Frontiers in Dentistry

Impact of Mesoporous Zinc Oxide Nanoparticles on Diametral Tensile Strength and Flexural Strength of Resin-Modified Glass Ionomer Cement: An In-Vitro Study

Zahra Jowkar[1]*, Mohammad Mahdi Abdolinezhad[2], Seyed Ahmadreza Hamidi[3], Ali Moaddeli[4]

1. Oral and Dental Disease Research Center, Department of Operative Dentistry, School of Dentistry, Shiraz University of Medical Sciences, Shiraz, Iran
2. Department of Operative Dentistry, School of Dentistry, Shiraz University of Medical Sciences, Shiraz, Iran
3. Department of Oral and Maxillofacial Surgery, School of Dentistry, Shiraz University of Medical Sciences, Shiraz, Iran
4. Legal Medicine Research Center, Legal Medicine Organization, Tehran, Iran

Article Info

Article type:
Original Article

Article History:
Received: 05 Nov 2024
Accepted: 10 Apr 2025
Published: 22 Nov 2025

**** Corresponding author:***
Oral and Dental Disease Research Center, Department of Operative Dentistry, School of Dentistry, Shiraz University of Medical Sciences, Shiraz, Iran

Email: zahrajowkar66@gmail.com

ABSTRACT

Objectives: This study aimed to investigate the effects of incorporating zinc oxide nanoparticles (ZnONPs) and mesoporous ZnONPs into resin-modified glass ionomer cement (RMGIC) on diametral tensile strength (DTS) and flexural strength (FS).

Materials and Methods: A total of 70 RMGIC specimens were fabricated and randomly divided into 7 groups (n=10 per group). Group 1 served as the control group. Groups 2 to 4 contained 3wt.%, 5wt.%, and 7wt.% ZnONPs, respectively, and groups 5 to 7 had 3wt.%, 5wt.%, and 7wt.% mesoporous ZnONPs, respectively. ZnONPs and mesoporous ZnONPs were homogeneously incorporated into the RMGIC powder. Disc-shaped (for DTS) and bar-shaped (for FS) specimens were fabricated according to ISO standards. All specimens were stored in distilled water at 37°C for 24 hours before testing. The DTS was measured using a diametral compression test, and the FS was measured by a three-point bending test using a universal testing machine. Data were analyzed by one-way ANOVA and Tukey's post-hoc test (alpha=0.05).

Results: Statistically significant differences were observed in the DTS and FS among the groups ($P< 0.001$). The 5wt.% mesoporous ZnONPs group exhibited the highest DTS and FS values. The group with 7wt.% ZnONPs showed the lowest DTS and FS values ($P<0.05$).

Conclusion: Incorporation of 5wt.% mesoporous ZnONPs into RMGIC significantly improved its DTS and FS, suggesting that this concentration offers optimal reinforcement of mechanical properties.

Keywords: Dental Cements; Flexural Strength; Glass Ionomer Cements; Mechanical Tests; Nanoparticles; Zinc Oxide

➢ **Cite this article as:** Jowkar Z, Abdolinezhad MM, Hamidi SA, Moaddeli A. Impact of Mesoporous Zinc Oxide Nanoparticles on Diametral Tensile Strength and Flexural Strength of Resin-Modified Glass Ionomer Cement: An In-Vitro Study. *Front Dent*. 2025:22:48. http://doi.org/10.18502/fid.v22i48.20331

INTRODUCTION

Glass ionomer cements (GICs), and particularly resin-modified glass ionomer cement (RMGIC), are widely used in restorative dentistry due to their biocompatibility, chemical adhesion to tooth structure, and fluoride release potential, which imparts some degrees of antibacterial activity [1-3]. However, despite these benefits, secondary caries continues to be one of the leading causes of restoration failure, even when GICs are used [3]. A recent review reported that while fluoride release is beneficial, it may not be sufficient to prevent recurrent caries, prompting efforts to enhance the antibacterial properties of GICs through innovative approaches [3]. In addition, GICs are sensitive to moisture during setting, exhibit limited translucency that can affect esthetics, and have inadequate mechanical properties limiting their use in stress-bearing areas [4]. Strategies to improve their mechanical performance have focused on compositional modifications and incorporation of reinforcing fillers [4,5].

Compared to conventional GICs, RMGICs exhibit improved fracture toughness, hardness, flexural strength (FS), wear resistance, and diametral tensile strength (DTS) [6,7]. The added resin component also reduces the setting time, decreases moisture sensitivity, extends the working time, and enhances translucency and esthetics [6,7].

DTS testing, which applies diametral tension until fracture, provides a reliable measure of tensile strength in brittle materials like GICs [7]. Similarly, FS, assessed by using the three-point bending test, reflects the material's ability to withstand occlusal forces and deformation under loading [8].

Zinc oxide (ZnO), known for its antimicrobial properties, is widely incorporated into dental materials due to its stability, safety, and affordability [9]. It disrupts the bacterial membrane and enzymatic activity, and thus, ZnO nanoparticles (ZnONPs) were developed to enhance antibacterial efficacy [9,10]. ZnONPs demonstrate strong antibacterial activity against oral pathogens such as *Streptococcus mutans* and *Lactobacillus* spp., and are used in dental materials both for reinforcement, and prevention of biofilm formation [11,12].

Recently, mesoporous materials—featuring tunable pore sizes (2–50 nm), high surface area, and biocompatibility—have gained attention for biomedical applications [13-15]. Their pores are easily modifiable and functionalizable, and their synthesis allows for the optimization of composition, structure, and pore size [15]. Among them, mesoporous ZnONPs offer enhanced surface area, porosity, crystallinity, and antibacterial performance, making them promising candidates for therapeutic use [16]. Recent research has demonstrated that mesoporous ZnONPs exhibit superior antibacterial efficacy against *S. mutans* compared to conventional ZnONPs, underscoring their potential for use in restorative dentistry [17].

Nano-sized materials such as mesoporous ZnONPs exhibit significantly enhanced antibacterial properties, compared to their bulk counterparts due to their increased surface area-to-volume ratio [16]. However, it is crucial to ensure that incorporating these nanofillers into restorative materials to improve antibacterial efficacy does not negatively affect their mechanical performance. The effect of mesoporous ZnONPs on the mechanical properties of RMGICs—particularly their DTS and FS—remains underexplored. Therefore, this study aimed to evaluate and compare the DTS and FS of a RMGIC modified with mesoporous ZnONPs and ZnONPs. The null hypothesis was that there would be no significant difference in DTS and FS between RMGIC specimens with and without mesoporous ZnONPs and ZnONPs.

MATERIALS AND METHODS

The study protocol was approved by the Research and Ethics Committee of Shiraz University of Medical Sciences (Protocol # IR.SUMS.DENTAL.REC.1402.087). ZnONPs were purchased from ASEPE Company (Tabriz, Iran). Mesoporous ZnONPs were synthesized and characterized following a previously described method [18].

Specimen preparation:

Prior to specimen preparation, both types of ZnONPs were dried and manually mixed with the RMGIC powder (Fuji II LC Gold A2; GC, Tokyo, Japan) using a mortar and pestle to achieve homogeneous distribution. Subsequently, the powder-nanoparticle mixture was combined with the liquid component according to the manufacturer's instructions to maintain a powder-to-liquid ratio of 3.2:1 by weight. The experimental setup is illustrated in Figure 1.

For this study, 7 sets of specimens were prepared to evaluate the DTS, and an additional 7 sets were made for the FS assessment. Before initiating the experiment, the sample size was determined using G*Power 3.1 software (Heinrich Hein University, Dusseldorf, Germany) based on a prior study [2]. The sample size calculation considered an 80% power level, a 0.05 significance level, an effect size (f) of 1.30, a type I error (α) of 0.05, and a type II error (β) of 0.2. The analysis indicated that a minimum of 9 specimens per subgroup were required for this study, leading to selection of 10 specimens for each experimental group. Seventy carefully-fabricated specimens were distributed across 7 sets, each comprising 10 specimens for the DTS testing, and 7 sets, each containing 10 specimens for the FS testing, as outlined below:

Group 1: RMGIC specimens (control group).
Group 2: RMGIC specimens with 3wt.% ZnONPs.
Group 3: RMGIC specimens with 5wt.% ZnONPs.
Group 4: RMGIC specimens with 7wt.% ZnONPs.
Group 5: RMGIC specimens with 3wt.% mesoporous ZnONPs.
Group 6: RMGIC specimens with 5wt.% mesoporous ZnONPs.
Group 7: RMGIC specimens with 7wt.% mesoporous ZnONPs.

In group 1 (control), the discs were fabricated by mixing one scoop of pure RMGIC powder (Fuji II LC Gold A2; GC, Tokyo, Japan) with two drops of liquid for 25 seconds, according to the manufacturer's instructions, to maintain a powder-to-liquid ratio of 3.2:1 by weight.

For the other groups, the ZnONPs were accurately weighed using a precision balance (A and D, GR + 360, Tokyo, Japan) with an accuracy of 0.0001g according to the designated and required weight percentages.

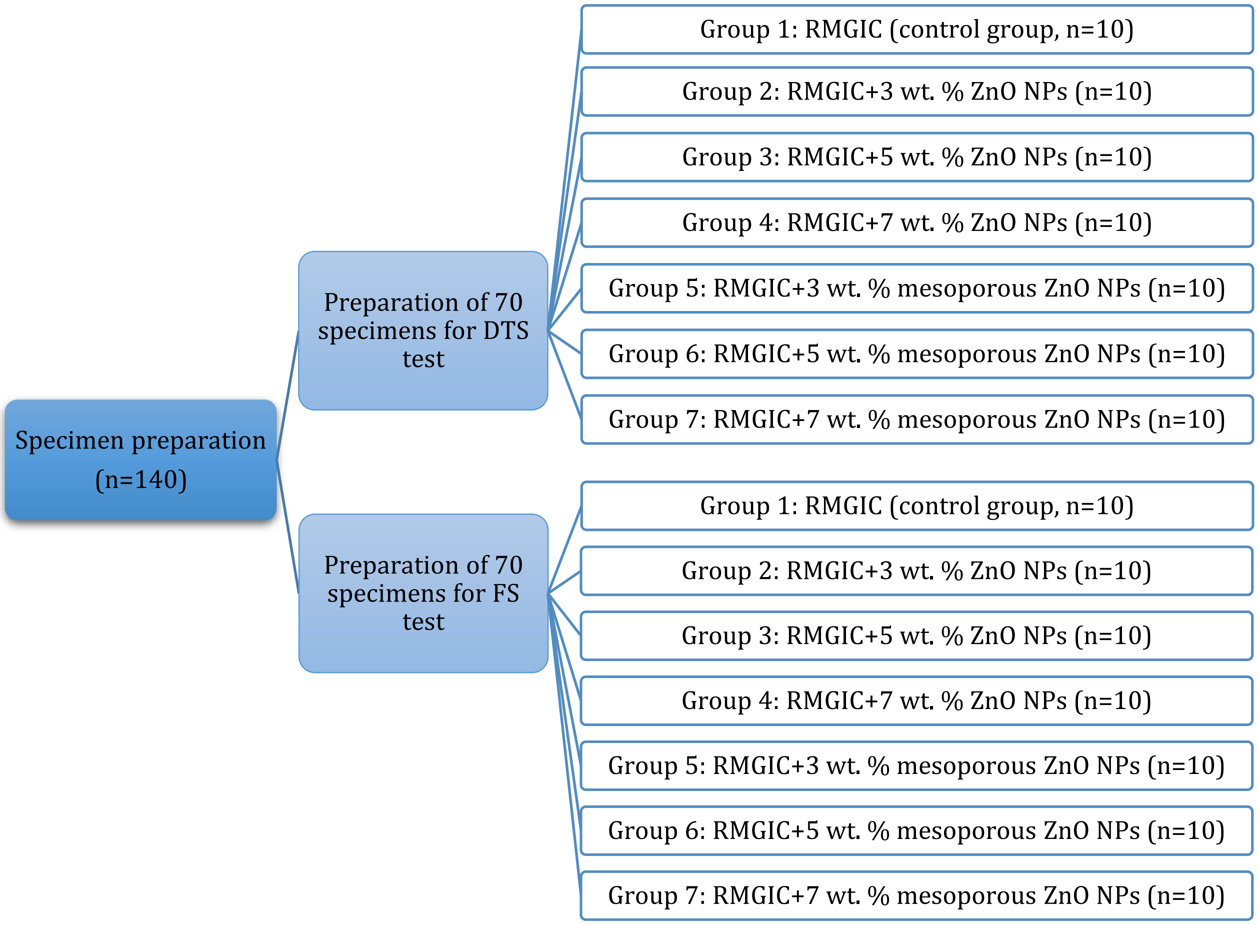

Fig 1. Experimental study setup (DTS: diametral tensile strength; FS: flexural strength; RMGIC: resin-modified glass

ionomer cement; ZnONPs: zinc oxide nanoparticles)

The weighed nanoparticles were then added to the RMGIC powder, and mixed in an amalgamator (FD-5000-A; Faghihi, Tehran, Iran) using clean amalgam capsules for 20 seconds to obtain a homogeneous mixture before incorporating the liquid component. Group 2 (RMGIC + 3wt.% ZnONPs, n=10) consisted of 97wt.% RMGIC and 3wt.% ZnONPs; group 3 (RMGIC + 5wt.% ZnONPs, n=10) comprised of 95wt.% RMGIC and 5wt.% ZnONPs; group 4 (RMGIC + 7wt.% ZnONPs, n=10) included 93wt.% RMGIC and 7wt.% ZnONPs. Similarly, group 5 (RMGIC + 3wt.% mesoporous ZnONPs, n=10) contained 97wt.% RMGIC and 3wt.% mesoporous ZnONPs; group 6 (RMGIC + 5wt.% mesoporous ZnONPs, n=10) had 95wt.% RMGIC and 5wt.% mesoporous ZnONPs, and group 7 (RMGIC + 7wt.% mesoporous ZnONPs, n=10) included 93wt.% RMGIC and 7wt.% mesoporous ZnONPs. All experimental groups were subsequently prepared and assessed following the same procedures used for group 1.

Assessment of DTS:

To measure the DTS, the specimens in each group were fabricated using a cylindrical stainless-steel split mold (4mm in diameter and 8mm in height) [19]. The stainless-steel mold was vibrated using a vibration device (Denstar-500; Denstar, Daegu, South Korea) for 15 seconds per specimen to eliminate air bubbles. After filling, a Mylar strip covered the mold, excess material was removed using a glass plate, and the specimens were cured for 20 seconds using a LED curing unit (Coltolux II; Coltene, OH, USA) with a light intensity of 1500mW/cm^2 and a wavelength range of 440- to 480nm, positioned at 1mm distance from the top surface of the specimens. Following a 30-minute rest, the specimens were carefully removed, molds and strips were taken off, and curing was completed from the opposite side to ensure thorough curing. The DTS was measured after immersion in water for one week. The DTS test was carried out using a universal testing machine (Z020; Zwick Roell, Germany) at a crosshead speed of 1mm/min (Fig. 2). A flat plate applied compressive force against the side of the short cylindrical specimen. The DTS was calculated using the formula: $DTS = 2F/\pi Dt$, where F is the applied load (N), D is the diameter of the specimen (mm), and t is the thickness of the specimen (mm).

Fig 2. A specimen positioned in a universal testing machine for the assessment of diametral tensile strength.

Assessment of FS:

For assessment of FS of each specimen, a 3-point bending test was employed [19]. The specimens required for FS testing were fabricated in the same 7 groups as explained for the DTS test, each consisting of 10 specimens. The RMGIC powder and ZnONPs were weighed and mixed following the previously described protocol using an amalgamator, ensuring uniform distribution. For FS testing, bar-shaped specimens were fabricated using a custom-made rectangular stainless-steel mold (25mm length × 2mm width × 2mm height). The mold was placed between Mylar sheets and a glass slide, filled with the RMGIC mixture, and light-cured according to the same protocol as explained for the DTS specimens. After curing, the specimens were stored in distilled water at 37°C for one week before testing with a three-point bending setup.

The FS specimens were positioned in the universal testing machine with their edges equidistant from the centerline, and testing was carried out at a constant crosshead speed of 1mm/min (Fig. 3). Data obtained from the FS test were recorded in Newtons (N), and later converted to megapascals (MPa; N/mm^2). The conversion to megapascals was done using the formula: $FS= (3\times F \times L)/(2wh^2)$, where F is the load in Newtons, L is the distance between the supporting rollers in millimeters, w is the width of the specimen in millimeters, and h is the height of the specimen in millimeters. In these experiments, the distance L was set at 20mm.

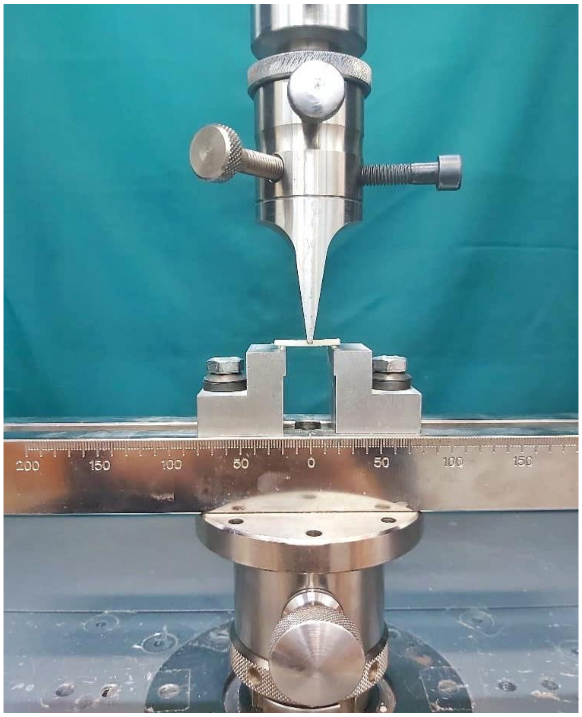

Fig 3. A specimen mounted in a universal testing machine for evaluation of flexural strength.

The experimental data underwent statistical analysis utilizing IBM SPSS version 20.0 for Windows (IBM SPSS software; SPSS, Chicago, IL, USA), where statistical methods were employed to evaluate data normality through the Shapiro-Wilk test. Next, the impact of inclusion of ZnONPs on both DTS and FS was investigated using one-way ANOVA, followed by the Tukey's post-hoc test (alpha=0.05).

RESULTS

The mean and standard deviation values of DTS and FS for all groups are presented in Table 1.

Table 1. Mean and standard deviation of diametral tensile strength and flexural strength (MPa) in the study groups

Group	DTS	FS
Control	18.31±1.94	20.74±2.17
RMGIC+ 3wt.% ZnONPs	19.55±1.93	23.51±2.72
RMGIC+ 5wt.% ZnONPs	21.46±2.36	28.41±2.40
RMGIC+ 7wt.% ZnONPs	19.65±2.53	15.20±1.94
RMGIC+ 3wt.% mesoporous ZnONPs	23.43±2.65	25.22±2.78
RMGIC+ 5wt.% mesoporous ZnONPs	25.61±2.48	28.99±2.18
RMGIC+ 7wt.% mesoporous ZnONPs	21.39±2.35	20.22±2.48

RMGIC: resin-modified glass ionomer cement; ZnONPs: zinc oxide nanoparticles.

One-way ANOVA revealed statistically significant differences in both DTS and FS among the groups (P<0.001 for both). The exact P values for all pairwise comparisons, based on the Tukey's post-hoc test, are shown in Table 2.

A graphical representation in Figure 4 illustrates the DTS values for the experimental groups. The Tukey's post-hoc test showed that the RMGIC with 3wt.% mesoporous ZnONPs had a significantly greater DTS than the control group (P<0.001), RMGIC with 3wt.% ZnONPs (P=0.008), and RMGIC with 7wt.% ZnONPs (P=0.010). There was no significant difference between the 3wt.% mesoporous ZnONPs and RMGIC with 5wt.% ZnONPs (P=0.5), or the RMGIC with 5wt.%

mesoporous ZnONPs (P=0.379) and RMGIC with 7wt.% mesoporous ZnONPs (P=0.453).

Table 2. Pairwise comparison of the groups regarding the diametral tensile strength (DTS) and flexural strength (FS)

Group	Control	RMGIC + 3wt.% ZnONPs	RMGIC + 5wt.% ZnONPs	RMGIC + 7wt.% ZnONPs	RMGIC + 3wt.% mesoporous ZnONPs	RMGIC + 5wt.% mesoporous ZnONPs	RMGIC + 7wt.% mesoporous ZnONPs
Control	-	0.900 0.149	0.054 <0.001*	0.858 <0.001*	<0.001* 0.002*	<0.001* <0.001*	0.066 0.999
RMGIC + 3wt.% ZnONPs	0.900 0.149	-	0.531 <0.001*	1.000 <0.001*	0.008* 0.686	<0.001* <0.001*	0.579 0.048*
RMGIC + 5wt.% ZnONPs	0.054 <0.001*	0.531 <0.001*	-	0.598 <0.001*	0.500 0.062	0.004* 0.998	1.000 <0.001*
RMGIC + 7wt.% ZnONPs	0.858 <0.001*	1.000 <0.001*	0.598 <0.001*	-	0.010* <0.001*	<0.001* <0.001*	0.646 <0.001*
RMGIC + 3wt.% mesoporous ZnONPs	<0.001* 0.002*	0.008* 0.686	0.500 0.062	0.010* <0.001*	-	0.379 0.014*	0.453 <0.001*
RMGIC + 5wt.% mesoporous ZnONPs	<0.001* <0.001*	<0.001* <0.001*	0.004* 0.998	<0.001* <0.001*	0.379 0.014*	-	0.003* <0.001*
RMGIC + 7wt.% mesoporous ZnONPs	0.066 0.999	0.579 0.048*	1.000 <0.001*	0.646 <0.001*	0.453 <0.001*	0.003* <0.001*	-

Top-row P values belong to DTS, and bottom-row P values belong to FS; RMGIC: resin-modified glass ionomer cement; ZnONPs: zinc oxide nanoparticles. * indicates a statistically significant difference at P<0.05.

Similarly, the RMGIC with 5wt.% mesoporous ZnONPs showed a significantly higher DTS than the control (P<0.001), RMGIC with 3wt.% ZnONPs (P<0.001), RMGIC with 5wt.% ZnONPs (P=0.004), and RMGIC with 7wt.% ZnONPs (P<0.001).

It also had a significantly higher DTS compared to the RMGIC with 7wt.% mesoporous ZnONPs (P=0.003).

Although the 5wt.% mesoporous ZnONPs group demonstrated a higher DTS than the 3wt.% mesoporous ZnONPs group, the difference was not statistically significant (P=0.379).

Notably, no significant differences were observed between the control group and the groups with 3wt.% ZnONPs (P=0.900), 5wt.% ZnONPs (P=0.054), 7wt.% ZnONPs (P=0.858), and 7wt.% mesoporous ZnONPs (P=0.066). Furthermore, no significant differences were found among the groups with 3wt.%, 5wt.%, and 7wt.% ZnONPs, as well as 7 wt.% mesoporous ZnONPs (P>0.05 for all pairwise comparisons; Table 2).

A graphical representation in Figure 5 illustrates the FS values for the experimental groups.

The Tukey's post-hoc test revealed that the RMGIC with 5wt.% ZnONPs and 5wt.% mesoporous ZnONPs exhibited a significantly higher FS than the control, 3wt.% ZnONPs, 7wt.% ZnONPs, and 7wt.% mesoporous ZnONPs groups (P<0.001 for all comparisons).

Although the 5wt.% mesoporous ZnONPs group demonstrated a higher FS than the 5wt.% ZnONPs group, this difference was not statistically significant (P=0.998).

The 3wt.% mesoporous ZnONPs showed a significantly higher FS than the control (P=0.002) and 7wt.% mesoporous ZnONPs (P<0.001) groups, and also a significantly lower FS than the 5wt.% mesoporous ZnONPs group (P=0.014), but did not differ significantly from the 5wt.% ZnONPs (P=0.062), or 3wt.% ZnONPs (P=0.686) groups.

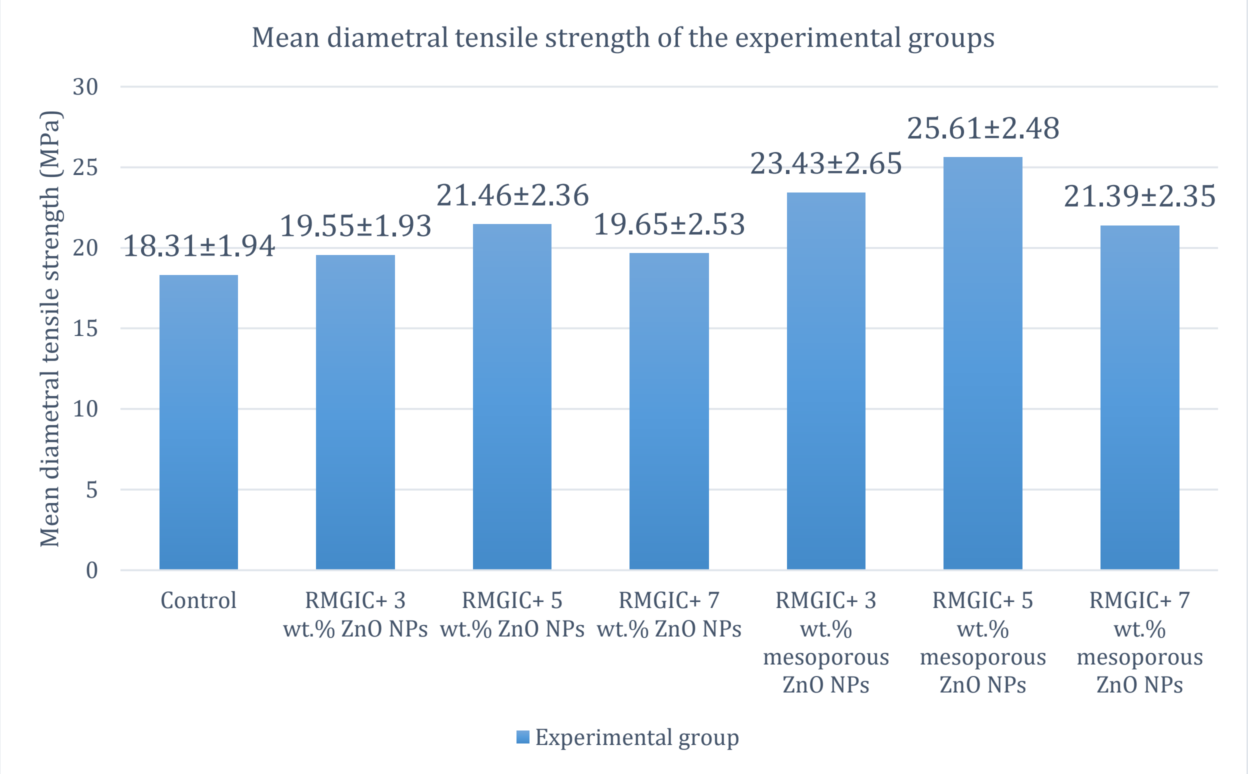

Fig 4. Bar chart illustrating the mean diametral tensile strength (MPa) of the study groups (RMGIC: resin-modified glass ionomer cement; ZnONPs: zinc oxide nanoparticles)

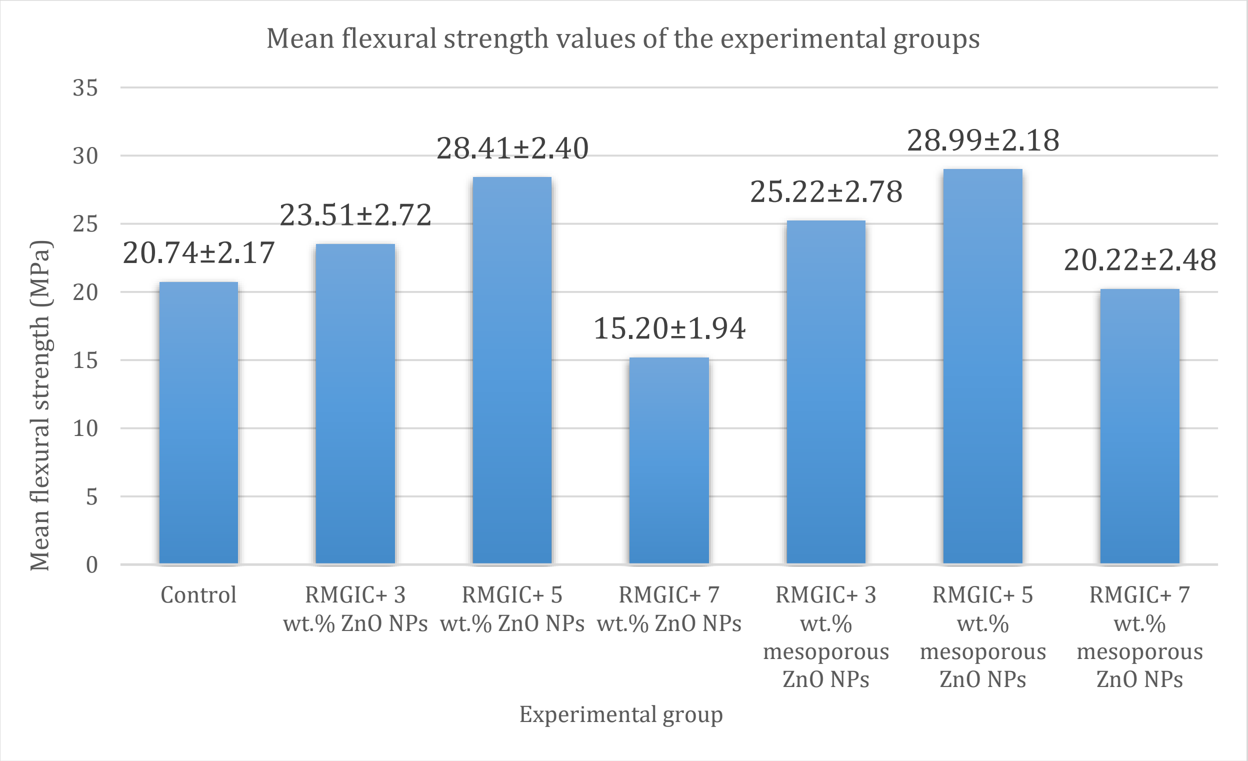

Fig 5. Bar chart showing the mean flexural strength of the study groups (RMGIC: resin-modified glass ionomer

cement; ZnONPs: zinc oxide nanoparticles)

No significant difference was found between the 3wt.% ZnONPs and the control group (P=0.149). Notably, except for the control group which did not show any significant difference with the 7wt.% mesoporous ZnONPs group (P=0.999), the 7wt.% ZnONPs group had significantly the lowest FS, which differed significantly from the FS of all other groups, including the 3wt.% ZnONPs (P=0.048), 5wt.% ZnONPs (P<0.001), and 3wt.%, 5wt.%, and 7wt.% mesoporous ZnONPs groups (P<0.001 for all comparisons). Moreover, the 7wt.% mesoporous ZnONPs group exhibited a significantly higher FS than the 7wt.% ZnONPs group (P<0.001).

DISCUSSION

The results of this study refuted the null hypothesis, revealing significant differences in DTS and FS among the RMGIC specimens that included mesoporous ZnONPs, and ZnONPs, and those that did not. The results revealed a clear trend where the inclusion of 5wt.% ZnONPs or mesoporous ZnONPs consistently led to superior FS compared to other concentrations and types tested. Moreover, the enhanced DTS observed in the 5wt.% and 3wt.% mesoporous ZnONPs groups established their potential as effective reinforcements for RMGIC formulations.

Despite thorough caries removal, complete bacterial elimination from treated tooth surfaces remains challenging [20]. Voids at the tooth-restorative material interface, such as with GIC, may allow bacterial ingress and secondary caries development [9,20].

The post-setting antibacterial performance of GICs is uncertain, with one study indicating that fluoride release alone may be insufficient to prevent bacterial growth and secondary caries [21]. To address this, various antimicrobial agents have been incorporated into GIC formulations, enhancing their antimicrobial properties to some extent [5,14,21].

ZnONPs are prominent in dental research for their strong antibacterial properties [9]. Their high surface area contributes to an 85% reduction in biofilm formation on ZnONP-coated tooth surfaces [22,23]. Incorporating at least 1% ZnONPs by weight significantly enhances the antibacterial properties of composite resins [12]. Mesoporous materials, such as mesoporous calcium-silicate nanoparticles loaded with chlorhexidine, effectively combat *Enterococcus faecalis* with low cytotoxicity, controlled ion release, and remineralization potential [24]. Similarly, expanded-pore mesoporous silica nanoparticles, capable of holding 44.62wt.% chlorhexidine, provide strong anti-biofilm effects when incorporated into GIC without compromising the mechanical properties [14]. Mesoporous ZnONPs, with their antibacterial activity, degradability, and drug release potential, are promising additives for RMGICs due to their unique attributes [25].

The choice to include ZnONPs and mesoporous ZnONPs in RMGIC in this study was motivated by their strong bonding with poly-acrylic liquid and proven antibacterial properties [26,27]. Incorporating 2wt.% ZnONPs maintained antimicrobial features, FS, and fluoride release in RMGIC [26]. Mesoporous ZnONPs, with superior antibacterial properties compared to traditional ZnONPs, show promise for RMGIC integration due to their unique structure, enhancing antibacterial efficacy. It is essential to ensure that addition of nanoparticles does not compromise the mechanical properties such as DTS and FS.

This study evaluated the DTS and FS of RMGIC modified with mesoporous ZnONPs and ZnONPs. The results showed that the 5wt.% and 3wt.% mesoporous ZnONPs had a significantly higher DTS, with the 5wt.% group demonstrating the highest strength, although not statistically significant compared to the 3wt.% group. The improved DTS in RMGIC with 3wt.% and 5wt.% mesoporous ZnONPs is attributed to several factors. Initially, this can be linked to the potential advantages of promoting physical interlocking between the matrix and inorganic fillers, facilitated by mesoporous ZnONPs. Mesoporous ZnONPs, due to their small size, might effectively occupy the spaces between RMGIC fillers and the matrix upon incorporation, leading to enhanced mechanical properties of the modified material. This discovery, particularly concerning mesoporous nanoparticles, corresponds with a prior study indicating that the mechanical strength of dental composite resins can be significantly improved by mesoporous fillers, primarily through the establishment of physical interlocking between the resin matrix and inorganic fillers [28]. A prior study further confirmed that inclusion of nanoparticles decreases porosity [4]. Consequently, addition of nanoparticles seems to fill the gaps and imperfections, impeding the propagation of existing pores by blocking their pathways, thus averting crack formation and improving the DTS of RMGICs [4]. The substantial enhancement of DTS can be attributed to the increased interaction surface area between the resin matrix and nanoparticles due to the very high surface area of mesoporous nanomaterials [28]. Furthermore, structured mesoporous ZnONPs up to 5wt.% showed promise in improving DTS by facilitating the resin matrix infiltration into the surface pores, creating micro-mechanical bonding [29]. The notable DTS increase with 3wt.% and 5wt.% mesoporous ZnONPs suggests potential chemical interactions, enhancing particle integration and uniform blending in RMGIC, warranting further investigations [29].

The significant DTS improvement with 3wt.% and 5wt.% mesoporous ZnONPs, compared to the minimal impact of ZnONPs, highlights the superior performance of mesoporous ZnONPs. Their large surface area and structured configuration enable stronger interactions with the resin matrix, enhancing adhesion and mechanical properties like DTS [28]. The physical interlocking mechanism and uniform distribution of mesoporous ZnONPs within the RMGIC further contribute to material strength. At these concentrations, specific chemical interactions likely optimize particle integration, suggesting that 3wt.% and 5wt.% represent an ideal range where surface area, interlocking, and chemical interactions synergistically enhance DTS.

This study found that incorporating 5wt.% ZnONPs and 5wt.% mesoporous ZnONPs significantly improved the FS compared to other groups. While the 5wt.% mesoporous ZnONPs group showed a slightly higher FS than the 5wt.% ZnONPs group, the difference was not statistically significant. This optimal performance at 5wt.% likely results from uniform nanoparticle dispersion within the RMGIC matrix, reinforcing it without aggregation. Higher concentrations may lead to clumping, reducing uniformity and weakening the material. Thus, 5wt.% provides an effective balance between reinforcement and maintaining structural integrity.

This study revealed that increasing the concentration of mesoporous ZnONPs from 5wt.% to 7wt.% did not notably enhance DTS, with the 7wt.% group showing a lower FS. This lack of improvement at higher concentrations may be due to saturation effects, causing uneven dispersion and potential clustering [29]. High nanoparticle concentrations can lead to agglomeration, disrupting uniformity and weakening material integrity [29]. Aggregation of mesoporous ZnONPs and ZnONPs, especially at higher levels, may create weak points in the RMGIC matrix, compromising structural integrity. Insufficient integration of nanoparticles within the matrix and limitations of chemical bonding may reduce the FS and DTS values. Maintaining a delicate balance in nanoparticle concentration is essential to enhance properties while preserving material integrity. A study by Horszczaruk et al, [30] also underscored the potential negative impact of large nanoparticle agglomerates on cement structure, shedding light on the current research's observation that addition of 7wt% ZnONPs or mesoporous ZnONPs did not yield as significant improvements in FS and DTS values as did the 5wt.% concentration. Furthermore, mesoporous ZnONPs and ZnONPs tend to aggregate more readily in larger quantities during mixing with basic aluminum fluoride silicate glass powder, or interaction with polyacrylic acid liquid. This aggregation could create weak points at the interface with the RMGIC matrix, potentially compromising the structural integrity, especially at higher nanoparticle concentrations. The decrease in Al^{3+} content as nanoparticle concentration rises can impact material strength, as Al^{3+} is vital for crosslinking with polyacrylic acid and other released ions. Poor integration of individual nanoparticles into the RMGIC matrix along with an abundance of mesoporous ZnONPs and ZnONPs could hinder complete interaction between the powder and liquid components [30, 31]. A higher concentration (7wt%) of mesoporous ZnONPs might limit polyacrylic polymer availability for chemical bonding within the RMGIC, potentially compromising internal crosslinking and leading to reduced DTS and FS.

In this study, both ZnONPs and mesoporous ZnONPs at 5wt.% concentration improved the RMGIC's FS, but only 3wt.% and 5wt.% mesoporous ZnONPs affected the DTS, unlike ZnONPs at the same concentrations. The reason for this disparity in effects on DTS and FS between ZnONPs and mesoporous ZnONPs remains unclear. The difference in performance could stem from the distinct molecular-level effects of mesoporous ZnONPs, which can better integrate within the RMGIC due to their porous structure, enhancing both DTS and FS. In contrast, conventional ZnONPs may not interact as effectively or distribute uniformly within the matrix to significantly improve DTS. This discrepancy likely explains why ZnONPs did not enhance the DTS to the same extent as did the mesoporous ZnONPs in this study. Further investigations are required to fully grasp the underlying molecular interactions and distribution within the matrix that lead to these differing outcomes.

This study showed that incorporating mesoporous ZnONPs at 5wt.% and 3wt.% concentrations significantly boosted the DTS of RMGIC; while levels beyond this range may not enhance strength. The optimal concentration for improving the FS is 5wt.%, leading to a notably higher strength compared to other groups. The pivotal role of mesoporous ZnONPs at 5wt.% concentration in enhancing the RMGIC's mechanical properties is underscored, emphasizing the importance of precise nanoparticle concentrations for substantial strength improvements in dental materials.

The limitations of this study included its reliance on in vitro settings that do not fully replicate oral conditions, and the synthetic nature of the nanoparticles used, potentially leading to uneven stress distribution. Future research could explore modifying mesoporous ZnONPs for better matrix interaction and assess nanoparticle size and morphology for improved performance of RMGICs.

CONCLUSION

In summary, adding 5wt.% ZnONPs or 5wt.% mesoporous ZnONPs to RMGIC resulted in a significantly higher FS than other groups. Additionally, the 5wt.% and 3wt.% mesoporous ZnONPs groups exhibited a notably higher DTS compared to other groups, highlighting the potential of mesoporous ZnONPs in improving both the DTS and FS.

ACKNOWLEDGEMENT

The authors would like to thank the Vice-Chancellery of Research, Shiraz University of Medical Sciences, for financially supporting this research, and Biomaterial Research Center of Shiraz University of Medical Sciences for testing the specimens (Number: 29203). This article is based on Dr. Mohammad Mahdi Abdolinezhad's dissertation. The authors thank Dr. Naeimehossadat Asmarian from the Dental Research Development Center for the statistical analyses.

CONFLICT OF INTEREST STATEMENT

None declared.

REFERENCES

1. Senthil Kumar R, Ravikumar N, Kavitha S, Mahalaxmi S, Jayasree R, Sampath Kumar TS, et al. Nanochitosan modified glass ionomer cement with enhanced mechanical properties and fluoride release. Int J Biol Macromol. 2017 Nov;104(Pt B):1860-5.
2. Sharafeddin F, Jowkar Z, Bahrani S. Comparison between the effect of adding microhydroxyapatite and chitosan on surface roughness and microhardness of resin modified and conventional glass ionomer cements. J Clin Exp Dent. 2021 Aug;13(8):e737-44.

3. Hafshejani TM, Zamanian A, Venugopal JR, Rezvani Z, Sefat F, Saeb MR, et al. Antibacterial glass-ionomer cement restorative materials: A critical review on the current status of extended release formulations. J Control Release. 2017 Sep;262:317-28.
4. Nicholson JW, Sidhu SK, Czarnecka B. Enhancing the mechanical properties of glass-ionomer dental cements: A review. Materials (Basel). 2020 May;13(11):2510.
5. Jowkar Z, Jowkar M, Shafiei F. Mechanical and dentin bond strength properties of the nanosilver enriched glass ionomer cement. J Clin Exp Dent. 2019 Mar;11(3):e275-81.
6. Malhotra S, Bhullar KK, Kaur S, Malhotra M, Kaur R, Handa A. Comparative evaluation of compressive strength and flexural strength of GC Gold hybrid, GIC conventional and resin-modified glass-ionomer cement. J Pharm Bioallied Sci. 2022 Jul;14(Suppl 1):S214-6.
7. Rêgo HMC, Butler S, Santos MJC. Evaluation of the mechanical properties of three resin-modified glass-ionomer materials. Biomed Res Int. 2022 Aug;2022:4690656.
8. Singer L, Bierbaum G, Kehl K, Bourauel C. Evaluation of the flexural strength, water sorption, and solubility of a glass ionomer dental cement modified using phytomedicine. Materials (Basel). 2020 Nov;13(23):5352.
9. Moradpoor H, Safaei M, Mozaffari HR, Sharifi R, Imani MM, Golshah A, et al. An overview of recent progress in dental applications of zinc oxide nanoparticles. RSC Adv. 2021 Jun;11(34):21189-206.
10. Jowkar Z, Hamidi SA, Shafiei F, Ghahramani Y. The effect of silver, zinc oxide, and titanium dioxide nanoparticles used as final irrigation solutions on the fracture resistance of root-filled teeth. Clin Cosmet Investig Dent. 2020 Apr;12:141-8.
11. Mirhosseini F, Amiri M, Daneshkazemi A, Zandi H, Javadi ZS. Antimicrobial effect of different sizes of nano zinc oxide on oral microorganisms. Front Dent. 2019 Mar-Apr;16(2):105-12.
12. Arun D, Adikari Mudiyanselage D, Gulam Mohamed R, Liddell M, Monsur Hassan NM, Sharma D. Does the addition of zinc oxide nanoparticles improve the antibacterial properties of direct dental composite resins? A systematic review. Materials (Basel). 2020 Dec;14(1):40.
13. Zhang JF, Wu R, Fan Y, Liao S, Wang Y, Wen ZT, et al. Antibacterial dental composites with chlorhexidine and mesoporous silica. J Dent Res. 2014 Dec;93(12):1283-9.
14. Yan H, Yang H, Li K, Yu J, Huang C. Effects of chlorhexidine-encapsulated mesoporous silica nanoparticles on the anti-biofilm and mechanical properties of glass ionomer cement. Molecules. 2017 Jul;22(7):1225.
15. Gunduz O, Yetmez M, Sonmez M, Georgescu M, Alexandrescu L, Ficai A, et al. Mesoporous materials used in medicine and environmental applications. Curr Top Med Chem. 2015;15(15):1501-15.
16. Katoch V, Singh J, Sharma NR, Singh RP. Synthesis and characterization of mesoporous zinc oxide nanoparticles. Inorg Nano-Metal Chem. 2024 Jan;54(1):58-66.
17. Jowkar Z, Askarzadeh S, Hamidi SA, Fattah Z, Moaddeli A. Assessment of the antimicrobial properties of mesoporous zinc oxide nanoparticles against Streptococcus mutans: An in vitro investigation. Int J Dent. 2025 May;2025:4438269.
18. Jowkar Z, Moaddeli A, Shafiei F, Tadayon T, Hamidi SA. Synthesis and characterization of mesoporous zinc oxide nanoparticles and evaluation of their biocompatibility in L929 fibroblasts. Clin Exp Dent Res. 2024 Feb;10(1):e844.
19. Moshaverinia M, Navas A, Jahedmanesh N, Shah KC, Moshaverinia A, Ansari S. Comparative evaluation of the physical properties of a reinforced glass ionomer dental restorative material. J Prosthet Dent. 2019 Aug;122(2):154-9.
20. Kasraei S, Sami L, Hendi S, Alikhani MY, Rezaei-Soufi L, Khamverdi Z. Antibacterial properties of composite resins incorporating silver and zinc oxide nanoparticles on Streptococcus mutans and Lactobacillus. Restor Dent Endod. 2014 May;39(2):109-14.
21. Hafshejani TM, Zamanian A, Venugopal JR, Rezvani Z, Sefat F, Saeb MR, et al. Antibacterial glass-ionomer cement restorative materials: A critical review on the current status of extended release formulations. J Control Release. 2017 Sep;262:317-28.
22. Demir E, Creus A, Marcos R. Genotoxicity and DNA repair processes of zinc oxide nanoparticles. J Toxicol Environ Health A. 2014;77(21):1292-303.
23. Eshed M, Lellouche J, Matalon S, Gedanken A, Banin E. Sonochemical coatings of ZnO and CuO nanoparticles inhibit Streptococcus mutans biofilm formation on teeth model. Langmuir. 2012 Aug;28(33):12288-95.
24. Fan W, Li Y, Sun Q, Ma T, Fan B. Calcium-silicate mesoporous nanoparticles loaded with chlorhexidine for both anti- Enterococcus faecalis and mineralization properties. J Nanobiotechnology. 2016 Oct;14(1):72.
25. Laurenti M, Grochowicz M, Dragoni E, Carofiglio M, Limongi T, Cauda V. Biodegradable and drug-eluting inorganic composites based on mesoporous zinc oxide for urinary stent applications. Materials (Basel). 2020

Aug;13(17):3821.
26. Malekhoseini Z, Rezvani MB, Niakan M, Atai M, Bassir MM, Alizade HS, et al. Effect of zinc oxide nanoparticles on physical and antimicrobial properties of resin-modified glass ionomer cement. Dent Res J (Isfahan). 2021 Sep;18:73.
27. Shirazi M, Qazvini FF, Mohamadrezaie S. Antimicrobial properties of glass-ionomer cement incorporated with zinc oxide nanoparticles against mutans streptococci and lactobacilli under orthodontic bands: An in vivo split-mouth study. Dent Res J (Isfahan). 2023 Mar;20:45.
28. Bai X, Lin C, Wang Y, Ma J, Wang X, Yao X, et al. Preparation of Zn doped mesoporous silica nanoparticles (Zn-MSNs) for the improvement of mechanical and antibacterial properties of dental resin composites. Dent Mater. 2020 Jun;36(6):794-807.
29. Samuel SP, Li S, Mukherjee I, Guo Y, Patel AC, Baran G, et al. Mechanical properties of experimental dental composites containing a combination of mesoporous and nonporous spherical silica as fillers. Dent Mater. 2009 Mar;25(3):296-301.
30. Horszczaruk E, Mijowska E, Cendrowski K, Mijowska S, Sikora P. Effect of incorporation route on dispersion of mesoporous silica nanospheres in cement mortar. Constr Build Mater. 2014 Sep;66:418-21.
31. De Caluwé T, Vercruysse CW, Ladik I, Convents R, Declercq H, Martens LC, et al. Addition of bioactive glass to glass ionomer cements: Effect on the physico-chemical properties and biocompatibility. Dent Mater. 2017 Apr;33(4):e186-203.