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# Comparative Evaluation of Water Sorption and Solubility of Conventional Glass Ionomer and Resin-Modified Glass Ionomer Luting Cements Incorporated with Zirconia Nanoparticles: An In Vitro Study

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**ABSTRACT**: Water sorption and solubility influence the long-term stability of glass ionomer-based luting cements. This study evaluated the effect of zirconia nanoparticles (ZrNPs) at 1 wt% and 3 wt% on the water sorption and solubility of conventional glass ionomer cement (GIC; Tokuso Ionomer) and resin-modified glass ionomer cement (RMGIC; Shofu HY-Bond Resiglass). Sixty specimens were divided into six groups (n = 10) and immersed in distilled water for 7 days at 37 ± 1°C. Water sorption and solubility were determined from mass changes and analyzed using one-way ANOVA with Tukey's post hoc test ($p < 0.05$). GIC showed higher water sorption and solubility than RMGIC controls (11.54 ± 0.44 and 0.28 ± 0.08 µg/mm³ vs. 5.30 ± 0.20 and 0.20 ± 0.05 µg/mm³, respectively). ZrNP incorporation reduced both properties in a concentration-dependent manner. A significant reduction was observed in GIC at 3 wt% ZrNP, with water sorption and solubility decreasing to 8.70 ± 0.35 and 0.17 ± 0.05 µg/mm³, respectively, whereas reductions in RMGIC were not significant. Incorporation of 3 wt% ZrNP may therefore improve the physicochemical stability of conventional GIC luting cement.

**KEYWORDS***:* Glass ionomer cement; Resin-modified glass ionomer cement; Luting cement, Zirconia nanoparticles; Water sorption; Solubility

## I. INTRODUCTION

Glass ionomer cement (GIC), first developed by Wilson and Kent in 1972, continues to be one of the most commonly used luting agents in fixed prosthodontics.[1] As a luting material, it is used to permanently cement crowns, bridges, inlays, onlays, and orthodontic bands, forming a thin adhesive layer that must remain stable between the prepared tooth and the fitting surface of the restoration under constant exposure to the oral environment. Its continued clinical use is attributed to its chemical bond to tooth structure through ion exchange, its cariostatic effect from sustained fluoride release, and its good biological compatibility.[1] Nonetheless, conventional GIC luting cements have long been recognized as brittle and comparatively weak in their early mechanical properties, and are known to be particularly sensitive to fluid uptake during the initial setting period, a limitation that has driven ongoing efforts to modify and reinforce the material.[2]

Resin-modified glass ionomer (RMGI) luting cements were subsequently developed to address

these shortcomings, by adding a resin component — commonly 2-hydroxyethyl methacrylate (HEMA) — along with a photo initiator system to the conventional powder-liquid formulation.[2,3] This allows the cement to set through both an acid-base reaction and light-activated polymerization, which generally improves handling characteristics and early strength while preserving fluoride release and adhesion to dentin.[2] Early formulations of RMGI cements, however, were noted to take up more water than their conventional counterparts, a tendency that has been reduced but not entirely eliminated in newer versions of the material.[3] Because a luting cement is applied as a thin, continuously exposed film around the entire circumference of an indirect restoration, even small changes in its dimensional or chemical stability on exposure to saliva can have an outsized clinical effect: fluid uptake can cause the cement layer to swell and generate internal stress at the tooth-cement and cement-restoration interfaces, while dissolution of unreacted material lost to solubility can open marginal gaps, allow microleakage and bacterial ingress, and ultimately weaken retention of the restoration. Water sorption and solubility are therefore regarded as key laboratory indicators of how a luting cement is likely to behave over the long term in the mouth.

Given these limitations, reinforcing glass ionomer materials with nano-sized fillers has become a widely explored strategy for improving their physicochemical behaviour without sacrificing their adhesive and fluoride-releasing benefits. Among the various nanoparticles studied for this purpose — including hydroxyapatite, bioactive glass, and metal oxides such as zinc oxide and titanium dioxide — zirconium oxide (zirconia, $ZrO_2$) nanoparticles are considered particularly attractive candidates.[4] Zirconia is chemically inert, highly biocompatible, and possesses considerably greater mechanical strength than the glass fillers conventionally used in GIC, properties that have long made it a preferred reinforcing ceramic in other areas of restorative and prosthetic dentistry.[4,5] At the nanoscale, zirconia particles are small enough to occupy the interstitial spaces within the set glass ionomer matrix, which can reduce internal porosity and voids that would otherwise act as sites for water penetration and stress concentration.[5] A denser, less porous matrix would be expected to resist fluid uptake more effectively and to release fewer unreacted components into solution, translating into lower water sorption and solubility values. Zirconia nanoparticles also carry the practical advantage of imparting radiopacity to the cement, aiding radiographic detection of the luting line beneath a restoration, and their antibacterial potential against cariogenic organisms has been reported as an additional benefit relevant to secondary caries prevention at the cement margin, with combined zirconia-yttria-alumina nanoparticle systems reported to produce even greater zones of bacterial inhibition than zirconia alone. [4,5,29]

Support for this rationale comes from studies of zirconia-nanoparticle-modified glass ionomer materials in other contexts. Working with two commercial glass ionomer formulations modified with zirconia nanoparticles at 2, 5, and 7 wt%, one study found that water sorption and solubility fell at nearly every tested concentration compared with an unmodified control, an improvement that was linked to visibly reduced surface porosity: electron microscopy of the modified specimens showed cracks in the cement narrowing progressively as nanoparticle concentration increased, closing almost completely at the highest concentration tested.[6] The same body of work also reported improvements in flexural strength and surface hardness with zirconia nanoparticle addition, reinforcing the idea that a modest weight-percentage loading of zirconia can measurably densify and strengthen the glass ionomer matrix.[6] Concentration-dependent effects of nanoscale fillers more broadly have also been documented in resin-modified glass ionomer luting cement, where the addition of a different nanofiller was shown to shift water sorption and solubility values in opposite directions as filler concentration increased — underscoring that even a small change in nanoparticle loading can meaningfully alter these two properties, and that identifying an optimal, clinically favourable concentration requires direct testing rather than extrapolation from a single dose.[7]

A wide range of other nanoparticle fillers have similarly been investigated as reinforcing agents for GIC and RMGIC, providing further support for nanoparticle incorporation as a viable modification strategy. Titanium dioxide nanoparticles incorporated into conventional GIC at 3%, 5%, and 7 wt% have been shown to improve fracture toughness, flexural strength, and compressive strength relative to unmodified controls, with the greatest improvement generally observed at the lower concentrations tested.[11,16] Hydroxyapatite nanoparticles, both alone and in combination with other fillers, have likewise been reported to increase the compressive strength of GIC, an effect attributed to interaction between the hydroxyapatite and the carboxylate groups of the polyacid component, improving cross-linking within the set cement.[13,14,16] Similar mechanical improvements have been documented for GIC modified with graphene oxide,[12] silver nanoparticles,[17] and green-synthesized nanocomposites combining chitosan, titanium,

zirconia, and hydroxyapatite,[15] with several of these studies also reporting concurrent improvements in antibacterial activity against cariogenic organisms such as Streptococcus mutans.[11,16,17] Collectively, this body of literature indicates that nanoparticle reinforcement of glass ionomer materials is a well-established strategy across multiple filler types, lending further credibility to the rationale for evaluating zirconia nanoparticles specifically in the present study.

Alongside mechanical and antibacterial studies, a smaller number of investigations have specifically explored zirconia nanoparticle incorporation into glass ionomer luting cement. One study evaluating a glass ionomer luting cement reinforced with zirconium oxide nanoparticles at 3% and 5% reported significant differences in film thickness and compressive strength compared with an unmodified control.[25] A related investigation of zirconia-nanoparticle-reinforced dental luting agents, including a resin-modified glass ionomer luting cement, found that nanoparticle incorporation did not adversely affect sorption behaviour or overall mechanical performance, although film thickness increased somewhat in all materials tested while remaining within clinically acceptable limits.[26] Zirconia nanoparticles synthesized by green methods have also been incorporated into GIC at higher concentrations (3%, 5%, and 10%) and evaluated for antimicrobial efficacy and compressive resilience, with favourable results reported at the tested concentrations.[27] Yttria-stabilized zirconia nanofillers synthesized specifically for dental cement applications have further been characterized for their biocompatibility with gingival fibroblasts, supporting the biological safety of this filler class at the concentrations typically used in dental materials.[28] These studies, however, have generally examined higher zirconia nanoparticle concentrations or restorative-grade materials, or have not directly compared conventional GIC and RMGIC luting cements under a single standardized protocol, leaving the specific low-concentration comparison undertaken in the present study largely unaddressed.

While this evidence base makes a reasonable case for the physicochemical benefits of zirconia nanoparticle incorporation, it is drawn largely from materials used in restorative rather than luting applications, and the specific effect of low-level zirconia nanoparticle addition — in the range relevant to a luting cement's need for a thin, low-viscosity film — on the water sorption and solubility of both conventional GIC and RMGI luting cements has not been well established. Since even minor property changes at these lower concentrations could influence long-term marginal seal and retention, there is a clear rationale for directly evaluating zirconia nanoparticle incorporation at low weight percentages in both luting cement types, in accordance with standard water sorption and solubility testing protocols.[8]

The present in vitro study was therefore designed to evaluate and compare the water sorption and solubility of conventional glass ionomer and resin-modified glass ionomer luting cements incorporated with zirconia nanoparticles at 1 wt% and 3 wt%, with the objective of determining whether this modification improves the physicochemical stability of these luting cements for more predictable long-term clinical performance.

## II. MATERIALS AND METHODS

### Study Design

This in vitro study evaluated and compared the water sorption and solubility of a conventional glass ionomer luting cement (Tokuso Ionomer, Tokuyama Dental Corp., Tokyo, Japan) and a resin-modified glass ionomer luting cement (Shofu HY-Bond Resiglass, Shofu Inc., Kyoto, Japan), each tested in unmodified form and after incorporation of zirconia nanoparticles at 1 wt% and 3 wt%. A total of six groups were formed, with ten specimens (n = 10) prepared for each group, giving a total sample size of 60 specimens (Table 1).

### Zirconia Nanoparticle Incorporation

Commercially available zirconium oxide nanoparticles (particle size <100 nm) were weighed using an electronic analytical balance (Figure 4) and incorporated into the powder component of each cement at 1 wt% and 3 wt% of the total powder weight for the respective groups. The nanoparticles were manually mixed with the cement powder for a standardized duration to ensure homogeneous dispersion prior to mixing with the liquid component.

### Specimen Preparation

Specimens for water sorption and solubility testing were fabricated in accordance with ISO 9917-2:2017 specifications.[8] Disk-shaped specimens measuring 15 ± 1 mm in diameter and 1.0 ± 0.1 mm in thickness were prepared using a split Teflon/acrylic mold. The powder and liquid of each cement were manually mixed according to the respective manufacturer's recommended powder-to-liquid ratio and working time, packed into the mold between two mylar strips, and compressed under a glass slab to extrude excess material and obtain a flat, uniform surface. For the RMGIC groups, specimens were light-cured according to the manufacturer's instructions for the recommended exposure time.

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Specimens were then removed from the mold and any flash was trimmed using a scalpel blade.

**Water Sorption and Solubility Testing (ISO 9917-2 Protocol)**

Each specimen was placed in a desiccator containing freshly dried silica gel and stored in an incubator at 37 ± 1°C. Specimens were weighed daily using an analytical balance (accuracy 0.0001 g) until a constant mass ($m_1$) was achieved, defined as a mass loss of no more than 0.2 mg in any 24-hour period. The diameter and thickness of each specimen were measured using a digital caliper to calculate the volume (V) in $mm^3$.

Following conditioning, specimens were immersed in individual containers of distilled water at 37 ± 1°C for 7 days. At the end of this period, specimens were removed, blotted dry with absorbent paper to remove surface moisture, waved in air for 15 seconds, and weighed to obtain mass $m_2$.Specimens were then returned to the desiccator and reconditioned to a second constant mass ($m_3$), following the same daily-weighing protocol used to obtain $m_1$.

Water sorption (Wsp) and solubility (Wsl) were calculated using the following formulas, expressed in micrograms per cubic millimeter (µg/$mm^3$):

$$\mathbf{Wsp = (m_2 - m_3) / V}$$

$$\mathbf{Wsl = (m_1 - m_3) / V}$$

**Statistical Analysis**

The data obtained were tabulated and statistically analyzed using SPSS software. Descriptive statistics (mean ± standard deviation) were calculated for water sorption and solubility values in each group. One-way ANOVA was used to compare values among the six groups, followed by post hoc Tukey's test for pairwise comparisons. A p-value of <0.05 was considered statistically significant.

## III. RESULTS

The mean water sorption and solubility values recorded for the six study groups are presented in Table 2 and depicted graphically in Figures 8 and 9. In the control groups, conventional GIC luting cement recorded a mean water sorption of 11.54 ± 0.44 µg/$mm^3$, more than double the mean water sorption recorded for RMGIC luting cement (5.30 ± 0.20 µg/$mm^3$). A similar pattern was observed for solubility, with GIC control recording a mean value of 0.28 ± 0.08 µg/$mm^3$ compared with 0.20 ± 0.05 µg/$mm^3$ for RMGIC control. One-way ANOVA confirmed a statistically significant difference among the six groups for both water sorption ($F = 978.4$, $p < 0.0001$; Table 3) and solubility ($F = 6.54$, $p < 0.001$; Table 5).

On incorporation of zirconia nanoparticles at 1 wt%, GIC water sorption decreased from 11.54 ± 0.44 to 11.15 ± 0.40 µg/$mm^3$, and RMGIC water sorption decreased from 5.30 ± 0.20 to 5.10 ± 0.20 µg/$mm^3$. Solubility likewise decreased at the 1% concentration in both materials, from 0.28 ± 0.08 to 0.26 ± 0.07 µg/$mm^3$ in GIC, and from 0.20 ± 0.05 to 0.18 ± 0.05 µg/$mm^3$ in RMGIC. Tukey's post hoc comparisons showed that neither of these reductions from control to 1% reached statistical significance, for either GIC or RMGIC, and for either water sorption or solubility(Tables 4 and 6).

At the 3 wt% concentration, GIC recorded a mean water sorption of 8.70 ± 0.35 µg/$mm^3$ and a mean solubility of 0.17 ± 0.05 µg/$mm^3$, representing reductions of 24.6% and 39.3% respectively from the GIC control group. These reductions, from control to 3% and from 1% to 3%, were both statistically significant on Tukey's post hoc testing (Tables 3 and 5). RMGIC at 3 wt% recorded a mean water sorption of 4.90 ± 0.18 µg/$mm^3$ and a mean solubility of 0.17 ± 0.05 µg/$mm^3$, representing smaller reductions of 7.5% and 15% respectively from the RMGIC control group; neither of these reductions reached statistical significance.

Water sorption remained significantly higher in GIC than in RMGIC at every corresponding concentration tested, including at 3 wt% (8.70 ± 0.35 versus 4.90 ± 0.18 µg/$mm^3$). Solubility, by contrast, converged between the two materials at the 3 wt% concentration: the mean solubility of GIC at 3 wt% (0.17 ± 0.05 µg/$mm^3$) was statistically indistinguishable from that of RMGIC at any of its three concentrations (control, 1%, or 3%), all of which also recorded values of 0.17–0.20 ± 0.05 µg/$mm^3$ (Table 5).

The concentration-dependent trend for both properties in both materials is illustrated in Graph 3. The decline in water sorption and solubility with increasing zirconia nanoparticle concentration followed a steeper trajectory in GIC than in RMGIC, with the GIC groups showing a marked drop between the 1% and 3% concentrations, while the RMGIC groups showed a comparatively flat trend across all three concentrations for both properties.

## IV. DISCUSSION

The present study evaluated the effect of zirconia nanoparticle incorporation, at 1 wt% and 3 wt%, on the water sorption and solubility of conventional GIC and RMGIC luting cements. The results demonstrated that while both materials showed a concentration-dependent reduction in water sorption and solubility, the magnitude of this reduction was considerably greater in conventional GIC than in RMGIC, with GIC reaching statistical

significance at the 3% concentration while RMGIC did not. This differential response between the two cement types is the central finding of the study and is discussed below in relation to the structural and compositional differences between conventional and resin-modified glass ionomer systems, and the known properties of the materials involved.

Conventional glass ionomer cement sets through an acid-base reaction between a polyacrylic acid liquid and a basic fluoroaluminosilicate glass powder, completing its initial set within approximately 2–3 minutes and forming a hard, translucent material with acceptable esthetics.[2] A substantial proportion of the glass powder remains unreacted within the set cement and functions as a reinforcing filler for the surrounding polysalt matrix.[2] GIC chemically bonds to enamel and dentin without the need for a separate adhesive, through an ion-exchange layer that forms at the tooth-cement interface, and this bond has been shown to strengthen and mature over time.[2],[3] The glass component typically incorporates calcium fluoride or sodium fluoroaluminate as a source of fluoride, which is taken up into the cement during the glass-forming process and is subsequently released from the set material, with an initial rapid burst of release followed by a slower, sustained phase.[3] Unlike resin-based restoratives, GIC also retains the capacity to take up fluoride from its surroundings and re-release it later, a property often described as fluoride "recharge".[3] Despite these advantages, the purely ionic set matrix of conventional GIC is comparatively brittle, has relatively low flexural and tensile strength, and is known to be sensitive to both moisture contamination and desiccation during the early stages of setting, limitations that have restricted its use in higher-stress-bearing clinical situations.[9]

Resin-modified glass ionomer cement retains the same basic powder-liquid, fluoroaluminosilicate glass and polyacrylic acid components as conventional GIC, but incorporates an additional water-soluble resin monomer, most commonly HEMA, together with a polymerization initiator that is typically light-activated.[2],[3] This gives RMGIC a dual-setting mechanism, in which the conventional acid-base reaction proceeds alongside a separate free-radical polymerization of the resin component, producing a more complex final microstructure whose properties depend partly on how quickly the light-cure polymerization is triggered after mixing.[3] This modification generally improves the early mechanical properties, handling characteristics, and resistance to moisture sensitivity of the cement relative to conventional GIC, while the physical properties of RMGIC overall remain broadly comparable to those of conventional glass-ionomers.[2] RMGIC continues to release and recharge fluoride in a manner similar to conventional GIC, though the presence of the HEMA resin component has also been reported to somewhat compromise the material's biocompatibility compared with resin-free conventional GIC.[2]

Zirconium dioxide (zirconia, $ZrO_2$) is a crystalline ceramic oxide that has been used as a biomaterial since the 1960s and has since become one of the most widely applied ceramics in restorative and implant dentistry.[4] At the nanoscale, zirconia is characterized by high mechanical strength, high fracture toughness, and considerable hardness, combined with excellent chemical stability, corrosion resistance, and biocompatibility.[4] These properties have made it a preferred reinforcing filler in a range of dental materials, including resin adhesives and cements, where its incorporation has been reported to improve fracture toughness, flexural strength, and shear bond strength.[5] Zirconia nanoparticles have also been shown to possess antibacterial and antifungal activity against common oral pathogens, including *Streptococcus mutans*, *Escherichia coli*, and *Candida albicans*, an effect that has been attributed in part to their surface interaction with bacterial cell membranes, with combined zirconia-yttria-alumina nanoparticle systems reported to produce even greater zones of bacterial inhibition than zirconia alone.[4],[5],[29] In addition, because of their inherently opaque, radiopaque nature, zirconia nanoparticles are able to impart radiopacity to the materials into which they are incorporated, a property considered useful for radiographic identification of cement margins and root-filling materials in clinical practice.[4] Taken together, this combination of mechanical reinforcement, chemical inertness, antibacterial potential, and radiopacity underpins the rationale for using zirconia nanoparticles as a reinforcing filler in glass ionomer-based cements, as investigated in the present study.

Even in the unmodified control groups, GIC luting cement recorded considerably higher water sorption and solubility than RMGIC luting cement. This finding is consistent with the fundamental setting chemistry of the two materials. Conventional GIC sets purely through an acid-base reaction between polyacrylic acid and the fluor aluminosilicate glass, producing a hydrophilic polysalt matrix that continues to absorb and desorb water reversibly long after clinical setting.[3] RMGIC, by contrast, incorporates a resin component that undergoes light-activated free-radical

polymerization alongside the acid-base reaction; this dual-setting mechanism has been reported to produce a denser, more cross-linked matrix that is comparatively less permeable to water at early stages, even though the resin component itself introduces a degree of hydrophilicity through unreacted HEMA groups.[2],[3] The higher baseline sorption and solubility of conventional GIC observed in this study is therefore attributable to its comparatively porous, purely ionic matrix, which offers a greater volume of interconnected pores and diffusion pathways for water uptake and leachable-component loss than the partially resin-sealed matrix of RMGIC.

The differential response of the two materials to zirconia nanoparticle incorporation can be explained largely by the mechanism through which nanoparticle fillers are understood to act within a glass ionomer matrix. A systematic review of nanoparticle reinforcement strategies in glass-ionomer cements concluded that the property improvements associated with nanoparticle incorporation are consistently linked to a measurable reduction in the internal porosity of the set cement, with nanoparticles occupying the void spaces that would otherwise exist between the larger glass filler particles.[9] This porosity-filling mechanism has also been demonstrated directly: nano-sized reinforcing particles have been shown to disperse readily into the glass ionomer matrix on hand mixing and to reduce the porosity of the set cement by occupying the empty interstitial spaces between glass particles.[10]

Because conventional GIC begins with a comparatively porous, unmodified ionic matrix, it presents a greater volume of accessible void space for the zirconia nanoparticles to occupy. As nanoparticle concentration increases from 1% to 3%, an increasing proportion of this void space is filled, progressively reducing the pathways available for water diffusion into, and dissolution of unreacted material out of, the cement.[9],[10] This would account for the pronounced, concentration-dependent, and statistically significant decline in both water sorption and solubility observed in the GIC groups of the present study between the control, 1%, and 3% concentrations.

RMGIC, on the other hand, already possesses a partially sealed, resin-reinforced matrix in its unmodified state, owing to the polymerized HEMA network that fills a substantial portion of the interstitial space between glass particles even before any nanoparticle is added.[2] Consequently, the additional volume of void space available for zirconia nanoparticles to occupy in RMGIC is inherently smaller than in conventional GIC, limiting the extent to which further densification can meaningfully reduce water sorption or solubility. This is consistent with the comparatively modest and statistically non-significant reductions observed in the RMGIC groups across all zirconia nanoparticle concentrations in the present study. It is also consistent with findings that the RMGIC setting reaction and its resulting microstructure are inherently more complex, and less governed by simple porosity-filling behaviour, than that of conventional glass ionomer cement.[3]

An additional finding of interest was that, at the 3% zirconia nanoparticle concentration, the solubility of GIC became statistically indistinguishable from that of RMGIC at any tested concentration, even though water sorption in GIC remained significantly higher than in RMGIC throughout. This suggests that zirconia nanoparticle incorporation at 3% was sufficient to bring the dissolution behaviour of the two materials into closer alignment, even though the underlying capacity of the GIC matrix to physically absorb water remained comparatively greater. Solubility is governed primarily by the loss of unreacted or loosely bound matrix components at the specimen surface and along pore walls, whereas water sorption reflects the total volumetric capacity of the material to take up fluid; a reduction in surface-accessible porosity, as would be expected with nanoparticle filling, would be expected to influence solubility more readily than it would influence bulk water sorption, which may explain why solubility values converged between materials while sorption values did not.[9],[10]

Beyond water sorption and solubility, the overall clinical performance of a luting cement also depends on properties such as film thickness and marginal seal, which together determine the completeness of restoration seating and the degree of protection against microleakage.[21],[28] Studies comparing marginal gap and microleakage of zirconia crowns luted with glass ionomer versus resin-based cements have reported measurable differences in marginal adaptation between cement types, underscoring that the choice and formulation of luting cement can meaningfully influence long-term restoration success.[18],[23] Film thickness itself has been shown to vary with cement type, mixing technique, and ambient temperature, with RMGIC generally demonstrating lower film thickness than conventional GIC or zinc phosphate cement in comparative evaluations, and with clinically simulated mixing techniques generally producing thinner films than standardized bench protocols.[22],[24],[30] Marginal sealing ability also

differs by cement type in restorative contexts beyond permanent luting: glass ionomer-based provisional cements, for instance, have been reported to show greater marginal microleakage than resin-based provisional alternatives.[19] Reinforcement strategies for glass ionomer luting cements, including the incorporation of natural biopolymers, have similarly been designed with the explicit aim of improving mechanical properties without adversely increasing film thickness beyond clinically acceptable limits.[20] These considerations reinforce the importance of evaluating any reinforcing filler, including zirconia nanoparticles, not only for its effect on water sorption and solubility but also for its potential influence on the practical handling and clinical seating of the luting cement, an aspect that was outside the scope of the present study but warrants investigation in future work.

These findings suggest that conventional GIC luting cement stands to benefit more substantially from zirconia nanoparticle reinforcement, at the concentrations tested, than RMGIC luting cement. Given that reduced water sorption and solubility are associated with improved dimensional stability and reduced marginal dissolution over time, incorporation of zirconia nanoparticles at 3 wt% may represent a particularly useful modification for improving the long-term physicochemical performance of conventional GIC luting cement in situations where its established weaknesses in this regard have limited its clinical use.[9] For RMGIC, the comparatively smaller improvement observed at the concentrations tested suggests that its already lower baseline sorption and solubility may leave less room for further improvement through this specific reinforcement strategy, at least within the low-concentration range examined in this study.[2]

## V. CONCLUSION

Within the limitations of this in vitro study, incorporation of zirconia nanoparticles reduced both water sorption and solubility of conventional GIC and RMGIC luting cements in a concentration-dependent manner, with the effect becoming more pronounced at the higher (3 wt%) concentration than at 1 wt%.[6],[9] Conventional GIC luting cement showed a substantially greater and statistically significant reduction in both properties at 3 wt% zirconia nanoparticle incorporation, whereas RMGIC luting cement showed comparatively smaller reductions that did not reach statistical significance at either concentration tested. This differential response is attributable to the greater baseline porosity of the conventional GIC matrix, which offers more void space for nanoparticle-mediated densification, compared with the already partially resin-sealed matrix of RMGIC.[2],[9],[10]

These findings suggest that zirconia nanoparticle incorporation, particularly at 3 wt%, may be a clinically useful modification for improving the physicochemical stability of conventional GIC luting cement, given the established role of water sorption and solubility in the long-term marginal integrity and retention of luted restorations.[3] Its benefit for RMGIC luting cement appears more limited at the concentrations evaluated in this study. Further studies incorporating a wider range of concentrations, extended immersion periods, mechanical property testing, and long-term clinical evaluation are recommended before these findings can be translated into clinical practice.[6],[7]

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**Figure 1:** Conventional glass ionomer luting cement **Figure 2:** Resin-modified glass ionomer luting cement

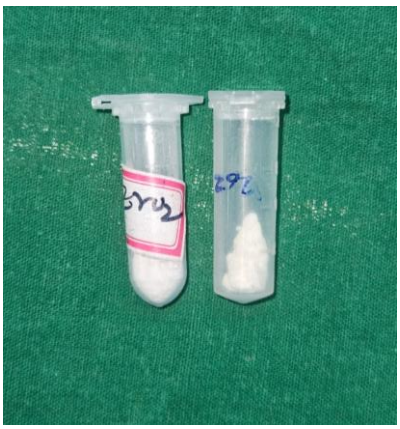

**Figure 3:** Zirconia ($ZrO_2$) nanoparticle powder
**Figure 4:** Electronic analytical balance used to weigh the zirconia nanoparticles at 1 wt% and 3 wt% concentrations of the cement powder.

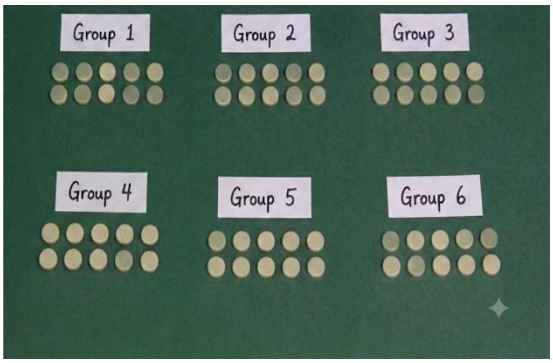

**Figure 5:** Fabricated disk specimens. **Figure 6:** Desiccator with silica gel.

| Group | Material | Concentration | Water Sorption (Mean ± SD) | Solubility (Mean ± SD) |
|---|---|---|---|---|
| I | GIC | Control | 11.54 ± 0.44 | 0.28 ± 0.08 |
| II | GIC | 1% ZrNP | 11.15 ± 0.40 | 0.26 ± 0.07 |
| III | GIC | 3% ZrNP | 8.70 ± 0.35 | 0.17 ± 0.05 |
| IV | RMGIC | Control | 5.30 ± 0.20 | 0.20 ± 0.05 |
| V | RMGIC | 1% ZrNP | 5.10 ± 0.20 | 0.18 ± 0.05 |

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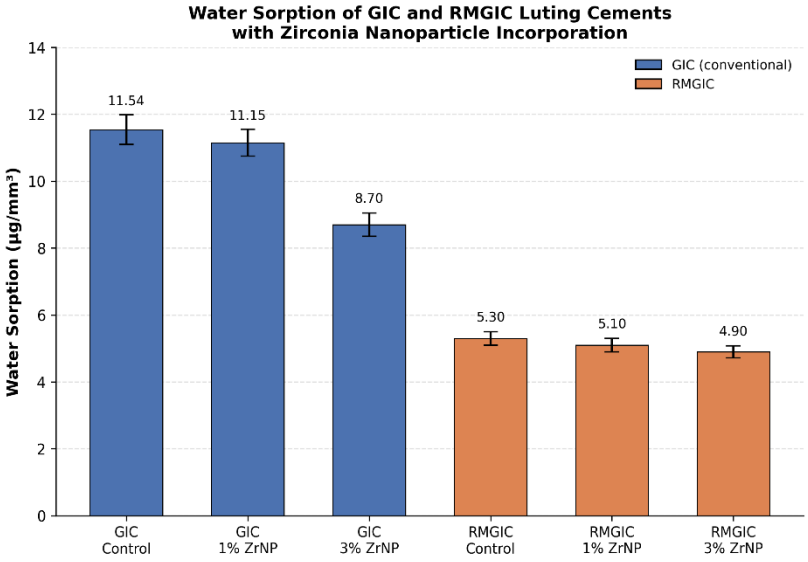
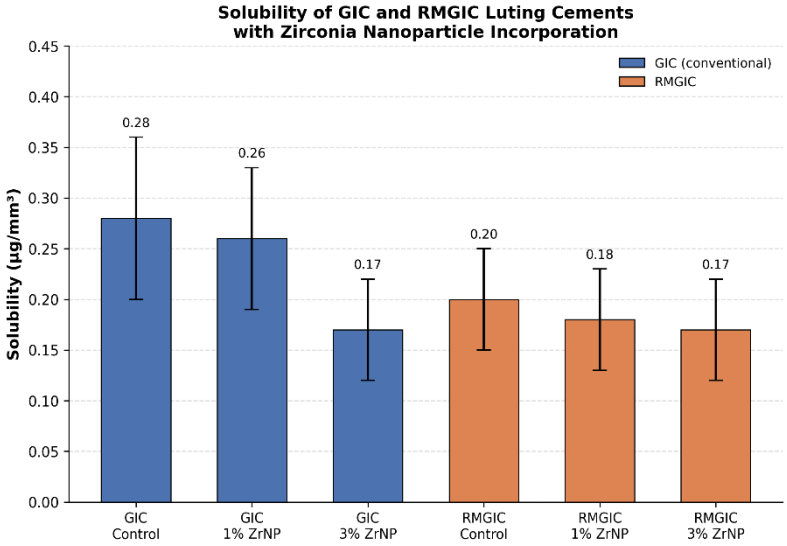
| | | | | |
|---|---|---|---|---|
| VI | RMGIC | 3% ZrNP | 4.90 ± 0.18 | 0.17 ± 0.05 |

**Table 1: Mean Water Sorption and Solubility Values (µg/mm³) by Group (n = 10 per group)**




**Graph 1: Mean water sorption (µg/mm³) across all six study groups, with error bars representing standard deviation.**




**Graph 2: Mean solubility (µg/mm³) across all six study groups, with error bars representing standard deviation.**

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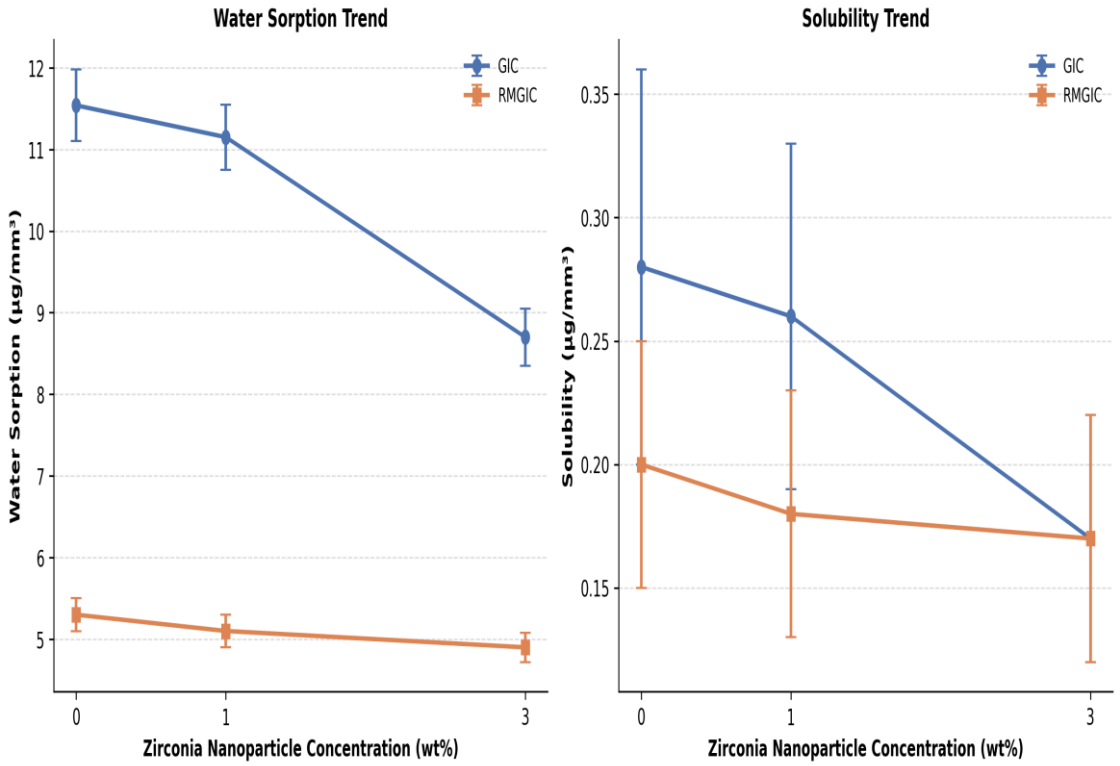


**Graph 3: Concentration-dependent trend (0%, 1%, 3% $ZrO_2$ nanoparticles) in water sorption and solubility for GIC versus RMGIC luting cements.**

**Table 2: One-Way ANOVA — Water Sorption**

| Source | SS | df | MS | F | p-value |
|---|---|---|---|---|---|
| Between Groups | 479.68 | 5 | 95.94 | 978.4 | < 0.0001 |
| Within Groups | 5.30 | 54 | 0.098 | — | — |
| Total | 484.98 | 59 | — | — | — |

Result: Statistically significant difference among the six groups (F = 978.4, p < 0.0001).

**Table 3: Tukey's HSD Post Hoc Comparisons — Water Sorption**

| Comparison | Mean Diff. | Significant (p<0.05)? |
|---|---|---|
| GIC Control vs GIC 1% | 0.39 | No |
| GIC Control vs GIC 3% | 2.84 | Yes |
| GIC 1% vs GIC 3% | 2.45 | Yes |
| RMGIC Control vs RMGIC 1% | 0.20 | No |
| RMGIC Control vs RMGIC 3% | 0.40 | No |
| RMGIC 1% vs RMGIC 3% | 0.20 | No |
| GIC vs RMGIC (matching concentration) | 3.60–6.64 | Yes (all pairs) |

**Table 4: One-Way ANOVA — Solubility**

| Source | SS | df | MS | F | p-value |
|---|---|---|---|---|---|
| Between Groups | 0.116 | 5 | 0.0232 | 6.54 | < 0.001 |

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| | | | | | |
|---|---|---|---|---|---|
| Within Groups | 0.192 | 54 | 0.00355 | — | — |
| Total | 0.308 | 59 | — | — | — |

Result: Statistically significant difference among the six groups ($F = 6.54$, $p < 0.00$

**Table 5: Tukey's HSD Post Hoc Comparisons — Solubility**

| Comparison | Mean Diff. | Significant (p<0.05)? |
|---|---|---|
| GIC Control vs GIC 1% | 0.02 | No |
| GIC Control vs GIC 3% | 0.11 | Yes |
| GIC Control vs RMGIC Control | 0.08 | Yes |
| GIC 1% vs GIC 3% | 0.09 | Yes |
| GIC 3% vs RMGIC (any group) | ≤ 0.03 | No |
| RMGIC Control vs RMGIC 1% vs RMGIC 3% | ≤ 0.03 | No |