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Bioactive Ceramics: A State-of-Art Survey

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Abstract

In nanotechnology, materials and systems are designed at the nanoscale to have unique physical and chemical properties such as low density, high thermal conductivity, or other properties which are not found in nature. The method and conditions utilized to create a nanomaterial, such as the particle size, porosity, and particular surface area, primarily define the structure of the substance. Ceramics are crystalline, whereas glasses are amorphous. Apatite crystallizes on the surfaces of glass-ceramics when calcium ions are present in the blood, so it appears that bioactive glass-ceramics are made by performing a number of steps, including creating a microstructure from dispersed crystals within the residual glass, which provides strength high bending strength. The hydrated silica causes apatite crystals to form on glass and ceramic surfaces. Due to their bioactivity and biocompatibility, these glasses are being used as implants in the human body to repair and replace broken or ill bones. Bioactive glasses are osteoconductive and osteoinductive materials because they promote the growth of new bone both at the bone-implant interface and within the implant itself. In this work, we investigated mechanical characteristics, apatite production methods, and possible orthopedic surgical applications for bioactive glass-ceramic, including load-bearing devices.

Introduction

The term “ceramic materials” refers to glass-ceramics, inorganic glasses, and ceramics together. Ceramics and glasses are related to metals, but they are not the same. Both have great strength, hardness, elastic modulus, and chemical inertness [1,2]. They are effective electrical and thermal insulators. Despite being crystalline, tougher, stronger (especially in compression), stiffer, and having a higher melting point than metals, ceramics are frequently more brittle and electrically and thermally insulating than metals [3]. Inorganic glasses manufactured from or related to ceramics are often transparent to light, yet although having comparable physical properties, they have vastly differing optical properties [4]. Glass-ceramics are more comparable to ceramics than glasses because they are crystalline materials created from amorphous inorganic glasses through a process known as devitrification [5,6]. Ceramics and glasses are difficult to fabricate into large and complex forms due to a number of qualities that make them desirable for certain functional features and harsh operating circumstances [7]. Aside from having different physical, electrical, thermal, optical, and chemical qualities from metals that make them more appealing, ceramics and glasses typically require coupling with metals in devices or structures where structural integrity is crucial. Therefore, it’s crucial to combine metals with various ceramics or glasses [8].

Medical devices are made from a wide range of materials, and each chemical will have some sort of interaction with the biological environment. These substances are frequently known as biomaterials [9]. A biomaterial is an artificial substance created with the intention of coming into contact with living tissue [10]. The majority of biomaterials are still synthetic and utilized as implants to repair diseased or damaged tissues, despite significant advancements in fields like tissue engineering [11]. Biomaterials are a broad category of substances that may be organic or inorganic, natural or manufactured, metal, polymer, or ceramic [12].

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Bioactive glasses and glass-ceramics have been developed in response to the need to restrict interfacial mobility in implanted bio inert ceramics [13]. Hench suggested in 1967 that research be done to modify the chemical composition of glasses in order to allow contact with the physiological system and create a chemical link between live tissue and the implant surface [14]. The replacement of hard tissues in the body, such as knee and hip joint prostheses, is the most common use of biomaterials. Another common use of biomaterials is to treat dental hard tissues, particularly enamel and dentine [15]. Despite the fact that bio ceramics are frequently used for bone replacement, people are more likely to learn about them when they need dental care [16,17].Enamel and dentine, which make up teeth, are not like bone in that they cannot repair themselves after being harmed by conditions like caries and periodontal disease [18].There is an increasing need for appealing tooth-like restorations due to the millions of people who seek dental treatment each year [19,20]. Ceramics are well suited to meet this need, and dental materials are one of the fastest-growing applications for bio ceramics [21,22].

This study aims to generalize prior discoveries on the preparation, characteristics, and medical applications of bioactive ceramics. The author would also investigate how bioactive ceramics may be tested more effectively in a lab to examine how the mechanical characteristics change for therapeutic uses.

Bioactive glasses and glass-ceramics

Surface reactive glass-ceramic biomaterials known as bioactive glasses include the original bioactive glass, Bioglass® [23]. These glasses are utilized as implant devices in the human body to replace and fix damaged or ill bones due to their bioactivity and biocompatibility [24]. “Because they encourage new bone formation within the implant and away from the bone-implant interface, bioactive glasses are both osteoconductive and osteoinductive materials”[25]. Glass is a state of matter and a subset of the solid state, not a specific component. Covalent interactions with oxygen atoms hold the network of atoms that make up glass together [26]. Silica tetrahedral are randomly joined together to form a silica-based glass, as illustrated in Figure 1 Glass-ceramic materials are polycrystalline solids with a remnant glassy phase that results from the controlled crystallization of glasses [27]. The most frequent figure of crystallinity, which ranges from 0.5 to 99.5 percent, is between 30 and 70 percent. It may be mass produced using any glass-forming technique. The material’s Nano- or microstructure can be designed. Most are completely or very sparsely porous. You may combine and match the needed qualities [26].

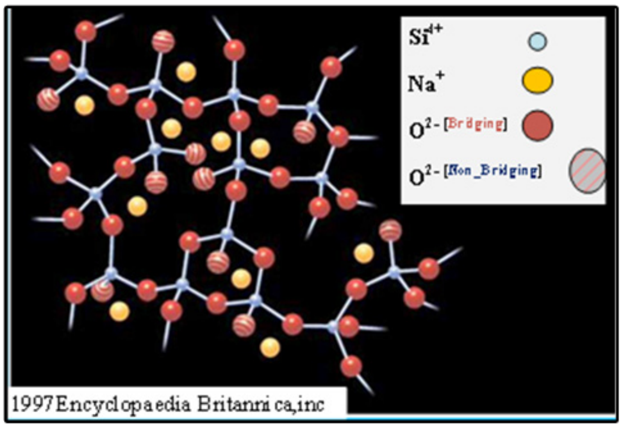


Figure 1: Atoms held together by covalent bonds in a glass network.

Soda-lime-silica (Na_2O-CaO-SiO_2) is a common combination used to make window glass [28]. Although in less quantities than in inert glasses, these elements can also be found in bioactive glasses. Silicate-based glasses, which dissolve in bodily fluids and can function as therapeutic ion transfer channels, make up the vast majority of bioactive glasses [29]. Bioactive Glass stands out from conventional synthetic bone grafting biomaterials due to its anti-infective and antigenic properties (such as hydroxyapatite, biphasic calcium phosphate, and calcium sulfate) [30]. Due to the oxygen atoms in Figure 2. That act as bridges. Connect the two neighboring polyhedral below; the strength of the network depends on the number of oxygen atoms that may be used as a bridge.

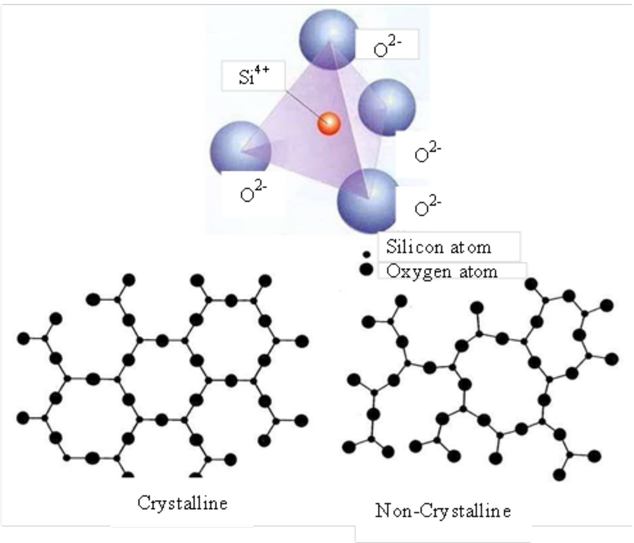


Figure 2: Network connection quantity of oxygen atoms.

Mechanism of apatite genesis in bioactive ceramics

Bioactive Glass is implanted into the bone cavity and activated by interacting with physiological fluids [31]. The bioactive Glass goes through a number of chemical reactions during this activation phase that create the ideal conditions for bone regrowth via osteoconduction [32]. It releases ions like Na, Si, Ca, and P. The surface of the bioactive glass forms a layer of silica gel. The surface of the bioactive Glass becomes covered in hydroxyapatite as a result of CaP crystallization [33]. The bioactive glass interacts with biological components including blood proteins, growth factors, and collagen once the hydroxyapatite layer has formed. This interactive, osteoconductive, and osteostimulative process results in new bone formation onto and between the bioactive glass structures [34]. Binding to bone, Bioactive Glass encourages the growth of new bone. Activating osteogenic cells is the first step in osteostimulating bone rebuilding [35]. Bioactive Glass's radio-dense properties allow for post-operative evaluation. In the last transformation stage, the process of bone remodeling and regeneration continues [36]. The patient's original structure is eventually restored when the bone fully regenerates over time and consolidation of the bones occurs. Bioactive glass keeps repairing into bone over time. Li et al. (1991) found that sol-gel produced bioactive glasses with no Na2O were more bioactive than melt formed bioactive glasses with the same composition, contrary to Hench and West's (1996) assertion that "Na_2O concentration of bioactive glasses impacts the rate of HCP synthesis [37]. Increased bioactivity is influenced by the number and size of pores in the gel [38]. Because of this, the presence of Na_2O does not indicate bioactivity. As Na_2O concentration rose, Tg and the peak crystallization temperature linearly dropped. CaO does not change the

NC when Na_2O is substituted in a glass. This alteration, however, has an impact on atomic packing. The density of the glass decreases as the Na_2O concentration increases due to the widening of the glass network. Because of this property, Na_2O is referred to as a network disrupter [39].

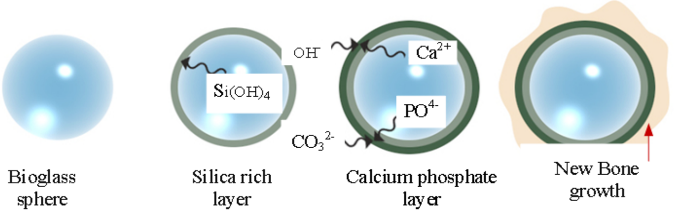


Figure 3: Biological interaction of bioactive ceramics with bone [40].

The bioactive properties of bioglass are derived from the material's ability to form a bone-like mineral layer as shown above Figure 3 on its surface hydroxyl-carbon-apatite (HCA) [41]. As the bioactive glass particles break down in vivo, the ions they create interact with the local ions to form an HCA coating on the surface. The HCA layer forms a chemical bond between the bioactive glass particles and the surrounding bone because it resembles bone minerals. Each set of bioactive glasses has its own composition and is divided into subgroups [42]. Some bioactive glasses, such Bioglass (45S5), are now being used intraorally as a bone grafting material with FDA approval. 45S5 bioactive Glass is made up of SiO_2 (46.1 mol%), CaO (26.9 mol%), Na_2O (24.4 mol%), and P_2O_5 (2.6-mole percent). In less than two hours, 45S5 can create HCAP (hydroxyl carbonated apatite) by attaching to tissues [43].

Network connectivity of bio ceramics

Since they join two nearby polyhedral, the number of bridging oxygen atoms affects network connectivity (NC). NC can be utilized to evaluate a glass's bioactivity, surface reactivity, and solubility [34]. Conversely, a greater NC value suggests that the glass has a low Tg but a higher solubility and reactivity. NC is a valuable tool for creating novel glasses with a variety of compositions for a range of purposes. Phosphate precipitates apatite in physiological solutions and is present in BG as a distinct orthophosphate phase. Aside from phosphate content, as shown from Figure 4 [44] below network polymerization has a major impact on glass dissolving and apatite formation, and NC or split network models are useful and successful in predicting bioactivity [45].

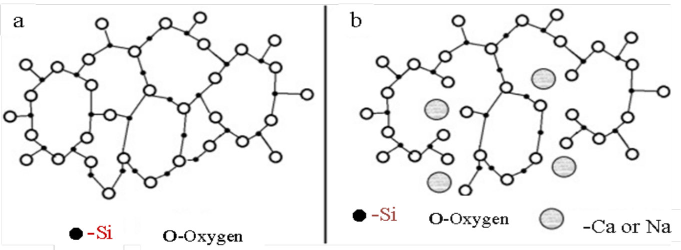


Figure 4: Schematic representation of **(a)**. Si-based glass **(b)**. Bioactive ceramics.

Bioactive ceramics are polycrystalline materials created by controlled crystallization of glass, and they can include up to 90% by volume of crystals embedded in the glass phase. According to the Nc model, the bridging oxygen atoms in glass are randomly distributed, and their relative concentrations control the likelihood that one atomic unit will link covalently through bridging oxygen with another [36,37]. Hydrolytic stability, bioactivity, and mechanical properties of glass are all directly impacted by the distribution of bridging and non-bridging species (fracture toughness, hardness) [44]. Low molecular mass structural units in silicate glasses are more likely to exist and can migrate into solutions [46]. As a result, glass solubility rises as network connection deteriorates. Glass systems with few network connections might therefore be bioactive. Because of their exceptional resistance to disintegration, glasses and glass-ceramics with Nc values greater than 2.6 are referred to be non-bioactive materials [32,47].

Bioactive ceramics' synthesis techniques

As shown in Table 1. Below, there are now around five macro-classes of manufacturing processes accessible for the production of bioactive ceramics. Since the ultimate goal is to get a particular composition capable of providing controlled bioactive activity, which is vital in potential therapeutics, several criteria are considered in order to select the optimum manufacturing procedure.

Table 1: Techniques for making bioactive ceramics.

No.	Method	Advantage	Disadvantage	Reference
1	Melt-quenching technique	• There is mass production	• These glasses' nonlinear properties • Nanoparticle surface imperfections and an impure semiconductor composition • Utilized to get around the inability of this method to produce thin films	[48-51]
2	Sol-Gel	• Best suited for deposition on a variety of substrates, including glass wool and silica/glass rushing rings. • Straightforward homogeneity, repeatability, affordable cost, dependability, and controllability • On substrates with complex forms and a large surface area, films can be easily fixed.	▪ A lengthy deposition period ▪ A dense coating of Nanoparticles cannot be attached to the substrate. ▪ Forming anatase nanocrystals at a high temperature ▪ High cost of fabrication	[52-62]
3	Spray pyrolysis	• Continuous process • Has shorter processing times • No vacuum needed • Generate supplies by synthesizing them as powders and films.	• Scaling up is difficult. • Low yield • Difficulties determining the growing temperature	[63-70]
4	Spray Drying	• Continuous and fully automated. • Suitable for both heat-resistant and heat-sensitive goods. • It is possible for spherical particles.	• Not established particles with microstructures. • Rapid dosage form rates and outcomes pop.	[71-73]

5	Modified Stöber	▪ Produce nearly monodisperse silica particles ▪ Provides an excellent model for investigating colloidal phenomena ▪ Enabling the manufacture of controlled-size spherical monodisperse silica particles	▪ Aerogel is delicate.	[74-76]

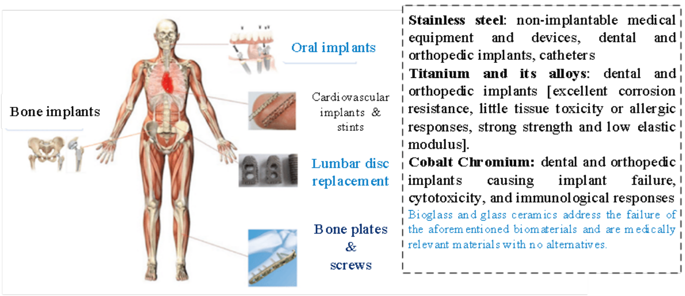
Clinical application

In medical applications, biomaterials-natural and synthetic-are utilized to repair, improve, or replace damaged tissue or biological processes. A modern discipline called "biomaterials" merges medicine with biology, physics, chemistry, and more recently, tissue engineering and materials science. The term "biomaterial," as employed in a medical device to interact with biological processes, was first used by the European Society of Biomaterials in 1987. Metals and metal alloys, bio stable plastics, bio absorbable polymers, bio composite polymers/ceramics, bio ceramics, collagen, and extracellular matrices are typical orthopedic materials [77]. They are effective and enhance the recipient's life, although they frequently fall short. Biomaterials are successful in terms of their traits and functions, but they will never be as successful as the original substance. The synthetic materials bioglass and glass ceramics, which are used to replace or restore the function of biological tissues, come into frequent or sporadic contact with physiological fluids.

A vast variety of medical devices, including those for orthopedics, cardiovascular applications, wound healing, and many more, employ biomaterials. To implant biomaterials [78], a body must meet the following criteria: biocompatible chemical composition to reduce unfavorable tissue responses, adequate resistance to deterioration, sufficient strength to withstand the cyclic load on the joint, and excellent wear resistance.

Unquestionably one of the most lethal illnesses affecting people, cancer is becoming more and more common in the globe [79]. To date, the most widely utilized treatments for malignant tissue and metastases are chemotherapy, radiation, and heat [80]. Ceramics materials are regarded as effective platforms for the uptake and release of anticancer medicines because of their porous structure and highly controlled diameter (2-50 nm) [81,82]. The development of novel bioactive ceramics formulations with the capacity to inhibit the growth of new blood vessels, controlled by the release of anti-angiogenic ions or the delivery of anti-angiogenic drugs and chemicals, could be of great significance for the development of new therapeutic approaches against cancer [83]. Angiogenesis is essential for the proliferation and metastatic spread of cancer cells [84].

The majority of biomaterials are used in orthopedic implant devices [85]. Both osteoarthritis and rheumatoid arthritis wreak havoc on the synovial (freely moving) structures of the hip, knee, shoulder, ankle, and elbow. Such joints, especially weight-bearing joints like the hip and knee, can experience severe agony, which can have devastating effects on ambulatory function [86]. It has been possible to replace these joints with prostheses since the development of anesthetic, antisepsis, and antibiotics [87], and the reduction of pain and restoration of movement in hundreds of thousands of patients has been well-documented. It must be biocompatible to avoid having an adverse effect on the body or bodily fluids as a biomaterial for body implants [88]. Additionally, it should not be harmful or carcinogenic. Due to these limitations, many engineering materials are no longer available. The biomaterial must possess strong physical and mechanical properties in order to supplement or replace biological tissues. Biomaterials are used in medical applications because they are biocompatible and help patients heal more quickly [89], as seen in Figure 5 below.



Stainless steel: non-implantable medical equipment and devices, dental and orthopedic implants, catheters
Titanium and its alloys: dental and orthopedic implants [excellent corrosion resistance, little tissue toxicity or allergic responses, strong strength and low elastic modulus].
Cobalt Chromium: dental and orthopedic implants causing implant failure, cytotoxicity, and immunological responses
Bioglass and glass ceramics address the failure of the aforementioned biomaterials and are medically relevant materials with no alternatives.

Figure 5: The use of biomaterials in medical technology [90].

Parent glass and glass-ceramic, which largely precipitate apatite, have bending strengths of 72 and 88 MPa, respectively. Due to the precipitation of apatite, glass-ceramic has a high bending strength [88]. The amazing "bending strength" of glass-ceramic is due to its high fracture toughness, which is above or comparable to steel surgical implantation, as seen in the image above. The value of bioactive glass in modern medicine has surpassed that of food and medication as it becomes more complex and diversified for use in medicinal applications [91]. This means that, especially in orthopedic applications, the implant surface is crucial for preventing unwelcome deterioration and creating a favorable environment for cell proliferation and differentiation. It is possible to selectively and controllably modify the surface of biomaterials to increase their cytocompatibility [92], osteoconductive [93] characteristics, and bacterial resistance while maintaining their bulk qualities, such as strength and robustness. Additionally, it could be able to alter the surfaces of bioactive glass to improve stability and functioning, such as by targeting particular tissue types or cell types, releasing substances in response to stimulation, monitoring the distribution of drugs, and photo thermal therapy [94].

Concluding remarks and recommendations

This overview covers the what, why, and how of bioglass and glass-ceramics, as well as manufacturing processes, therapeutic uses, apatite formation, and bone-bonding properties. The bioglass and glass-ceramic materials in this review exhibit therapeutically acceptable mechanical properties, such as fracture toughness and flexural strength, and excellent osteointegration. However, the challenge of bulk nucleation using this approach and the scarcity of bioresorbable materials provide significant challenges for research and development. Despite the fact that freshly made chlorapatite GCs exhibit the necessary resorb ability and Osseo integration, more study is required to determine the substance's in vivo activity and mode of action. The author wishes to draw the conclusion that knowledge obtained from research on biomaterials, such as Glass and glass-ceramics, continues to astound and communicate new ideas in the structural solid-state covered in this book, with undeniably significant future potential. Glass-ceramic systems are not one-component systems, and the crystal composition differs from the parent glass. As a result, the leftover glass in the glass-ceramic must be designed differently than the parent glass. A glass-crystal composite may be obtained by heating glass. The content and size of the crystalline phase may be controlled, and have distinct challenges in surface coating since their thermal expansion coefficient does not match that of the substrate. In comparison to parent glass and sintered ceramic, a glass-ceramic can outperform it; the mechanical strength of monophasic bioactive ceramics is higher. The purpose of this essay is to demonstrate how the field of biomaterials research-more specifically, research on bioactive glass-ceramics-continues to astound and transmit novel ideas about the composition of solids, with an undeniably bright future. The relationship between structure and property, particularly the microstructure and mechanical qualities, has to be studied further.

Conflicts of Interest

The author declares that there are no conflicts of interest.

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