cost, and the potential to cause tooth discoloration.⁶ Furthermore, its prolonged setting time—which can take several hours and requires continuous moisture to fully set—can significantly delay subsequent restorative procedures and reduce clinical convenience.⁶

These limitations support continued investigation of alternative materials that can maintain comparable performance with improved practicality or accessibility.³ Portland cement has been discussed as a potential alternative root repair and bioactive material because of its similarities to calcium silicate systems used in dentistry.⁷ In Indonesia, Indonesian White Portland Cement (IWPC) has been specifically compared with MTA in terms of chemical composition as a candidate pulp capping material.⁸

Material modification using nanoparticles has been proposed to improve cement-based dental materials by influencing physicochemical properties and mechanical behavior.⁹ Silver nanoparticle incorporation into Portland cement has been explored to enhance functional performance, including antimicrobial-related characteristics relevant to dental applications.¹⁰ Tricalcium silicate white Portland cement systems have also been developed and evaluated as cost-effective dental materials with additional antibacterial considerations.¹¹ Resin-modified and light-curable calcium silicate-based materials have been introduced to improve handling and allow immediate curing in clinical workflows.¹² TheraCal LC is one example of a resin-modified calcium silicate material with reported biochemical and clinical applications in dentistry.¹³

Nevertheless, comparative studies have reported varying results for TheraCal LC relative to other bioactive materials.¹⁴ Despite these reported variations, its handling advantages, TheraCal LC presents several clinical and material shortcomings. These include lower calcium ion release compared with conventional cements, potential cytotoxicity from unreacted resin monomers, and suboptimal mechanical properties—such as compressive strength—when exposed to moist environments. Additionally, as an imported commercial product, its relatively high cost can be a barrier in certain clinical settings.

These limitations highlight the need to develop a more cost-effective, locally accessible alternative with comparable or superior mechanical performance, such as Indonesian White Portland Cement (IWPC) modified with nanoparticles and resin.^{13,14}

Compressive strength is a key mechanical parameter for pulp capping or liner materials

because it reflects resistance to deformation and fracture under functional or restorative stresses.¹⁵ Therefore, this study aimed to compare the compressive strength of two materials: a nano-IWPC–resin mixture and a commercial resin-modified calcium silicate (TheraCal LC). Furthermore, this study evaluated how compressive strength was affected by environmental conditions by comparing samples incubated in Ringer’s lactate with non-incubated samples. These evaluations were conducted to assess the mechanical potential of nano-IWPC–resin as an alternative pulp capping material.¹⁵

In this study, Indonesian White Portland Cement (IWPC) is proposed as a locally sourced base material for pulp capping, considering its reported similarity to MTA-related cement chemistry in dental applications.⁸ The novelty lies in formulating a light-curable nano-IWPC–resin mixture and evaluating its compressive strength as an initial mechanical parameter critical for pulp capping/liner materials.¹⁵ In addition, this study specifically assesses the effect of Ringer’s lactate incubation as a physiological-like medium on the compressive strength of the developed material.¹⁶ The results are benchmarked against TheraCal LC to provide a direct comparison with a resin-modified calcium silicate material used clinically.¹³

Therefore, this study aimed to evaluate a nanoparticle-Indonesian White Portland Cement-resin mixture by analyzing its compressive strength and comparing its performance with that of a resin-modified calcium silicate (TheraCal LC) control under incubated and non-incubated conditions. The study focused on compressive strength as an initial mechanical parameter and did not directly assess biocompatibility or overall clinical performance.

METHODS

This study used a true experimental design and was conducted at the Integrated Research Laboratory, Faculty of Dentistry, Universitas Padjadjaran. The procedures followed several international standards, including ISO 6876:2012, which specifies the characteristics of cement-based materials used in pulp capping procedures, and ISO 4049:2019, which regulates the materials used for permanent applications and requires compressive strength that meets the criteria of restorative materials.

Additional experimental procedures were conducted at the Functional Nano Powder Laboratory of the University Center of Excellence (Finder U-CoE) in April 2025. The materials evaluated in this study consisted of the nanoparticle-Indonesian White Portland Cement-resin mixture and TheraCal LC. The sample size was determined using Federer’s formula for experimental studies, $(t-1)(n-1) \geq 15$, where t is the number of treatment groups and n is the number of specimens per group. For four groups, $(4-1)(n-1) \geq 15$; therefore, $n \geq 6$ specimens per group. To allow for potential specimen defects during preparation and storage, eight specimens per group were prepared, resulting in 32 specimens in total. The specimens were allocated to four treatment groups and subsequently subjected to compressive strength testing.

Specimens that cracked, broke, or exhibited structural defects during the preparation and storage process were excluded from this study because they did not meet the predefined specimen criteria. The data obtained were presented in a table with an interval scale and consisted of four specimen groups: 1) a mixture of nanoparticle-Indonesian White Portland Cement-resin tested after incubation in Ringer’s lactate for 24 hours at 37°C, 2) a mixture of nanoparticle-Indonesian White Portland Cement-resin tested directly after irradiation, 3) resin-modified calcium silicate tested after incubation in Ringer’s lactate for 24 hours at 37°C, and 4) resin-modified calcium silicate tested directly after irradiation.

The test results were analyzed using One-Way ANOVA statistical analysis to determine whether significant differences existed among the groups. If a significant difference was found, a post hoc test was performed to determine which groups showed a significant difference. The variables studied included independent variable (a mixture of nanoparticle-Indonesian White Portland Cement-resin and resin-modified calcium silicate), the dependent variable (compressive strength), and the controlled variables (compressive strength testing procedures using a Universal Testing Machine).

The nanoparticle-Indonesian White Portland Cement (IWPC) was initially prepared and processed using 99.9% isopropanol (*Manufacturer Name, City, Country*). The homogenization and particle separation processes were conducted using a magnetic stirrer and a centrifuge, followed by drying in a drying oven (*Manufacturer Name*). The resin matrix was formulated by mixing di urethane dimethacrylate (UDMA) and triethylene glycol dimethacrylate (TEGDMA), activated by camphorquinone as a photoinitiator. (Trimethoxysilyl) propyl methacrylate was utilized as a coupling agent to enhance the bond between the cement and resin.

All materials were precisely measured using an analytical balance, and small volumes were handled using a micropipette and a 200 ml beaker. The formulated nano-IWPC-resin mixture and the control material, resin-modified calcium silicate (TheraCal LC) (*Bisco Inc., Schaumburg, IL, USA*), were carefully placed into a specimen mold. The specimens were then irradiated using a light curing unit, with the output intensity verified by a light meter. Following polymerization, the designated specimen groups were stored in an incubator (*Manufacturer Name*) at 37°C for incubation.

The research procedures began with mixing the IWPC powder with isopropanol at a ratio of 4:1. The milling process was carried out for 24 hours using a high-speed bead mill machine, followed by filtration and evaluation using a Particle Size Analyzer (PSA) with a synthesis result of 62.0 nm. The nanoparticle-Indonesian White Portland Cement-resin mixture was prepared by mixing the materials in a beaker using a magnetic stirrer, after which the mixture was poured into cylindrical specimen molds (4x6 mm) for irradiation using a light curing unit. A resin-modified calcium silicate control sample was also poured into a cylindrical mold (4x6 mm) and irradiated using a light-curing unit.

Compressive strength testing was conducted using a universal testing machine equipped with a 5 kN load cell at a crosshead speed of 1.0 mm/min until failure or fracture occurred. The compressive strength values were recorded in megapascals (MPa). The data obtained were analyzed using a normality test, a homogeneity of variance test, and one-way analysis of variance (ANOVA). If a significant difference was observed ($p < 0.05$), a post hoc test was carried out to determine which groups showed significant differences.

RESULTS

The compressive strength values for each experimental group are summarized in Table 1. The mean compressive strength in the Incubated Nano-IWPC-Resin group was 104.46 ± 8.55 MPa, representing the highest mean compressive strength among the treatment groups. This was followed by the Non-Incubated Control group (83.85 ± 16.57 MPa) and the Non-Incubated Nano-IWPC-Resin group (67.21 ± 6.60 MPa).

Table 1. Results of compressive strength testing for the nanoparticle-IWPC-resin mixture and resin-modified calcium silicate

No. sample in each group	Stress at maximum load (MPa)			
	Incubated nano-IWPC-resin	Non-incubated nano-IWPC-resin	Incubated Control	Non-Incubated Control
1	98.45	60.53	34.95	79.77
2	114.70	61.86	27.86	108.46
3	112.77	62.52	44.13	76.02
4	109.01	78.41	45.80	91.61
5	95.06	71.18	35.33	60.21
6	106.17	66.13	50.60	92.95
7	91.23	62.87	38.95	64.78
8	108.29	74.14	34.68	97.01
Mean	104.46	67.21	39.04	83.85
Standard Deviation	8.55	6.60	7.37	16.57

Source: Processed data, 2025

Conversely, the Incubated Control group exhibited the lowest compressive strength at 39.04 ± 7.37 MPa. Prior to the one-way ANOVA, the data were tested for normality using the Shapiro-Wilk test and for homogeneity of variance using the Levene test. The results confirmed a normal distribution across all treatment groups: Incubated Nano-IWPC-Resin ($p=0.483$), Non-Incubated Nano-IWPC-Resin ($p=0.204$), Incubated Control ($p=0.806$), and Non-Incubated Control ($p=0.837$). Furthermore, the Levene test indicated homogeneous data variance among the groups ($p=0.056$). Consequently, a parametric one-way ANOVA was conducted to evaluate differences in compressive strength among the treatment groups.

Table 2. Results of One-Way ANOVA

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	18342.315	3	6114.105	54.894	0.001
Within Groups	3118.649	28	111.380		
Total	21460.963	31			

Source: Processed data 2025

The results of the one-way ANOVA test (Table 2) demonstrated a significant difference in compressive strength among the treatment groups. The Sig. Value obtained from the one-way ANOVA was 0.001, where this value was lower than the predetermined significance level ($p<0.05$). A post hoc analysis was subsequently performed to observe the difference among the treatment groups in more detail to determine which measurement points demonstrated lower or higher compressive strength. According to the results of the variance test, data variance was not homogeneous ($p<0.05$). Therefore, the post hoc Games-Howell test was conducted.

The one-way ANOVA results in Table 2 demonstrated a significant difference in compressive strength among the treatment groups ($F=54.894$, $p<0.001$). Although the Levene test did not indicate a statistically significant variance difference, the Games-Howell procedure was used as a conservative pairwise comparison because the group standard deviations differed appreciably. The significant pairwise differences identified by this test are presented in Table 3.

Table 3. Significant pairwise differences in compressive strength according to the Games-Howell post hoc test

Group comparison	p-value	Result
Incubated Control vs. Non-Incubated Nano-IWPC-Resin	0.001	Significant
Incubated Control vs. Non-Incubated Control	0.001	Significant
Incubated Control vs. Incubated Nano-IWPC-Resin	0.001	Significant
Non-Incubated Nano-IWPC-Resin vs. Incubated Nano-IWPC-Resin	0.001	Significant
Non-Incubated Control vs. Incubated Nano-IWPC-Resin	0.043	Significant

Source: Processed data, 2025

Note: Only statistically significant pairwise differences are shown ($p<0.05$). The remaining pairwise comparison, between Non-Incubated Nano-IWPC-Resin and Non-Incubated Control, was not statistically significant.

DISCUSSION

Mineral Trioxide Aggregate (MTA) is a cement-based material that is commonly used in dental procedures for pulp capping and root canal treatment. MTA consists of a mixture of tricalcium silicate (58.3%), dicalcium silicate, and tricalcium aluminate.^{4,5,6} The addition of bismuth oxide (Bi_2O_3) in MTA serves as a radiopaque agent that allows visualization of the material on radiographs. The main function of MTA is to stimulate dentin formation and protect vital pulp tissue. MTA has several disadvantages, including high cost, prolonged setting time, difficulty in handling, and reduced stability in a humid environment.^{4,5,6}

The control material used was TheraCal LC, which is a resin-modified calcium silicate material with a calcium silicate content ranging from 20% to 60%. This material was introduced as a solution to the disadvantages of MTA, with a faster setting time, easier handling, and improved properties for stimulating pulp-tissue remineralization.^{3,12,13,14} Although this material offers various advantages, it has disadvantages, including limited ability to

generate a hard tissue structure and mechanical strength that is lower than that of MTA, particularly in the long term.^{14,17,18}

This study was conducted to investigate an alternative material that is potentially suitable for local production and may offer economic advantages. However, the focus of this study is strictly limited to compressive strength testing as an initial parameter to assess the mechanical characteristics of the material. Consequently, while the nanoparticle-Indonesian White Portland Cement-resin mixture demonstrates higher compressive strength than TheraCal LC, it cannot yet be definitively concluded to be an overall superior material. Further comprehensive evaluations—encompassing other mechanical properties and biological assessments—are required before establishing its full clinical performance.

Nanoparticles offer various benefits in dentistry, especially in restorative materials and tissue treatment.^{19,20,21} Their main benefit is the potential to improve the mechanical properties of Portland cement and calcium-silicate-based materials.^{9,22,23} Nanoparticles may also increase material strength, although mechanical improvement alone does not establish biological safety.^{9,24,25} Ezawa et al.,²⁴ reported that tricalcium-silicate nanoparticles can accelerate hydration, improve compressive strength, and reduce porosity. This finding is directionally consistent with the present result, in which the Nano-IWPC-Resin group showed higher compressive strength after incubation. However, the formulation and test conditions in the present study differ from those of Ezawa et al.;²⁴ therefore, the results should be compared in terms of overall trend rather than as directly equivalent numerical values.

Two of the four groups in this study were evaluated after incubation in Ringer's lactate for 24 hours at 37°C. Ringer's lactate contains sodium, potassium, calcium, chloride, and lactate ions and was selected as an electrolyte-containing medium that more closely represents a physiological fluid than an inert medium.¹⁶ Although artificial saliva is commonly used for restorative materials exposed to the oral cavity, pulp-capping materials may interact with pulpal and interstitial fluids rather than saliva. Therefore, Ringer's lactate was used to provide a physiologically relevant incubation condition.

Previous compressive-strength research by Ranjbar Omrani et al. also compared TheraCal LC immediately after setting and after 24 hours, but reported an increase from 81.⁴⁷ to 114.⁴⁰ MPa.¹⁵ The different response observed in the present study may be related to the incubation medium, specimen geometry, curing protocol, material formulation, or testing conditions. This comparison highlights the importance of specifying the medium and incubation protocol when interpreting the mechanical behavior of pulp-capping materials.

Table 1 shows that the compressive strength of the Nano-IWPC-Resin group increased from 67.21 ± 6.60 MPa without incubation to 104.46 ± 8.55 MPa after incubation in Ringer's lactate. This increase may be associated with continued hydration of the calcium-silicate phase, which can promote the formation of calcium-silicate-hydrate and calcium hydroxide that may contribute to a denser internal structure.^{24,28}

The direction of this result is consistent with Ezawa et al.,²⁴ who reported improved mechanical behavior in a tricalcium-silicate-nanoparticle-containing cement after maturation. In contrast, the present formulation combines the nanoparticle cement phase with a resin matrix, so the magnitude of the effect cannot be assumed to be identical. Saghiri et al.,²⁸ reported a high calcium-silicate content in Portland cement, whereas Arandi and Rabi described TheraCal LC as a resin-modified material containing approximately 45% Portland cement.¹³ These compositional differences provide a plausible explanation for the different responses to incubation.

Beyond the descriptive comparison in Table 1, the inferential analysis in Table 2 confirmed that compressive strength differed significantly among the four treatment groups ($F=54.894$, $p<0.001$), indicating that the differences in mean strength were unlikely to have occurred by chance. The Games-Howell post hoc comparisons in Table 3 clarified which specific between-group differences accounted for this overall effect. Incubated Control (TheraCal LC after incubation) differed significantly from all three other groups ($p=0.001$ – 0.043), consistent with its markedly lower mean strength (39.04 ± 7.37 MPa) and supporting the interpretation that incubation in Ringer's lactate weakened this resin-modified calcium-silicate material rather than strengthening it. In contrast, Incubated Nano-IWPC-Resin differed significantly from both

Non-Incubated Nano-IWPC-Resin ($p=0.001$) and Non-Incubated Control ($p=0.043$), confirming that incubation produced a statistically supported increase in the mechanical performance of the nanoparticle-cement-resin mixture. Notably, the comparison between Non-Incubated Nano-IWPC-Resin and Non-Incubated Control was not statistically significant, even though their mean values differed numerically (67.21 ± 6.60 MPa versus 83.85 ± 16.57 MPa). This indicates that, before incubation, the compressive strength of the nanoparticle-cement-resin mixture was not yet statistically distinguishable from that of the commercial control material, and that its mechanical advantage became evident only after incubation. Taken together, the ANOVA and post hoc findings indicate that the two materials exhibited different compressive-strength responses under the incubation conditions tested, while no statistically significant difference was observed between the two materials in the non-incubated condition.

In this study, the incubated and non-incubated Nano-IWPC-Resin groups contained 58% Portland-cement nanoparticles. This cement fraction may provide a reactive calcium-silicate phase that may continue hydrating during incubation, which could explain the higher strength of the incubated group. The earlier chemical-composition study by Nurdin et al. reported a high similarity between Indonesian White Portland Cement and MTA, supporting the use of IWPC as a calcium-silicate-based research material.⁸ Nevertheless, the 58% proportion represents the nanoparticle cement component and does not by itself determine the final mechanical behavior; the resin matrix, particle dispersion, and solution chemistry also contribute. The calcium and other electrolytes in Ringer's lactate may participate in ion exchange or influence hydration kinetics rather than acting only as an inert medium. Future studies should therefore include pH monitoring and ion-release quantification, or use a standardized non-ionic medium, to separate intrinsic material hardening from effects of the incubation solution.

The results demonstrate that the nanoparticle-Indonesian White Portland Cement-resin mixture had higher compressive strength than TheraCal LC after incubation in Ringer's lactate. The incubated Nano-IWPC-Resin group reached 104.46 ± 8.55 MPa, whereas the incubated TheraCal LC group reached 39.04 ± 7.37 MPa. This pattern differs from the study by Ranjbar Omrani et al.,¹⁵ in which TheraCal LC increased from 81.47 MPa immediately after setting to 114.40 MPa after 24 hours. The discrepancy does not necessarily indicate that one material is universally stronger; rather, it suggests that the response of TheraCal LC is sensitive to the storage medium and test protocol. In the present experiment, incubation was associated with an increase in compressive strength of Nano-IWPC-Resin but with a decrease in compressive strength of TheraCal LC under the specified Ringer's lactate condition.

Nano-IWPC-Resin demonstrated higher compressive strength than TheraCal LC after incubation, while TheraCal LC showed lower strength after exposure to Ringer's lactate. Arandi and Rabi described TheraCal LC as a hybrid material containing a substantial resin fraction and noted that its hydration depends on moisture entering the material.¹³ This composition may make the material sensitive to water sorption, solubility, and plasticization of the resin network during aqueous exposure. The present result is therefore mechanistically compatible with the previous review, but the study did not directly measure water sorption, solubility, or resin conversion; the proposed mechanism should consequently be regarded as an interpretation rather than a direct causal finding. The contrast with Ranjbar Omrani et al.,¹⁵ who observed increased TheraCal LC strength after 24 hours, further indicates that the storage medium and experimental protocol must be considered when comparing results.^{13,15}

From a comparative perspective, the higher strength of incubated Nano-IWPC-Resin is notable but remains specific to the formulation and in vitro conditions used in this study. The finding is consistent with previous research showing that nanoparticle modification can improve the mechanical behavior of calcium-silicate-based materials.²⁴ It should not, however, be interpreted as proof of overall clinical superiority, because pulp-capping materials must also be assessed for sealing ability, solubility, ion release, biocompatibility, and clinical performance.^{13,15}

These findings suggest that Nano-IWPC-Resin may have potential as an alternative to a commercially available light-curable pulp-capping material, particularly where locally sourced and cost-effective materials are desired. The observed change associated with Ringer's lactate incubation indicates that the storage or moisture condition may influence early strength.

Further studies should evaluate sealing ability, solubility, ion release, biocompatibility, thermocycling, and longer-term aging before clinical application can be considered.

This study has several limitations. First, the evaluation was limited to compressive strength as an initial mechanical parameter, so the results cannot fully represent overall clinical performance of pulp capping materials. Second, the incubation condition used Ringer's lactate for 24 hours at 37°C, which may not reflect the long-term oral environment; therefore, the mechanical behavior after longer aging periods remains unknown. Third, the study did not incorporate thermocycling procedures to simulate thermal stress and temperature fluctuations typically occurring in the oral cavity, which can significantly affect the bonding and structural integrity of resin-modified and cement-based materials. Fourth, the study was conducted using an in vitro experimental setting with standardized cylindrical specimens, so clinical factors such as intraoral temperature fluctuation, occlusal fatigue, moisture contamination, and restorative interface conditions were not fully simulated. Fifth, only one comparator material (TheraCal LC) and a single formulation of nano-IWPC–resin (including the nanoparticle size and composition used in this study) were tested; thus, the findings may not be generalizable to other formulations or materials. Finally, the total sample size was 32 across four groups, and specimens damaged during preparation/storage were excluded, which may affect the final sample composition and generalizability of the findings.

CONCLUSION

This study demonstrates that the nano-IWPC–resin mixture had higher compressive strength than resin-modified calcium silicate (TheraCal LC) under the conditions tested. Incubation with Ringer's lactate was associated with an increase in the compressive strength of the nano-IWPC–resin mixture, while a decrease was observed in TheraCal LC. This result indicates a significant difference between the two materials, with the Nano-IWPC-resin mixture demonstrating higher compressive strength under the conditions tested. These findings suggest that the nano-IWPC-resin mixture warrants further investigation as a potential alternative pulp capping material. However, its long-term clinical performance, affordability, and ability to support the success of vital pulp therapy require further evaluation.

The practical implications of this study are twofold. Clinically, the development of a nano-IWPC-resin material may offer a potential pulp-capping material with high compressive strength under the conditions tested. Economically and industrially, utilizing locally available Indonesian White Portland Cement may provide an opportunity to develop a locally sourced alternative to imported dental materials. This economic accessibility could have implications for the accessibility of pulp-capping materials; however, the actual economic and public health benefits require evaluation of production costs, regulatory requirements, clinical effectiveness, and implementation in healthcare settings.

Acknowledgement: The authors would like to express their sincere gratitude to the institution, all participants, and everyone who provided permission, assistance, and support throughout the research process and manuscript preparation. The authors also gratefully acknowledge all those who contributed to the successful completion of this study.

Author Contributions: Conceptualization, S.A.I.F., P.I. and N.D.; methodology, S.A.I.F., P.I. and N.D.; software, S.A.I.F., P.I. and N.D.; validation, S.A.I.F., P.I. and N.D.; formal analysis, S.A.I.F., P.I. and N.D.; investigation, S.A.I.F., P.I. and N.D.; resources, S.A.I.F., P.I. and N.D.; data curation, S.A.I.F., P.I. and N.D.; writing—original draft preparation, S.A.I.F., P.I. and N.D.; writing—review and editing, S.A.I.F., P.I. and N.D.; visualization, S.A.I.F., P.I. and N.D.; supervision, S.A.I.F., P.I. and N.D.; project administration, S.A.I.F., P.I. and N.D. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from the corresponding author, subject to the approval of all researchers and in compliance with research ethics.

Conflicts of Interest: The authors declare no conflict of interest. The authors have no financial or personal relationships that could have appeared to influence the work reported in this paper. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

REFERENCES

- Islam R, Islam MRR, Tanaka T, Alam MK, Ahmed HMA, Sano H. Direct pulp capping procedures - Evidence and practice. *Jpn Dent Sci Rev.* 2023;59:48-61. <https://doi.org/10.1016/j.jdsr.2023.02.002>.
- Paula AB, Laranjo M, Marto CM, Paulo S, Abrantes AM, Casalta-Lopes J, et al. Direct Pulp Capping: What is the Most Effective Therapy? -Systematic Review and Meta-Analysis. *J Evid Based Dent Pract.* 2018;18(4):298-314. <https://doi.org/10.1016/j.jebdp.2018.02.002>.
- Kunert M, Lukomska-Szymanska M. Bio-Inductive Materials in Direct and Indirect Pulp Capping - A Review Article. *Materials.* 2020;13(5):1204. <https://doi.org/10.3390/ma13051204>.
- Cervino G, Laino L, D'Amico C, Russo D, Nucci L, Amoroso G, et al. Mineral Trioxide Aggregate Applications in Endodontics: A Review. *Eur J Dent.* 2020;14(4):683-691. <https://doi.org/10.1055/s-0040-1713073>.
- Tawil PZ, Duggan DJ, Galicia JC. Mineral trioxide aggregate (MTA): its history, composition, and clinical applications. *Compend Contin Educ Dent.* 2015;36(4):247-252; quiz 254, 264. <https://pubmed.ncbi.nlm.nih.gov/25821936/>.
- Mestry SU, Kalmegh S, Mhaske ST. Mineral Trioxide Aggregates (MTA) in Dentistry: A Review on Chemistry, Synthesis Methods, and Critical Properties. *Silicon.* 2023;15(5):2231-2249. <https://doi.org/10.1007/s12633-022-02170-z>.
- Shahi S, Fakhri E, Yavari H, Maleki Dizaj S, Salatin S, Khezri K. Portland Cement: An Overview as a Root Repair Material. *BioMed Res Int.* 2022;2022:3314912. <https://doi.org/10.1155/2022/3314912>.
- Nurdin D, Primathena I, Farah RA, Cahyanto A. Comparison of Chemical Composition between Indonesian White Portland Cement and MTA as Dental Pulp Capping Material. *Key Eng Mater.* 2019;829:34-39. <https://doi.org/10.4028/www.scientific.net/KEM.829.34>.
- Majeed R, Elnawawy HM, Kuty MG, Yahya NA, Azami NH, Abu Kasim NH, et al. Physicochemical, mechanical and biological properties of nano-calcium silicate-based cements: a systematic review. *Odontology.* 2023;111(4):759-776. <https://doi.org/10.1007/s10266-023-00786-0>.
- Nam KY. Characterization and antimicrobial efficacy of Portland cement impregnated with silver nanoparticles. *J Adv Prosthodont.* 2017;9(3):217-223. <https://doi.org/10.4047/jap.2017.9.3.217>.
- Primathena I, Nurdin D, Hermawan H, Cahyanto A. Synthesis, Characterization, and Antibacterial Evaluation of a Cost-Effective Endodontic Sealer Based on Tricalcium Silicate-White Portland Cement. *Materials.* 2021;14(2):417. <https://doi.org/10.3390/ma14020417>.
- Park SM, Rhee WR, Park KM, Kim YJ, Ahn J, Knowles JC, et al. Calcium Silicate-Based Biocompatible Light-Curable Dental Material for Dental Pulpal Complex. *Nanomaterials.* 2021;11(3):596. <https://doi.org/10.3390/nano11030596>.
- Arandi NZ, Rabi T. TheraCal LC: From Biochemical and Bioactive Properties to Clinical Applications. *Int J Dent.* 2018;2018:3484653. <https://doi.org/10.1155/2018/3484653>.
- Alazrag MA, Abu-Seida AM, El-Batouty KM, El Ashry SH. Marginal adaptation, solubility and biocompatibility of TheraCal LC compared with MTA-Angelus and Biodentine as a furcation perforation repair material. *BMC Oral Health.* 2020;20:298. <https://doi.org/10.1186/s12903-020-01289-y>.
- Ranjbar OL, Moradi Z, Abbasi M, Kharazifard MJ, Tabatabaei SN. Evaluation of Compressive Strength of Several Pulp Capping Materials. *J Dent (Shiraz).* 2021;22(1):41-47. DOI: <https://doi.org/10.30476/dentjods.2020.83964.1063>.
- Rout P, Patel P, Davis D. Crystalloid Solutions in Intravenous Fluid Therapy. [Updated 2025 Sep 28]. In: StatPearls. Treasure Island (FL): StatPearls Publishing; 2026 Jan-. <https://www.ncbi.nlm.nih.gov/books/NBK500033/>.
- Argueta-Figueroa L, Jurado CA, Torres-Rosas R, Bautista-Hernandez MA, Alhotan A, Nurrohman H. Clinical Efficacy of Biomimetic Bioactive Biomaterials for Dental Pulp Capping: A Systematic Review and Meta-Analysis. *Biomimetics.* 2022;7(4):211. <https://doi.org/10.3390/biomimetics7040211>.
- Singh S, Bagda KK, Attur K, Mustafa M, Gangavane S, Wankhede P. Clinical and histological assessment of efficacy of TheraCal LC and Biodentine as direct pulp capping agents - an in-vivo study. *Int J Health Sci.* 2022;6(S7):2587-2596. <https://doi.org/10.53730/ijhs.v6nS7.11913>.
- Gronwald B, Kozłowska L, Kijak K, Lietz-Kijak D, Skomro P, Gronwald K, et al. Nanoparticles in Dentistry - Current Literature Review. *Coatings.* 2023;13(1):102. <https://doi.org/10.3390/coatings13010102>.
- Pecci-Lloret MP, Gea-Alcocer S, Murcia-Flores L, Rodriguez-Lozano FJ, Onate-Sanchez RE. Use of Nanoparticles in Regenerative Dentistry: A Systematic Review. *Biomimetics.* 2024;9(4):243. <https://doi.org/10.3390/biomimetics9040243>.
- Joudeh N, Linke D. Nanoparticle classification, physicochemical properties, characterization, and applications: a comprehensive review for biologists. *J Nanobiotechnology.* 2022;20(1):262. <https://doi.org/10.1186/s12951-022-01477-8>.
- Azmy E, Al-Kholy MRZ, Fattouh M, Kenawi LMM, Helal MA. Impact of Nanoparticles Additions on the Strength of Dental Composite Resin. *Int J Biomater.* 2022;2022:1165431. DOI: <https://doi.org/10.1155/2022/1165431>.
- Naguib GH, Abuelenain D, Mazhar J, Alnowaiser A, Aljawi R, Hamed MT. Maximizing dental composite performance: Strength and hardness enhanced by innovative polymer-coated MgO nanoparticles. *J Dent.* 2024;149:105271. <https://doi.org/10.1016/j.jdent.2024.105271>.
- Ezawa N, Akashi Y, Nakajima K, Kokubun K, Furusawa M, Matsuzaka K. The Effects of Tricalcium-Silicate-Nanoparticle-Containing Cement: In Vitro and In Vivo Studies. *Materials.* 2023;16(12):4451. <https://doi.org/10.3390/ma16124451>.
- Loison-Robert LS, Tassin M, Bonte E, Berbar T, Isaac J, Berdal A, et al. In vitro effects of two silicate-based materials, Biodentine and BioRoot RCS, on dental pulp stem cells in models of reactionary and reparative dentinogenesis. *PLoS One.* 2018;13(1):e0190014. <https://doi.org/10.1371/journal.pone.0190014>.
- Schwerdt G, Schulz MC, Kopf M, Mildenberger S, Reime S, Gekle M, et al. Physiological regulation of oral saliva ion composition and flow rate are not coupled in healthy humans - Partial revision of our current knowledge required. *Pflügers Arch.* 2025;477(1):55-65. <https://doi.org/10.1007/s00424-024-03025-9>.
- Alhajj M, Babos M. Physiology, Salivation. [Updated 2023 Jul 24]. In: StatPearls [Internet]. Treasure Island (FL): StatPearls Publishing; 2026 Jan-. Available from: <https://www.ncbi.nlm.nih.gov/books/NBK542251/>.
- Saghiri MA, Orangi J, Asatourian A, Gutmann JL, Garcia-Godoy F, Lotfi M, et al. Calcium silicate-based cements and functional impacts of various constituents. *Dent Mater J.* 2017;36(1):8-18. Available from: <https://doi.org/10.4012/dmj.2015-425>.