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Bioceramic Materials in Fixed Prosthodontics: A Comprehensive Review

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Abstract

Bioceramic materials are widely used in fixed prosthodontics due to their favorable mechanical properties, excellent biocompatibility and superior esthetics. The development of advanced ceramic systems has enabled clinicians to fabricate durable, metal-free restorations that closely mimic the optical and functional characteristics of a natural tooth. Contemporary dental bioceramics include glass-based ceramics, glass-infiltrated ceramics, polycrystalline ceramics and hybrid resin-ceramic materials. This review summarizes the evolution, classification, composition, microstructural characteristics, fabrication techniques and mechanical properties of commonly used materials such as zirconia, lithium disilicate, alumina ceramics and hybrid ceramics. Special attention is given to digital manufacturing technologies, including CAD/CAM systems and emerging additive manufacturing approaches that significantly improves precision, marginal fit, and reproducibility of ceramic restorations. The article also discusses optical properties, adhesion protocols, and cementation strategies that influence the long-term success of bioceramic restorations. Clinical applications and survival outcomes reported in the literature are also reviewed to highlight the reliability of these materials in contemporary prosthodontic practice. Finally, recent innovations such as nanoceramic composites, bioactive ceramics, and antibacterial surface modifications are discussed as potential future directions in dental materials research. Bioceramic materials continue to shape fixed prosthodontics by providing restorations that combine strength, esthetics and biological compatibility. Ongoing advancements in material science and digital dentistry are expected to further expand their clinical applications and improve long term treatment outcomes.

1. Introduction

The evolution of fixed prosthodontics has gradually shifted from traditional metal-based systems toward all-ceramic restorations driven by patient's growing demand of highly esthetic, biocompatible and metal-free alternatives. [1,2] Bioceramic materials—engineered ceramics specifically designed for biological applications—have become increasingly important because of their ability to mimic natural tooth properties while maintaining superior strength and stability in the oral environment. [3,4]

Initially introduced in implantology and endodontics, bioceramics now play a central role in crown, bridge and implant-supported prosthesis fabrication. [5] The integration of CAD/CAM systems, digital workflows, and adhesive bonding

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technology has further broadened their applicability.

The purpose of this review is to evaluate the classification, composition, fabrication, mechanical and optical behavior, cementation strategies, clinical performance and future directions of bioceramic materials used in fixed prosthodontics.

2. Materials And Methods

An electronic literature search was conducted using PubMed, Scopus and Web of Science databases covering publications from 1990 to 2025. Keywords included- bioceramics, zirconia, lithium disilicate, CAD/CAM restorations, fixed prosthodontics, dental ceramics, cementation, marginal fit.

Inclusion criteria were English-language peer-reviewed articles, systematic reviews and laboratory and clinical studies focusing on bioceramic materials in fixed prosthodontics. Exclusion criteria included studies on temporary restorations, resin composites and non-prosthodontic bioceramic applications.

Relevant data were organized and synthesized into thematic sections summarizing classification, properties, fabrication, clinical outcomes and innovations.

3. Classification of Bioceramics in Fixed Prosthodontics

Table 1: Bioceramics can be classified based on composition and microstructure: [6,7]

Category	Examples	Key Characteristics
Glass-based ceramics	Feldspathic porcelain, Leucite-reinforced ceramics, Lithium disilicate	Excellent esthetics, moderate strength
Glass-infiltrated ceramics	In-Ceram Alumina, In-Ceram Spinell	Improved strength with reduced translucency
Polycrystalline ceramics	Alumina, Yttria-stabilized Zirconia (3Y-TZP, 4Y-PSZ, 5Y-PSZ)	High fracture toughness, opaque appearance
Hybrid/resin-infiltrated ceramics	Vita Enamic, Lava Ultimate, Cerasmart	Intermediate strength, improved

Each category offers a distinct balance between optical and mechanical properties, influencing material selection for specific clinical scenarios.

4. Composition and Microstructural Features

4.1 Glass-Based Ceramics

Feldspathic and lithium disilicate ceramics possess a silica-based glass matrix with crystalline reinforcements. Lithium disilicate ($Li_2Si_2O_5$), with its fine crystalline microstructure, exhibits flexural strength of 360–400 MPa and superior translucency—ideal for anterior restorations. [8,9]

4.2 Polycrystalline Ceramics

Zirconia (ZrO_2), stabilized with yttria, exists in three crystal phases: monoclinic, tetragonal, and cubic. Transformation toughening from tetragonal to monoclinic phases at crack tips provides outstanding fracture resistance (900–1200 MPa flexural strength). [10–12]

4.3 Hybrid Bioceramics

Hybrid ceramics combine a sintered ceramic network with a polymeric matrix, offering elastic modulus similar to dentin (20–30 GPa). This reduces brittleness and allows more conservative preparations. [13,14]

Advanced bioceramic materials and their clinical applications in fixed prosthodontics

Bioceramic materials used in fixed prosthodontics have evolved considerably over the last three decades. Modern dental ceramics are engineered with controlled microstructures that optimize strength, translucency, and bonding ability. While zirconia and lithium disilicate remain the most widely used materials, several additional ceramic systems contribute significantly to restorative dentistry. These include alumina-based ceramics, leucite-reinforced ceramics, resin-infiltrated hybrid ceramics and emerging nanoceramic materials. Each of these materials demonstrates unique structural characteristics that influence their clinical indications and long-term performance.

1. Zirconia-Based Bioceramics

Yttria-stabilized zirconia is considered one of the most significant breakthroughs in dental materials science. Zirconium dioxide (ZrO_2) exists in three crystallographic phases: monoclinic, tetragonal, and cubic. Stabilization with yttrium oxide allows the tetragonal phase to remain stable at oral temperatures. This structural stabilization gives rise to the phenomenon known as transformation toughening, in which the tetragonal phase converts to the monoclinic phase when stress is applied at crack tips. The resulting volumetric expansion produces compressive stresses that arrest crack propagation, thereby enhancing fracture resistance.

Conventional zirconia used in dentistry is 3Y-TZP (3 mol% yttria-stabilized tetragonal zirconia polycrystal), which exhibits flexural strengths ranging between 900–1200 MPa and fracture toughness values significantly higher than most other dental ceramics. Because of its exceptional mechanical properties, 3Y-TZP has traditionally been used in posterior restorations and long-span fixed dental prostheses.

Recent developments have led to the introduction of translucent zirconia materials, including 4Y-PSZ and 5Y-PSZ, which contain higher concentrations of cubic zirconia. The cubic phase improves light transmission and esthetic outcomes but slightly reduces mechanical strength compared with conventional zirconia. These new formulations allow zirconia to be used in anterior restorations where esthetics are critical.

Zirconia restorations are commonly fabricated using CAD/CAM technology, where partially sintered zirconia blocks are milled and subsequently sintered to full density. This digital workflow enables high precision, consistent marginal adaptation, and improved efficiency in prosthesis fabrication.

Clinical applications of zirconia include:

- Monolithic posterior crowns
- Long-span fixed dental prostheses
- Implant-supported prosthetic frameworks
- Custom implant abutments
- Full-arch prostheses
- Resin-bonded fixed partial dentures

Despite its superior strength, zirconia lacks a silica-based glass phase, making traditional hydrofluoric acid etching ineffective. Consequently, durable bonding requires airborne particle abrasion followed by the application of phosphate monomer (MDP)-containing primers or resin cements. Proper surface treatment significantly enhances the retention and long-term success of zirconia restorations.

2. Lithium Disilicate Glass Ceramics

Lithium disilicate ceramics represent one of the most successful glass-ceramic systems used in dentistry. These materials consist of a silica glass matrix reinforced with interlocking lithium disilicate crystals ($Li_2Si_2O_5$), which occupy approximately 60–70% of the microstructure. The elongated crystal morphology improves crack deflection and increases resistance to fracture.

Lithium disilicate ceramics typically exhibit flexural strength values of 360–400 MPa, making them significantly stronger than traditional feldspathic porcelain while maintaining excellent translucency and color stability. These characteristics make lithium disilicate particularly suitable for highly esthetic restorations in both anterior and posterior regions.

One of the major advantages of lithium disilicate ceramics is their predictable adhesive bonding capability. Surface treatment using hydrofluoric acid etching followed by silane coupling agents produces strong micromechanical and chemical bonds with resin cements. This adhesive interface enhances fracture resistance and allows for more conservative tooth preparations.

Lithium disilicate restorations can be fabricated through heat-pressing techniques or CAD/CAM milling systems, providing versatility in clinical workflows.

Common clinical applications include:

- Anterior crowns and veneers
- Posterior single crowns
- Short-span anterior fixed dental prostheses
- Implant-supported crowns
- Inlays, onlays, and overlays
- Partial coverage restorations

Long-term clinical studies have reported survival rates exceeding 94% over ten years, demonstrating the reliability of lithium disilicate restorations when proper case selection and adhesive protocols are followed.

3. Alumina-Based Ceramics

Alumina-based ceramics were among the earliest high-strength ceramic materials developed for dental applications. These ceramics consist primarily of densely packed aluminum oxide (Al_2O_3) crystals, which provide high compressive strength and excellent resistance to fracture. Early systems such as In-Ceram Alumina utilized slip-casting methods followed by glass infiltration to produce a reinforced ceramic structure.

Alumina ceramics exhibit flexural strengths in the range of 450–600 MPa, which represented a significant improvement over conventional porcelains at the time of their introduction. However, their relatively low translucency limited

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their esthetic performance, particularly in anterior restorations.

With the development of zirconia-based ceramics offering superior strength and improved esthetics, the use of alumina frameworks has declined. Nevertheless, alumina ceramics played an important role in the transition from metal-ceramic restorations to metal-free prosthodontic systems.

Historical and limited contemporary applications include:

- Core frameworks for porcelain-veneered crowns
- Short-span fixed dental prostheses
- Single crowns in posterior regions

Despite being largely replaced by zirconia systems, alumina ceramics remain significant in the historical evolution of all-ceramic restorative materials.

4. Leucite-Reinforced Glass Ceramics

Leucite-reinforced ceramics were developed to enhance the mechanical performance of traditional feldspathic porcelains while preserving excellent esthetic qualities. The incorporation of leucite crystals within the glass matrix increases resistance to crack propagation and improves flexural strength.

These ceramics demonstrate flexural strength values typically ranging between 120–160 MPa, which is higher than conventional porcelains but lower than lithium disilicate ceramics. Their high translucency and enamel-like optical properties make them particularly suitable for restorations in the esthetic zone.

Leucite ceramics are highly amenable to adhesive bonding techniques due to their silica-based glass matrix, allowing hydrofluoric acid etching and silane coupling to create durable bonds with resin cements.

Common clinical applications include:

- Porcelain laminate veneers
- Anterior crowns
- Inlays and onlays
- Esthetic laminate restorations

Although lithium disilicate ceramics have largely replaced leucite-reinforced materials in many clinical situations, leucite ceramics remain valuable for minimally invasive esthetic restorations.

5. Hybrid and Resin-Infiltrated Bioceramics

Hybrid ceramics represent a newer category of restorative materials designed to combine the favorable properties of ceramics and polymers. These materials are produced using polymer infiltration of ceramic networks (PICN) or resin nanoceramic technologies, resulting in a dual-network structure that integrates ceramic rigidity with polymer resilience.

The elastic modulus of hybrid ceramics typically ranges between 20–30 GPa, which is closer to that of natural dentin compared with traditional ceramics. This similarity allows improved stress distribution during occlusal loading and may reduce the risk of catastrophic fracture.

Another advantage of hybrid ceramics is their excellent machinability during CAD/CAM milling, which allows efficient chairside fabrication with minimal tool wear. Additionally, these materials exhibit favorable wear characteristics against opposing dentition.

Common clinical applications include:

- CAD/CAM fabricated crowns
- Inlays and onlays
- Occlusal veneers
- Implant-supported crowns in low-load situations
- Minimally invasive restorations

However, long-term clinical evidence for hybrid ceramics is still emerging, and further studies are needed to evaluate their durability under high functional loads.

6. Emerging Nanoceramic and Bioactive Ceramics

Recent research in dental materials science has focused on the development of nanostructured ceramics and bioactive ceramic systems. Nanoceramic materials incorporate nanoscale ceramic particles within a polymer or glass matrix, improving mechanical strength, polishability, and wear resistance. The uniform distribution of nanoparticles enhances fracture resistance and improves surface smoothness, contributing to long-term esthetic stability.

Bioactive ceramics, including calcium silicate and hydroxyapatite-based materials, have demonstrated the ability to interact with biological tissues and promote mineral deposition. These materials may release calcium and phosphate ions, which can stimulate remineralization and improve the biological integration of prosthetic restorations.

Emerging research is also exploring antibacterial surface modifications, where ceramic surfaces are functionalized with antimicrobial nanoparticles to reduce bacterial colonization and plaque accumulation.

Potential future applications include:

- Bioactive implant abutments
- Restorations capable of releasing therapeutic ions
- Antibacterial prosthetic surfaces
- Regenerative prosthodontic materials

Although many of these technologies are still under investigation, they represent promising directions for the next generation of dental bioceramics.

Table 2: Comparison of Major Bioceramic Materials

Material	Microstructure	Flexural Strength	Typical Applications
Feldspathic porcelain	Glass-based ceramic	60–120 MPa	Veneers, anterior crowns
Leucite-reinforced ceramics	Glass with leucite crystals	120–160 MPa	Veneers, inlays, onlays
Lithium disilicate	Glass ceramic with lithium crystals	360–400 MPa	Crowns, veneers
Alumina ceramics	Polycrystalline alumina	450–600 MPa	Core frameworks
Zirconia (3Y-TZP)	Polycrystalline zirconia	900–1200 MPa	Crowns, bridges, implants
Hybrid ceramics	Polymer-infiltrated ceramic network	150–200 MPa	CAD/CAM restorations

5. Fabrication Techniques

5.1 Hot Pressing and Sintering

Pressable ceramics, such as IPS e.max Press, are fabricated using heat and pressure to produce dense, homogeneous restorations with optimal esthetics [15].

5.2 CAD/CAM Milling

Digital milling systems enable precise fabrication of monolithic restorations with reproducible marginal integrity and reduced human error [16,17]. Pre-sintered zirconia blocks are milled in oversized form and subsequently sintered to full density.

5.3 Additive Manufacturing

Recent developments in 3D printing—including stereolithography and binder jetting—have shown promise in producing complex ceramic geometries with improved efficiency [18,19].

6. Mechanical Properties

Key parameters influencing clinical performance include flexural strength, hardness, fracture toughness, and wear resistance.

Table 3: Mechanical Properties

Material	Flexural Strength (MPa)	Fracture Toughness ($MPa \cdot m^{1/2}$)	Elastic Modulus (GPa)
Feldspathic Porcelain	60–120	1.0	60–65
Lithium Disilicate	360–400	2.5–3.0	95
Alumina	500	4.0	380
Zirconia (3Y-TZP)	900–1200	5–10	210
Hybrid Ceramics	150–200	1.5–2.0	25–30

Zirconia demonstrates superior mechanical performance, while lithium disilicate offers a balance between esthetics and strength [20–23].

7. Optical and Biological Properties

Translucency and color stability are vital for esthetic restorations. The introduction of multilayered and cubic-phase zirconia (5Y-PSZ) has enhanced translucency without compromising strength [24,25].

Bioceramics also exhibit excellent tissue compatibility, low plaque accumulation, and minimal ion release, promoting healthy gingival margins and soft tissue integration[26,27].

8. Adhesion and Cementation Protocols

Cementation varies with ceramic type [28,29]:
Glass-based ceramics: etched with 5–10% hydrofluoric acid, silanated, and bonded using dual-cure resin cements.

Zirconia: air abrasion with 50 µm alumina, followed by application of MDP-containing primers or cements (e.g., Panavia V5).
Hybrid ceramics: can be both etched and silanated, allowing strong micromechanical and chemical bonding. Proper bonding improves marginal seal, retention, and fracture resistance, crucial for long-term clinical success [30–32].

9. Marginal Fit and Clinical Performance

CAD/CAM systems have significantly improved marginal adaptation, with gaps typically ranging between 30–80 µm, within clinically acceptable limits [33,34].
Long-term clinical studies report survival rates of:
Lithium disilicate crowns: 94–96% at 10 years [35,36].
Monolithic zirconia restorations: >95% at 10 years, with minimal chipping [37,38]
Failures are mainly related to cementation errors or veneering fractures rather than core failure [39].

10. Limitations and Challenges

a. Despite advancements, several challenges persist:
b. Brittleness of veneered ceramics
c. Low-temperature degradation (aging) in zirconia
d. Technique sensitivity during cementation
e. High production cost and equipment dependency [40–42]
f. Research continues toward enhancing bonding reliability, reducing aging, and improving optical properties without sacrificing strength [43].

11. Future Perspectives

a. Future innovations include:
b. Bioactive ceramics capable of stimulating remineralization and tissue bonding
c. Nanoceramic composites with improved flexural strength and translucency
d. 3D printed gradient ceramics for patient-specific restorations
e. Surface-functionalized ceramics with antibacterial properties [44–46]
f. Integration of AI-assisted design and machine learning-based predictive modeling may further refine prosthodontic outcomes.

12. Conclusion

Bioceramic materials have transformed fixed prosthodontics, providing restorations that are durable, esthetically superior, and biologically harmonious. Continuous research into nanoengineering, surface modification, and digital fabrication promises even greater clinical success. Proper material selection, adherence to manufacturer-specific cementation protocols, and evidence-based clinical execution remain the keys to longevity and success of bioceramic restorations.

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