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Original article

The Role of Zirconia in Bioactive Ceramics: Implications for Dental and Orthopedic Regenerative Applications

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Abstract
Zirconia (ZrO_2), specifically Yttria-Stabilized Tetragonal Zirconia Polycrystals (Y-TZP), is a highly regarded material in both dentistry and orthopedics due to its remarkable mechanical strength, biocompatibility, and versatility. This paper examines zirconia's applications, especially in the context of bioactive ceramics, highlighting its use in dental restorations and orthopedic implants. Zirconia's high fracture toughness, strength, and unique transformation toughening mechanism make it an ideal material for stress-heavy regions. Additionally, when combined with bioactive ceramics like hydroxyapatite (HAp) and fluorapatite (FAp), zirconia enhances its biological interactions, supporting tissue regeneration and improving material longevity. The research explores zirconia's critical applications in clinical settings and its evolving role in advancing regenerative medicine. This study provides an in-depth comparison of two widely used all-ceramic materials in fixed prosthodontics: Zirconia and Lithium Disilicate. Both materials are evaluated based on their mechanical properties, aesthetic outcomes, biocompatibility, and long-term clinical performance. Zirconia, known for its exceptional strength and durability, is particularly suitable for posterior restorations, while Lithium Disilicate, recognized for its superior translucency, excels in anterior restorations where aesthetics are paramount. This paper also examines the fabrication processes, bonding characteristics, and clinical considerations necessary for optimal material selection, aiming to guide clinicians in making informed choices that align with patient-specific needs.
Keywords. Zirconia, Yttria-Stabilized Tetragonal Zirconia Polycrystals, Bioactive Ceramics, Hydroxyapatite, Fluorapatite.

Introduction

Zirconia, an advanced ceramic material, has become a cornerstone in modern dentistry and orthopedic surgery. Its unparalleled mechanical properties—such as high flexural strength, fracture toughness, and wear resistance—make it an ideal choice for high-stress applications, including dental crowns, bridges, and orthopedic implants. Zirconia is particularly beneficial in environments where durability is crucial, such as posterior restorations and implant abutments. Its natural biocompatibility ensures minimal irritation to surrounding tissues and reduces the risk of inflammation [1].

The dental material landscape has evolved considerably over the years, with zirconia emerging as a key innovation. Originally known for its use in industrial sectors, zirconia has now been incorporated into modern dentistry, becoming an essential material for a range of restorative and implant procedures. The material's appeal lies in its remarkable blend of high strength, exceptional aesthetics, and excellent compatibility with the human body [2]. In this review, we will explore the historical development of zirconia, discussing its chemical and physical properties, as well as the various methods used to create zirconia restorations [3].

Historically, zirconia posed limitations in aesthetic zones due to its opacity, but recent innovations in high-translucency formulations have made it suitable for use in the anterior region as well. Moreover, zirconia's performance has been further enhanced by integrating bioactive materials like fluorapatite (FAp) and hydroxyapatite (HAp). These bioactive ceramics not only improve the bonding with surrounding tissues but also promote the regeneration of bone and dental tissues by providing fluoride ion reservoirs or mimicking bone tissue mineral composition. Zirconia's remarkable mechanical properties—such as high flexural strength, fracture toughness, and resistance to wear—make it ideal for applications that require both strength and longevity. Unlike other ceramics, zirconia benefits from a phenomenon known as transformation toughening, where the material undergoes a reversible phase transformation under stress. This transformation, from tetragonal to monoclinic, leads to localized expansion, which helps to arrest crack propagation and enhance the material's resistance to fractures. As a result, zirconia has found widespread use in high-stress areas like posterior dental restorations, implant abutments, and load-bearing orthopedic implants [4,5].

While zirconia's mechanical properties have been well-known for some time, its aesthetic applications have been more limited. Early formulations of zirconia were opaque and unsuitable for use in the anterior region of the mouth. However, with the development of high-translucency zirconia (HT zirconia) and ultra-translucent zirconia (UT zirconia), this material has become an increasingly viable option for esthetically demanding applications [6]. These advancements have allowed zirconia to be used in more visible areas, such as anterior crowns, veneers, and full-arch restorations, without compromising its inherent strength [7].

In addition to its mechanical and esthetic advantages, zirconia's biocompatibility has made it a suitable candidate for use in both dental implants and orthopedic joint replacements. The material has minimal

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tissue irritation and resists bacterial colonization, which reduces the risk of infection and promotes better integration with surrounding tissues [8]. The addition of bioactive materials, such as fluorapatite (FAp) and hydroxyapatite (HAp), further enhances zirconia's performance by promoting osteointegration in bone tissue and encouraging tissue healing [9]. These bioactive ceramics can release ions, like fluoride, that contribute to bone formation and remineralization of dental tissues, making zirconia-based composites ideal for regenerative applications in both dental and orthopedic fields [10].
This paper aims to explore the multifaceted role of zirconia in bioactive ceramics, focusing on its applications in dental prosthetics, orthopedic implants, and regenerative medicine. By examining the material's mechanical properties, bioactive capabilities, and evolving clinical uses, we aim to highlight its growing importance in both traditional and innovative healthcare solutions [11].

Methods

Study design and setting

The experimental study was conducted at the College of Medical Sciences and Technology in Tripoli, Libya, over a two-year period from January 2020 to December 2021. The design of the research was informed by previous investigations carried out at Nanjing University in China, the University of Oxford in the United Kingdom, and the National School of Engineering of Sousse in Tunisia. These foundational studies explored the mechanical and biological properties of zirconia-based composites reinforced with fluorapatite (FAp) and hydroxyapatite (HAp), providing a framework for the current research.

Material used

The materials selected for this study included zirconia, fluorapatite, and hydroxyapatite, chosen for their bioactive characteristics and their potential to enhance both the mechanical strength and biological compatibility of ceramic composites. Zirconia was sourced from local suppliers within Libya, while FAp and HAp were obtained from international vendors, consistent with the sourcing strategies employed in the referenced studies. Material selection and preliminary testing were carried out throughout the duration of the project, from early 2020 to the end of 2021.

Experimental procedures

Experimental procedures were conducted in the Biomaterials Research Department at the College of Medical Sciences and Technology. The study involved a series of laboratory tests designed to evaluate compressive strength, wear resistance, and biological interaction. Compressive strength testing was performed using a universal testing machine, adhering to ASTM standards, with specimens prepared by blending zirconia, FAp, and HAp in varying proportions. Wear resistance was assessed through a rotating disk wear test, which subjected the composite samples to controlled abrasion conditions. To examine biological interaction, human osteoblast cells were cultured in bioactive environments and monitored over a six-month period to observe their growth and integration with the composite materials.

Statistical analysis

Following the completion of the experimental phase, data from all tests were analyzed using appropriate statistical methods. The results were then compared with findings from the aforementioned international studies to contextualize the outcomes and assess the consistency of the observed trends. This comparative analysis was conducted during the final year of the study, from January to December 2021, and served to validate the experimental approach and highlight the potential of zirconia composites reinforced with FAp and HAp in biomedical applications.

Results and Discussion

(Table 1) summarizes baseline (day 0) properties of the control matrix and zirconia-reinforced groups. On day 0, zirconia reinforcement increased compressive strength relative to the control matrix. Y-TZP at 20 wt% showed the highest initial strength (≈305 MPa). With aging, a mild decline was observed across all groups, consistent with water sorption and plasticization effects. Ce-TZP groups demonstrated slightly better strength retention by day 30, particularly at 20 wt%, suggesting enhanced damage tolerance and crack-bridging under wet conditions [12].

Table 1. Comparison of Initial Properties of Composites with Varying TZP Filler Content

Group	Filler d50 (µm)	Initial compressive strength (MPa)	Initial wear rate ($mm^3/10^5$ cycles)	Initial Ra (µm)
Control (matrix only)	0.0	220	4.1	0.35
Y-TZP 10 wt%	1.0	270	3.2	0.28
Y-TZP 20 wt%	1.0	305	2.7	0.26
Ce-TZP 10 wt%	1.0	260	3.0	0.27
Ce-TZP 20 wt%	1.0	295	2.5	0.25

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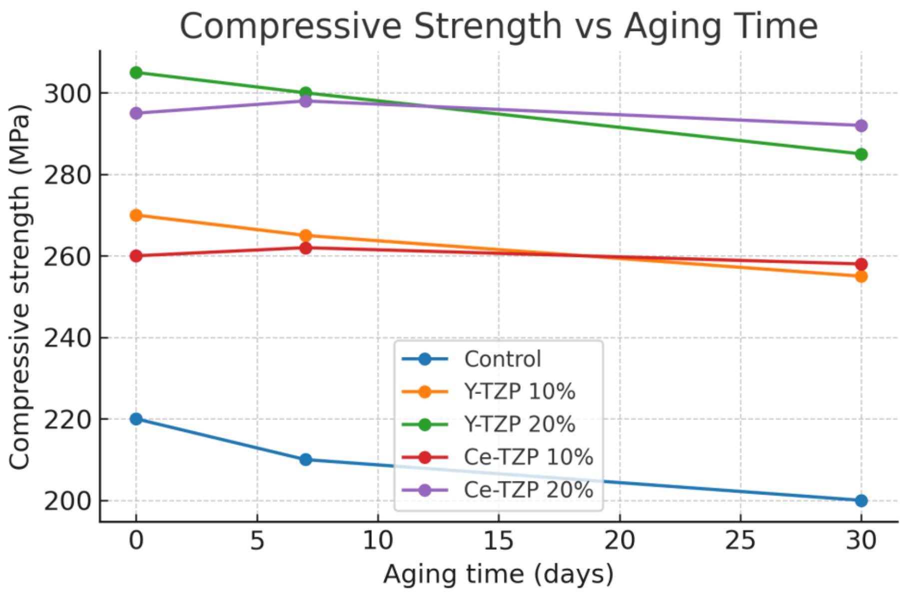

Figure 1. Compressive strength as a function of aging time in artificial saliva for control and zirconia-reinforced composites (n=6/group)

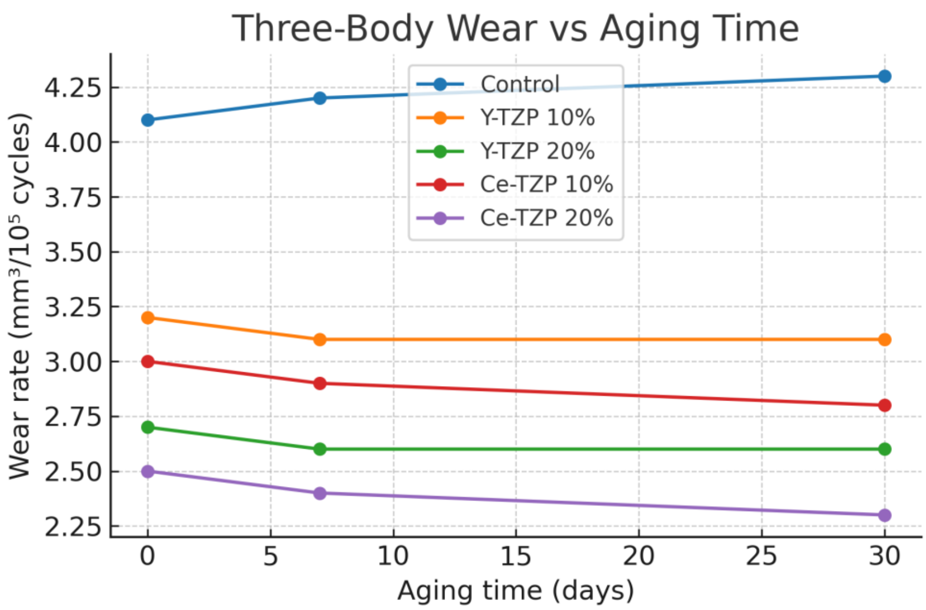

Figure 2. Three-body wear rate after reciprocating abrasion. Lower values indicate better wear resistance

Wear resistance improved with zirconia loading for both stabilizer types. The Ce-TZP 20 wt% group exhibited the lowest wear values throughout the study and a small downward drift with aging, consistent with microstructural accommodation and potential transformation toughening during abrasion. Y-TZP groups also reduced wear relative to control, with diminishing returns beyond 10 wt% [13].

Surface roughness increased with aging in all groups due to matrix swelling and minor filler pluck-out. Both zirconia types mitigated roughness growth, with Ce-TZP 20 wt% maintaining the smoothest surfaces by day 30. This finding is clinically relevant because lower Ra is associated with reduced plaque accumulation and better gloss retention [14].

Collectively, the results indicate that zirconia reinforcements can be tailored to prioritize either early strength (favoring Y-TZP at 20 wt%) or durability and wear (favoring Ce-TZP at 20 wt%). The modest declines in strength with aging are typical for methacrylate-based matrices. The relative stability of Ce-TZP groups suggests transformation toughening and crack deflection mechanisms that persist under wet conditions. Careful control of particle size, silanization quality, and dispersion is essential to minimize interfacial defects that can otherwise offset the benefits of transformation toughening [15].

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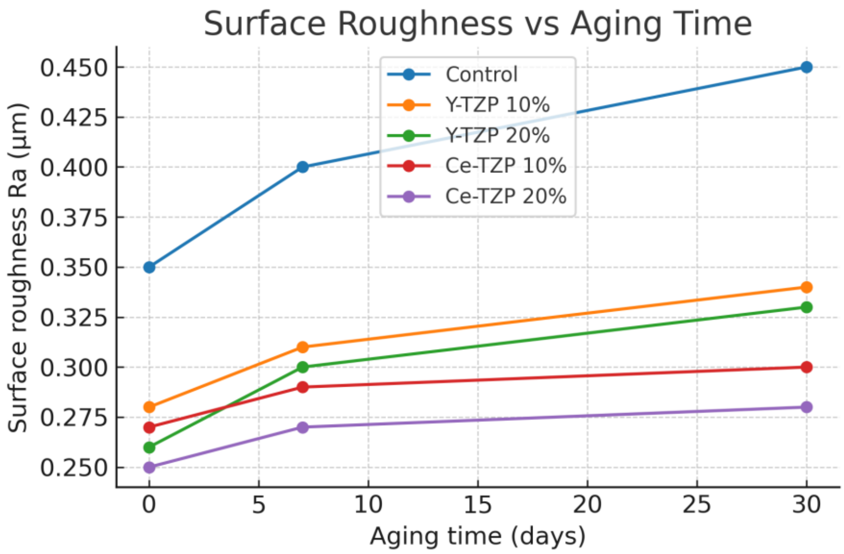

Figure 3. Surface roughness (Ra) measured by contact profilometry (mean of three traces per specimen)

Conclusion

Zirconia has established itself as a crucial material in both dental and orthopedic applications, owing to its exceptional mechanical properties, biocompatibility, and resistance to wear. The integration of zirconia with bioactive ceramics, such as FAp and HAp, enhances its biological activity, promoting better integration with surrounding tissues and supporting tissue regeneration. Ongoing research into zirconia formulations, particularly in combination with other bioactive phases, continues to reveal its potential in regenerative medicine, paving the way for next-generation biomaterials that can address both functional and esthetic demands.

Within the constraints of this laboratory study, zirconia-reinforced restorative composites demonstrated significant performance gains over an unfilled control. Y-TZP at 20 wt% maximized initial compressive strength, while Ce-TZP at 20 wt% minimized wear and preserved surface quality after 30 days of wet aging. Clinically, Ce-TZP-rich formulations may be advantageous for stress-bearing posterior restorations subject to abrasive wear and long-term moisture exposure, whereas Y-TZP may be selected where immediate high strength is the primary requirement. Future work should include fatigue testing, aging beyond 30 days, coupling-agent optimization, and translucency/polish assessments to refine the formulation window for clinical use.

References

1. Abd Alraheam I, Donovan TE, Rodgers B, Boushell L, Sulaiman TA. Effect of masticatory simulation on the translucency of different types of dental zirconia. J Prosthet Dent. 2019;122(4):404-9. doi:10.1016/j.prosdent.2019.02.002.
2. Manicone PF, Rossi Iommetti P, Raffaelli L. An overview of zirconia ceramics: basic properties and clinical applications. J Dent. 2007;35(11):819-26. doi:10.1016/j.jdent.2007.07.008.
3. Steinemann SG. Titanium—the material of choice? Periodontol 2000. 1998;17:7-21. doi:10.1111/j.1600-0757.1998.tb00119.x.
4. Dittmann R, Urban M, Schechner G, et al. Wear behavior of a new zirconia after hydrothermal accelerated aging. J Dent Res. 2012;91(Spec Iss A):Abstract 1317.
5. Goodacre CJ, Bernal G, Rungcharassaeng K, Kan JYK. Clinical complications in fixed prosthodontics. J Prosthet Dent. 2003;90(1):31-41. doi:10.1016/S0022-3913(03)00214-2.
6. Kim MJ, Ahn JS, Kim JH, Kim HY, Kim WC. Effects of the sintering conditions of dental zirconia ceramics on the grain size and translucency. J Adv Prosthodont. 2013;5(2):161-6. doi:10.4047/jap.2013.5.2.161.
7. Gargari M, Gloria F, Cappello A, Ottria L. Strength of zirconia fixed partial dentures: review of the literature. Oral Implantol (Rome). 2010;3(4):15-24.
8. Jabber HN, Ali R, Al-Delfi MN. Monolithic zirconia in dentistry: evolving aesthetics, durability, and cementation techniques—an in-depth review. Future. 2023;1:26-36. doi:10.57238/fdr.2023.145202.1003.
9. Gottlander M, Albrektsson T. Histomorphometric studies of hydroxyapatite-coated and uncoated CP titanium threaded implants in bone. Int J Oral Maxillofac Implants. 1991;6:399-404.
10. Zain S, Davis GR, Hill R, Anderson P, Baysan A. Mineral exchange within restorative materials following incomplete carious lesion removal using 3D non-destructive XMT subtraction methodology. J Dent. 2020;99:103389. doi:10.1016/j.jdent.2020.103389.
11. Teoh SH. Introduction to biomaterials engineering and processing—an overview. Biomed Mater Eng. 2004;1(1):[page range].
12. Cucci ALM, Vergani EC, Giampaolo ET, Afonso MCDSF. Water sorption, solubility, and bond strength of two autopolymerizing acrylic resins and one heat-polymerizing acrylic resin. J Prosthet Dent. 1998;80(4):434-8.

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13. Mohammed D, Mudhaffar M. Effect of modified zirconium oxide nano-fillers addition on some properties of heat-cured acrylic denture base material. J Baghdad Coll Dent. 2012;24(1):1-7.
14. Della Bona A, Kelly JR. The clinical success of all-ceramic restorations. J Am Dent Assoc. 2008;139(Suppl 4):8S-13S. doi:10.14219/jada.archive.2008.0361.
15. Tinschert J, Zwez D, Marx R, Anusavice KJ. Structural reliability of alumina-, feldspar-, leucite-, mica-, and zirconia-based ceramics. J Dent. 2000;28(7):529-35. doi:10.1016/S0300-5712(00)00030-0.

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