EVALUATION OF MECHANICAL PROPERTIES OF GLASS IONOMER CEMENT INCORPORATED WITH ZIRCONIA NANOTUBES: AN *IN VITRO* STUDY

Chatarasupalli Durga AjayTeja[1], Satyanarayana Raju Mantena[1], Rama Krishna Alla[2*], Bheemalingeswara Rao Donimukkala[1], Alluri Venkata Ramaraju[1], Narasimha Rao Guddala[1]

[1]Department of Prosthodontics, Crown and Bridge, Vishnu Dental College, Bhimavaram, Andhra Pradesh, India.
[2]Division of Dental Materials, Vishnu Dental College, Bhimavaram, Andhra Pradesh, India

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This study aimed to evaluate and compare the mechanical properties of Glass ionomer cement (GIC) modified with varying concentrations of Zirconia nanotubes (ZNTs). Different proportions (0.5%, 1.0%, 2.0%, 5.0% by weight) of ZNTs were added to the GIC powder to prepare a total of 200 specimens, divided into five groups of 40 specimens according to modifications., The eight specimens from each group (n=8) were allocated for testing each mechanical property. The mechanical properties investigated were compressive strength (CS), diametral tensile strength (DTS), flexural strength (FS), shear bond strength (SBS), and microhardness. CS, DTS, FS, and SBS were measured using the universal testing machine, while microhardness was assessed using a Vickers hardness tester. The GIC modified with 0.5 Wt% ZNTs exhibited the highest CS, DTS, and FS values. The highest Vickers hardness was observed with the 1.0 Wt% ZNTs group. However, all ZNT-modified groups showed lower SBS values compared to the control group. The findings suggest that incorporating 0.5 Wt% % ZNTs significantly enhances the CS, DTS, and FS of GIC, while 1.0 Wt% ZNTs improves microhardness. However, ZNTs' incorporation negatively affects the SBS.

Keywords: Glass Ionomer Cement, mechanical strength, nanofillers, nanotubes.

Introduction

Glass Ionomer Cement (GIC), was invented by Wilson and Kent in 1969 through the reaction of glass particles and polyacrylic acid. GICs are widely used in dental procedures as restorative materials, liners, sealants, and luting agents [1,2]. GICs are valued for their aesthetics [2,3], biocompatibility, colour stability [4], fluoride release [5], a coefficient of thermal expansion (CTE) similar to the tooth, chemical bonding to tooth structure, and remineralization potential [2,3]. However, limitations like low wear resistance [6], moisture sensitivity, formation of cracks and gaps [7], high initial water sorption [8] and low compressive strength prompted advancements in their formulation. To improve the mechanical properties of GICs, various metal fillers, including silver alloy and resin materials like Polymethyl methacrylate (PMMA), Bis-GMA, etc., have been used with variable success [1,2].

With the advancements in nanotechnology, numerous nanofillers like zirconia, titania, alumina, etc., have been incorporated into GIC to enhance its biological and mechanical characteristics [8,9]. Zr nanoparticles in particular received more interest due to their high refractive index, ionic conductivity, high surface area and catalytic activity [10], biocompatibility and bioinertness [11], chemical stability, high thermal stability, high strength and toughness [12,13], and wear resistance. However, these nanoparticles require surface treatments to improve mechanical strength; otherwise, they tend to agglomerate and create voids, resulting in weakening of the set matrix [8].

Recently, zirconia nanotubes (ZNTs) have been introduced due to their unique properties like biocompatibility, strength, white colour [10], high abrasion resistance, and a unique tubular structure with large surface area, allowing better adsorption and catalytic activity. Their hollow geometry allows for more efficient drug loading and sustained release, unlike nanoparticles that offer limited control over release kinetics [11]. Additionally, the aligned and porous nanotube architecture promotes improved ion transport, better biological responses such as cell adhesion and osseointegration, and offers enhanced photocatalytic efficiency due to better light trapping and surface reactivity [12,13]. These superior characteristics show promise to use ZNTs for various biomedical applications, including improving the bone-implant contact, bone mineral deposition [12], controlled and targeted drug loading and release [11].

Golla VP *et al.* [14] examined the effect of incorporat-

***Author address**: Rama Krishna Alla, Division of Dental Materials, Vishnu Dental College, Bhimavaram, Andhra Pradesh, India.
e-mail: rkdentalbiomaterials@gmail.com, ramakrishna.a@vdc.edu.in.
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ing various concentrations of ZNTs on the mechanical properties of denture base resin materials and reported that they were dose-dependent. However, no substantial research was found on the effect of ZNTs on the properties of GICs. Therefore, this study aimed to investigate the effect of the addition of various amounts of ZNTs on the mechanical properties of GICs.

Materials and methods

In this *in vitro* study, Type-I GIC (GC Fuji I, GC Corporation, Japan), Zirconia nanotubes (Nanoresearch Lab, Ranchi, India), with an average size of 80 – 100 nanometres, were used.

Specimen preparation: Two hundred specimens were fabricated using glass molds with the inner dimensions of 4 X 6 mm, 4 X 8 mm, 25 X 2 X 2 mm, and 12 X 6 mm for evaluating compressive strength (CS), diametral tensile strength (DTS), flexural strength (FS), and Vickers microhardness (VHN), respectively. For measuring shear bond strength, the GIC specimens were cemented to the dentin. The GIC powder was incorporated with different concentrations of ZNTs (0.5 wt%, 1.0 wt%, 2.0 wt% and 5.0 wt%). The GIC that did not contain ZNTs (0.0 wt%) served as the control group. A total of 200 specimens were prepared and allocated into five groups, each group containing 40 specimens. From each group, eight specimens (n=8) were allocated for testing each mechanical property, including CS, DTS, FS, SBS and VHN. For sample preparation and testing procedure, ISO 9917 were employed for all the mechanical properties [15]. For easy removal of the specimens, the inner walls of the glass molds (Figure 1a) were coated with a thin layer of Vaseline (Kemphasol, Bombay, India), and placed on a Vaseline-coated glass slab (Jenco Industries, India). The specified concentrations of ZNTs (as mentioned above) were added to the GIC powder, and then mixed with the polyacrylic acid liquid as per the manufacturer's instructions. The mix was packed into the glass mold (Figure 1b) and covered with a glass cover slip (Figure 1c) to obtain a uniform and smooth surface. Another glass slab was placed over it, and a standard weight of 200 grams was applied (Figure 1d) until the mass had set, after which the specimens were carefully retrieved from the mold. The excess material on the sample was trimmed, followed by finishing with 400-grit emery paper. The specimens were stored in distilled water at 37 °C ± 1 °C until they were subjected to testing.

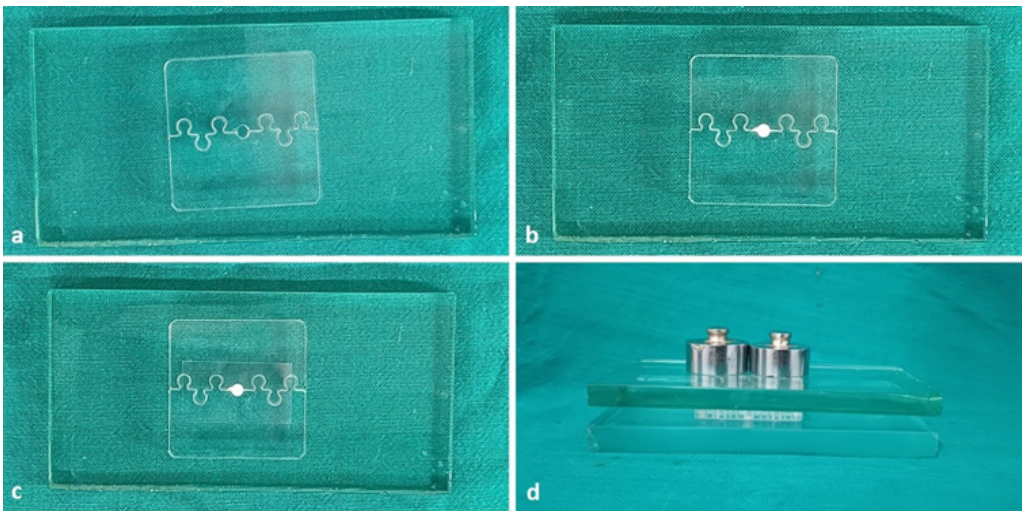

Figure 1. The procedure involved in making the GIC specimens., a. Glass split mold, b. Glass mold condensed with the GIC mix, c. GIC mix covered with a glass cover slip, and d. Application of a standard weight of 200 g during the setting of the GIC mix.

Evaluation of compressive strength: The cylindrical specimen was placed between the compression grips of the Universal testing machine (UTM) (AE UTM-LC2, Advanced Equipment, Thane, India). A compressive load was applied at a cross-head speed of 0.5 mm/minute until a fracture occurred. The force required for fracture was recorded in newtons (N), and the compressive strength (F) in MPa was determined using the following formula:

$$F=P/A \quad \text{.....(1)}$$

where: P is the maximum load at failure (N), and A is the cross-sectional area of the specimen (mm²)

Evaluation of diametral tensile strength: The specimen was placed between the compressive grips of the UTM. A load was applied diametrically at a crosshead speed of 0.5 mm/minute until fracture. Load to fracture was recorded in newtons, and the diametral tensile strength (σt) in MPa was calculated using the following formula:

$$\sigma t = 2P / \pi dt \quad \text{.....(2)}$$

where P is the maximum load at failure (N), d is the

diameter of the specimen (mm), t is the thickness(mm), and π is the constant (3.14).

Evaluation of flexural strength: The sample was mounted on the anvils of a UTM and subjected to loading at a crosshead speed of 2 mm/min until a fracture occurred. The fracture load value was obtained in newtons (N), and the flexural strength (S) was measured using the following formula:

$$S=3WL/2bd^2 \quad \text{.....(3)}$$

where S is the flexural strength (MPa), W is the fracture load in Newtons (N), L is the span length (mm), b is the width (mm), and d is the thickness (mm) of the specimen.

Evaluation of shear bond strength: The GIC samples were bonded to the dentin layer of the natural teeth. The teeth with abrasions, macroscopic cracks, caries, and staining on the surface were excluded from the study. A total of forty (n = 40) extracted maxillary first molar teeth were collected and stored in 10 percent neutral buffered formalin until they were used. Tissue residues and hard deposits on the teeth surfaces were removed with ultrasonic scaler tips, followed by polishing with 600-grit emery paper in accordance with ISO 6344-1:2014 [16]. The samples were then rinsed with water spray, gently air-dried, and stored in deionised water until the procedure commenced.

The cleaned teeth were sectioned into buccal and lingual halves at the cemento-enamel junction using double-faced diamond discs. Enamel was removed to expose the dentin. A wax (MAARC dental, Maharashtra, India) block with measurements of 30 X 20 X 15 mm was made using modelling wax (Shiva products, Vasai, India). A putty index of the modelling wax block was made using polyvinyl siloxane impression (Zhermack S.p.A., Italy). A self-cure acrylic (Dental Products of India, India) resin dough was packed into the putty index mold, and the decoronated tooth samples were immediately placed into the acrylic resin and allowed to set. The decoronated tooth was placed 5 mm below the tip of the acrylic block, exposing the dentin surface to provide bonding with GIC. The samples were retrieved from the putty index after setting. The excess material was trimmed and polished using conventional procedures to avoid the presence of any uneven surfaces.

The tooth surfaces were conditioned with polyacrylic acid. A thin polythene tube with an inner diameter and a height of 4 X 4 mm was placed on the conditioned tooth surface. The GIC mix with various concentrations of ZNTs was packed into the polythene tubes and allowed to set. The polythene tubes were carefully removed after setting.

The acrylic block with the GIC specimen was secured in a metal jig on the universal testing machine and a loading chisel was allowed to have contact at the interface of the dentin and the GIC specimen. The load was applied to debond the specimen from the dentin surface at a cross-head speed of 0.5 mm/min. The force required to debond was recorded in newtons (N). The shear bond strength in megapascals (MPa) was calculated using the following formula:

$$\text{Shear bond strength (MPa)} = \frac{\text{(Failure load (N))}}{\text{(Bonded surface area (mm2))}} \quad \text{.....(4)}$$

Evaluation of Vickers hardness: The specimens were placed on the Vickers hardness tester (Daksh -quality system Pvt. Ltd., India), and the ocular lens was focused to locate the area of indentation on the specimen. Then, the lens was replaced with a diamond indenter. A 30-gram load was applied for about 30 seconds of dwell time to create an indentation on the surface of the specimen. The indenter was replaced with the lens, and the diagonals length was assessed by positioning two visible lines through the ocular lens at both ends of the diagonal formation. The hardness value was taken directly from the Vickers hardness testing apparatus. Similarly, three indentations were made on each specimen, and the average of them was considered as the Vickers hardness number of the specimens.

Statistical analysis: The statistical analyses were performed with the Statistical Package for Social Sciences, SPSS version 20 software (IBM SPSS, IBM Corp., Armonk, NY, USA). Descriptive statistics were represented with mean and standard deviation (SD). The statistical tests used were one-way ANOVA to compare the means between the groups (intragroup comparisons). Tukey post hoc analysis was used for pairwise comparisons, and a p-value less than 0.05 was considered statistically significant.

Results and discussion

Compressive strength, diametral tensile strength and flexural strength:

The mean compressive strength, diametral tensile strength and flexural strength are presented in Table 1. The control group exhibited less CS, DTS and FS compared to the modified groups. Among the modified groups, the GIC modified with 0.5 wt% demonstrated more CS, DTS and FS compared to other modified groups. Zirconia's stable crystal structure reinforces the aluminosilicate matrix, improving its strength. This reinforcing effect is comparable to the strengthening of porcelain materials modified with alumina nanoparticles [17,18]. However, in the present study, a decreasing trend in the CS, DTS and FS was observed with an increase in the concentration of NTs. This declining trend in the mechanical properties can be attributed to the nanotube agglomeration at higher concentrations, which interrupts polymer cross-linking and forms stress-inducing voids. These voids create stress concentrations, resulting in crack development in the GIC. These cracks propagate under continuous application of masticatory loads, leading to fracture [7,19,20]. One-way ANOVA (Table 1) showed a

Table 1. Comparison of mechanical properties of GIC modified with different concentrations of ZNTs (One-way ANOVA)

Concentratio	Compressive strength		Diametral tensile strength		Flexural strength	
n	Mean ± SD#	P - value	Mean ± SD#	P - value	Mean ± SD#	P - value
Control	51.53 ± 6.13	0.001*	5.32 ± 0.70		11.22 ± 3.95	
0.5 Wt%	82.69 ± 7.75		10.10 ± 2.22	0.001*	19.53 ± 2.18	
1.0 Wt%	70.35 ± 5.12		9.30 ± 2.31		13.73 ± 2.43	0.001*
2.0 Wt%	66.12 ± 8.58		7.73 ± 1.38		10.91 ± 3.31	
5.0 Wt%	64.51 ± 5.77		5.60 ± 1.95		9.20 ± 1.80	

#standard deviation, *significant difference.

Table 2. Pair-wise comparison of the mechanical properties of GIC modified with different concentrations of ZNTs (Tukey's Post-Hoc Test)

Concentrations		Shear bond strength		Vickers hardness	
		Mean Difference ±Standard Error	P value	Mean Difference ± Standard Error	P value
Control	0.5 wt%	3.052±0.323	0.000*	44.420±5.201	0.000*
	1.0 wt%	2.812±0.323	0.000*	58.275±5.201	0.000*
	2.0 wt%	2.373±0.323	0.000*	52.560±5.201	0.000*
	5.0 wt%	3.245±0.323	0.000*	36.956±5.201	0.000*
0.5 wt%	1.0 wt%	0.239±0.323	0.945	13.855±5.201	0.080
	2.0 wt%	0.679±0.323	0.244	8.140±5.201	0.529
	5.0 wt%	0.193±0.323	0.975	7.463±5.201	0.610
1.0 wt%	2.0 wt%	0.439±0.323	0.658	5.715±5.201	0.806
	5.0 wt%	0.432±0.323	0.670	21.318±5.201	0.002*
2.0 wt%	5.0 wt%	0.871±0.323	0.075	15.603±5.201	0.037*

*Significant difference

significant difference among the groups (CS: p = 0.001, DTS: p = 0.001 and FS: p = 0.001).

Pair-wise comparisons between the unmodified and modified groups, as well as between the modified groups, are presented in Table 2. In post-hoc analysis, the control group showed significant differences with all the ZNT-modified groups in CS. Among the modified groups, the 0.5 wt% ZNTs group exhibited a significant difference in CS with the other modified groups. In diametral tensile strength, the unmodified group displayed a significant difference with 0.5 and 1.0 wt% ZNTs modified groups. Among the modified groups, the 5.0 wt% ZNTs modified group demonstrated a significant difference with the 0.5 wt% and 1.0 wt% modified groups. In FS, the control group showed a significant difference only with the 0.5 wt% ZNTs modified group. Among modified groups, the 0.5 Wt% group showed a significant difference with all the modified groups. GIC modified with 1.0 wt% ZNTs exhibits a significant difference with 5.0 Wt% modified group.

Research reported that the smaller, well-dispersed nanofillers can integrate between polyacid chains, preventing their movement and improving strength [22,23,24,25]. Among the modified groups, the GIC incorporated with 0.5 wt% of ZNTs showed more CS, DTS and FS compared to the other modified groups. At lower concentrations, the NTs might have been distributed uniformly between the polyacid chains and filled the voids, resulting in increased mechanical properties [26]. Though the finer NTs with an average dimension of 80-100 nanometres were added, there was a decrease in the CS, DTS and FS values, which can be attributed to the agglomeration of nanotubes. These findings align with Fathi U A *et al.* (2023) [20], who also observed lower CS and DTS with increased nanoparticle content, although their study used titania nanoparticles.

In the clinical scenario, the dental materials are subjected to combinations of different stresses. Therefore, the materials used in the oral cavity should withstand multi-directional forces. Investigating the flexural strength of materials is crucial to mimic these stresses and evaluate a material's capacity to sustain various types of forces. In the present study, similar to CS and DTS, a reduction in the FS was also observed. This decrease can be attributed to the agglomeration of NTs [7]. In addition, the bonding between the ZNTs and PAA plays a crucial role in defining the mechanical strength. The results of this study suggest that the weak bonding strength between zirconia and PAA ions result in decreased FS under bending forces [27]. Additionally, the viscosity of GIC mass increased following the addition of nanotubes, which could also be attributed to the reduced FS, as observed in this study [27].

Anastasia Beketova *et al.* [27] reported an increase in the FS of RMGICs. Alhough weak bonding between carboxylate groups and Zirconia ions can occur, a pos-

sible reaction of NPs can be expected in the interface since the primer contains MDP and 4-META monomers. Additionally, they observed that the viscosity of RMGI increased after the NP loading, which could partially explain the reduced SBS. However, the present study used the conventional GIC and also observed an increased viscosity in the GIC mix with the increase in the concentration of NTs. Therefore, it can be inferred that the increased viscosity might also hinder the FS of ZNTs-modified GICs [23,28].

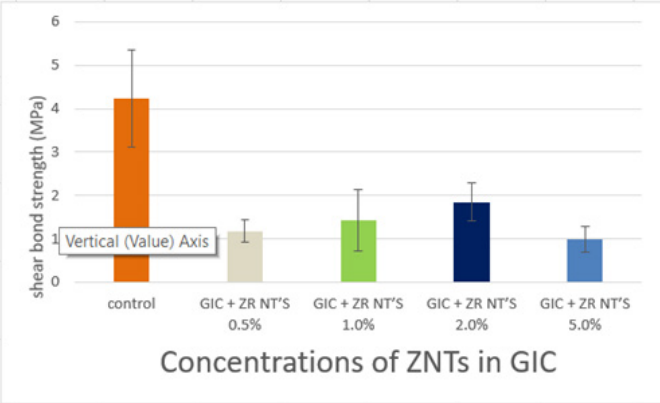

Figure 2. Shear bond strength (MPa) of GIC modified with different concentrations of ZNTs

Shear bond strength:

Bond strength defines the durability of the restoration in the prepared tooth. The greater the bond strength, the longer the durability of the restoration. Poor adhesion to the tooth surfaces may lead to the debonding of restorations, even under minimal force. Hence, this study assessed the effect of different concentrations of ZNTs incorporation on the SBS of GIC with the natural tooth. In this study, the control group had higher SBS compared to the ZNTs-modified groups.

The control group (4.23 ± 1.12 MPa) showed higher shear bond strength compared to the modified groups (Figure 2). Among the modified GIC groups, an increase in the SBS was observed from 0.5 wt% to 2.0 wt% (for 0.5 wt%: 1.18 ± 0.25, 1.0 wt%: 1.42 ± 0.71 MPa, 2.0 wt%: 1.85 ± 0.44 MPa) of ZNTs. However, the addition of 5.0 wt% (0.98 ± 0.30 MPa) of ZNTs recorded the lowest SBS. One-way ANOVA showed a significant difference (p = 0.001) among the groups. Pair-wise comparisons (Table 3) revealed a significant difference in SBS between the control group and all the ZNT-modified groups. However, no significant differences in SBS were observed between the modified groups.

Table 3. Pair-wise comparison of Shear bond strength and Vickers hardness of GIC modified with different concentrations of ZNTs (Tukey's Post-Hoc Test)

Concentrations		Shear bond strength		Vickers hardness	
		Mean Difference ±Standard Error	*P* value	Mean Difference ± Standard Error	*P* value
Control	0.5 wt%	3.052±0.323	0.000*	44.420±5.201	0.000*
	1.0 wt%	2.812±0.323	0.000*	58.275±5.201	0.000*
	2.0 wt%	2.373±0.323	0.000*	52.560±5.201	0.000*
	5.0 wt%	3.245±0.323	0.000*	36.956±5.201	0.000*
0.5 Wt%	1.0 wt%	0.239±0.323	0.945	13.855±5.201	0.080
	2.0 wt%	0.679±0.323	0.244	8.140±5.201	0.529
	5.0 wt%	0.193±0.323	0.975	7.463±5.201	0.610
1.0 Wt%	2.0 wt%	0.439±0.323	0.658	5.715±5.201	0.806
	5.0 wt%	0.432±0.323	0.670	21.318±5.201	0.002*
2.0 Wt%	5.0 wt%	0.871±0.323	0.075	15.603±5.201	0.037*

*Significant difference

The reduced bond strength in ZNTs-modified GICs may be due to fewer free carboxyl groups available for bonding with calcium in tooth tissue. This is caused by ZNTs interacting with polyacrylic acid (PAA), altering its conformation and reducing chemical bonding potential [25,29]. Additionally, increased film thickness, observed with higher ZNT concentrations, negatively affects SBS. According to ISO 9917-1, luting agents should have a film thickness of less than or equal to 25 µm for optimal bonding. Agglomerated nanofillers can increase viscosity and film thickness, weakening adhesion [15]. Similar to the present study, Perdawd B.A. *et al.* and Beketova A. *et al.* observed decreased SBS. They also reported that this decrease in SBS was due to the agglomeration of nanofillers and an increase in the film thickness of the cement [27,30].

Dentin is heterogeneous, having dentinal tubules that contain odontoblastic processes with low surface energy. The lower the surface energy, the poorer the bond strength with the dentin [2]. The reduction in SBS with the modified groups in the present study could be attributed to the decrease in the surface energy of dentin with the addition of various concentrations of ZNTs [17]. On the contrary, Tahir A *et al.* reported an increase in the bond strength between the dentin and the nanoparticle-modified GICs. They proposed that the shear bond strength

(SBS) is dose-dependent up to a specific concentration [29]. However, in the present study, all the modified GICs demonstrated less SBS compared to the control group.

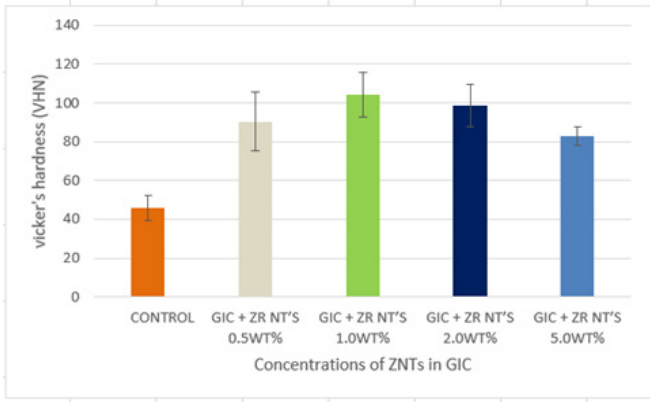

Figure 3. Vickers hardness (VHN) of GIC modified with different concentrations of ZNTs

Vickers' microhardness:

Surface hardness is vital for wear resistance and maintaining restoration integrity. A harder surface resists deformation and wear, reducing the likelihood of roughness, bacterial colonization, and failure under friction. This study, as presented in Figure 3, found increased surface hardness in ZNTs-modified groups compared to the control group (45.96 ± 6.59). GIC with 1.0 wt% ZNTs exhibited the highest hardness (104.23 ± 11.30 VHN), followed by 2.0 wt% (98.52 ± 10.99 VHN), 0.5 wt% (90.38 ± 15.00 VHN), and 5.0 wt% (82.91 ± 4.89 VHN). At low concentrations, well-aligned nanotubes reinforce the matrix and increase resistance to indentation. This could have been the reason for increased VHN at a lower concentration of ZNTs compared to the 5.0 wt% incorporation. In addition, the increased VHN at lower concentrations can also be attributed to the smaller size of NTs used in the study resulted in improved NTs packing and density. This packing might have resisted the penetration of the Vickers indenter through the surface [20]. In the present study, One-way ANOVA showed a significant difference (p = 0.001) in microhardness among the groups. Pair-wise comparisons (Table 3) showed a significant difference for Vickers hardness between the control group and all the ZNT-modified groups. The GIC modified with 5.0 Wt% ZNTs showed significant differences for Vickers hardness with 1.0 wt% (p = 0.002) and 2.0 wt% (p = 0.037) ZNTs modified groups (Table 3).

Generally, aging in deionised water significantly reduces the mechanical properties of GIC specimens. In the present study, all the specimens were stored in deionised water for 24 hours before the testing. This 24-hr aging can also be considered a reason for the observed decrease in the CS, DTS, FS and SBS values. Despite 24-hour water storage, the modified GICs retained superior hardness, possibly due to hydrogen bonding between zirconia and polyacid chains, limiting solubility [2,9,14].

However, the decrease in the hardness in the group with 5.0 wt% ZNTs suggested that the nanotube agglomerations could have inhibited polymer cross-linking, thereby decreasing the resistance to indentation [23]. This trend aligns with studies on various nanotubes, such as titania, where high concentrations negatively affected microhardness [7].

Testing in this study was conducted under '*in vitro*' conditions, which may not completely replicate the oral environment. Future studies may focus on *in vivo* conditions and also focus on biocompatibility and cytotoxicity of ZNTs-modified GICs.

Conclusion

Within the limitations of this in vitro study, it can be concluded that the incorporation of 0.5 wt% zirconia nanotubes into glass ionomer cement significantly enhanced its compressive strength, diametral tensile strength and flexural strength compared to the control group and other modified groups. While the unmodified GIC group demonstrated superior shear bond strength, a decreasing trend in shear bond strength was observed with increased ZNT concentration, indicating an inverse relationship. Additionally, ZNTs-modified groups demonstrated higher surface microhardness compared to the control group, with the 1.0 wt% ZNTs group exhibiting the highest Vickers hardness.

These findings suggest that incorporating ZNTs at optimal concentrations, particularly between 0.5 and 1.0 wt%, can improve key mechanical properties of GIC; however, higher concentrations may lead to nanoparticle agglomeration and disruption of the matrix structure, potentially compromising performance.

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Izvod

PROCENA MEHANIČKIH OSOBINA GLASS-JONOMERNOG CEMENTA SA UGRAĐENIM NANOCEVIMA CIRKONIJUMA: *IN VITRO* STUDIJA

Chatarasupalli Durga AjayTeja[1], Satyanarayana Raju Mantena[1], Rama Krishna Alla[2*], Bheemalingeswara Rao Donimukkala[1], Alluri Venkata Ramaraju[1], Narasimha Rao Guddala[1]

[1]·Department of Prosthodontics, Crown and Bridge, Vishnu Dental College, Bhimavaram, Andhra Pradesh, India.
[2].Division of Dental Materials, Vishnu Dental College, Bhimavaram, Andhra Pradesh, India.

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Cilj ovog rada bio je da proceni i uporedi mehanička svojstva glass-jonomernog cementa (GC) modifikovanog različitim koncentracijama cirkonijumskih nanocevi (ZNT). ZNT u različitim masenim procentima (0,5%, 1,0%, 2,0% i 5,0%) su dodati u GC prah da bi se pripremilo ukupno 200 uzoraka, podeljenih u pet grupa od po 40 uzoraka, prema modifikacijama. Osam uzoraka iz svake grupe (n=8) je uzeto za ispitivanje sledećih mehaničkih svojstava: čvrstoće na pritisak (CS), čvrstoće na dijametralno zatezanje (DTS), čvrstoće na savijanje (FS), čvrstoće veze na smicanje (SBS) i mikrotvrdoće. CS, DTS, FS i SBS su merene pomoću univerzalne mašine za ispitivanje, dok je mikrotvrdoća procenjena pomoću Vikersovog testera tvrdoće. GC modifikovan sa 0,5 masenih procenata (wt%) ZNT-a pokazao je najviše vrednosti CS, DTS i FS. Najveća Vikersova tvrdoća je primećena kod grupe sa 1,0 wt% ZNT-a. Međutim, sve grupe modifikovane ZNT-om pokazale su niže vrednosti SBS u poređenju sa kontrolnom grupom. Rezultati pokazuju da ugradnja 0,5 wt% ZNT-a značajno poboljšava CS, DTS i FS GIC-a, dok 1,0 wt% ZNT-a poboljšava mikrotvrdoću. Međutim, ugradnja ZNT-a negativno utiče na SBS.

Ključne reči: Glass-jonomerni cement, mehanička čvrstoća, nanopunila, nanocevi.

CRediT authorship contribution statement:
Chatarasupalli Durga AjayTeja: conceptualization, literature review, methodology, investigation, data curation, writing-original draft.
Satyanarayana Raju Mantena: formal analysis, data curation, supervision.
Rama Krishna Alla: conceptualization, validation, Investigation, editing of the draft, supervision.
Bheemalingeswara Rao Donimukkala: methodology, visualisation, supervision.
Alluri Venkata Ramaraju: methodology, investigation, validation.
Narasimha Rao Guddala: literature review, investigation, writing original draft.
All authors contributed to the article and approved the submitted version.