Int. J. Chem. Sci.: 14(3), 2016, 1339-1348
ISSN 0972-768X
www.sadgurupublications.com

BIOACTIVE GLASSES FOR TECHNOLOGICAL AND CLINICAL APPLICATIONS

K. RAVINDRANADH[*]

Physics Division, Department of Basic Sciences & Humanities, Chirala Engineering College,
CHIRALA – 523 157 (A.P.) INDIA

ABSTRACT

Corrosion resistant metals and insoluble, non-toxic polymeric materials became the standard biomaterials. Biomaterials are artificial or natural materials that are used to replace lost or diseased tissue and to restore form and function. Bioactive glasses are novel dental materials that are different from conventional glasses and are used in dentistry. Bioactive glasses are composed of calcium and phosphate, which are present in a proportion that is similar to the bone hydroxyapatite. Bioactive glasses have a wide range of applications. Bioglass also known as 45S5 is most commonly used for bone grafts. Bioactive materials, including bioactive glasses and glass-ceramics, are special compositions made typically from the Na_2O-CaO-MgO-P_2O_5-SiO_2 system. The potential range of biomedical applications of glass fibers encompasses the fields of muscle and ligament tissue engineering and nerve regeneration.

Key words: Biomaterials, Bioactive glasses, Composition, Technological, Clinical applications.

INTRODUCTION

The evolution of dentistry is closely associated with the advancements in dental materials. From the dawn of history dental practitioners have been in the quest of ideal restorative dental materials. Though initially ideal restorative materials were thought to be the one, which were biologically inert and hence biocompatible the past two decades have seen the emergence of bioactive materials as a promising alternative. The interaction between restorative dental materials and tooth tissue encompasses multiple aspects of dental anatomy and materials science. Until relatively recently, many adhesive dental restorative materials were thought to have a passive hard tissue interaction based on simple infiltration with the enamel or dentin upon which they were placed. However, there is increasing interest in mapping the interactions between materials and tooth tissues, where the former has a more aggressive interaction with the latter, while promoting bioactivity.

---

[*] Author for correspondence; E-mail: raomc72@gmail.com; Ph.: 0866-2453485

The first generation of materials used for tissue replacement was selected by surgeons and materials scientists and engineers to be as biologically inert as possible; therefore, they are called bio-inert materials. Corrosion resistant metals and insoluble, non-toxic polymeric materials became the standard biomaterials. However, all bio-inert materials are a compromise because of the incompatibility of the interface between the material and living tissue. Tissue breakdown and loosening over time is a common mode of failure of devices made from bio-inert materials. Stress shielding due to mismatch of elastic moduli of high strength biomaterials and bone leads to resorption of bone and long term implant failure and revision surgeries. Wear of articulating surfaces also leads to creation of wear debris and osteolysis leading to degradation of the interfacial supporting bone. An alternative, second generation concept for tissue replacement using a special type of glass was discovered in 1969. This concept of bioactivity has made it possible to expand greatly the approaches taken in tissue replacement. Bioactive materials form a bond with living tissues.

Biomaterials

Biomaterials are artificial or natural materials that are used to replace lost or diseased tissue and to restore form and function. Thus, the field of biomaterials has become an imperative area, as these materials are helpful in improvement of the quality and the longevity of human life. Nowadays, two main strategies are used to replace the missing or dysfunctional tissues: transplantation and implantation. In spite of the success of transplantation, the number of donors is limited and there are potential risks of disease transmission. To solve these issues, instead of transplantation, the dysfunctional tissues can be repaired by using implants made from biomaterials. Bioactive materials, e.g. bioactive ceramics and bioactive glass (BG), which can facilitate direct interfacial bond between implant and tissue without scar tissue formation, in contrast to conventional biomaterials, e.g. stainless steel and cobalt-chrome alloys, have been widely studied and used[1,2]. However, the bulk bioactive ceramics, like hydroxyapatite and BGs usually do not degrade rapidly enough and may remain in the human body for a long time. Hence, a different approach to the treatment has been proposed based on tissue engineering: rather than providing an implant as a replacement for the diseased tissue, a scaffold is implanted.

An ideal bioscaffold would not only provide a three dimensional (3D) structure to facilitate the regeneration of natural tissue, but also degrade gradually and, eventually is replaced by the natural tissue completely.

One of the major challenges for the use BG as a bioscaffold is its degradability. Several methods can be used to control the degradation rate, including both extrinsic and intrinsic factors. The extrinsic factors are pH, humidity and temperature. If the pH of solution increases by one unit, the silicon (glass network former) release rate would enhance by two orders of magnitude. In addition, enhancement of humidity or temperature will also increase the degradation rate of glass. However, when a biomaterial is implanted into a physiological system, the surrounding environment is unlikely to be changed arbitrarily. Therefore, to control the degradation rate for tissue engineering purpose, it is suitable to tune the intrinsic factors, such as the composition and the specific surface area. Among the intrinsic factors, introducing more glass network modifier (e.g. Na_2O) in glass composition is a traditional method to modify degradability. However, the composition range to maintain bioactivity is narrow and thus it is difficult to find an acceptable composition, in which the glass is bioactive as well as biodegradable. Another way to modify degradability is tailoring the surface area by introducing pores, which can enlarge the surface area and therefore tune the degradability of bioscaffold. Introducing controlled macropores and/or nanopores may serve this purpose.

Importance of bioactive glasses

Bioactive glasses are novel dental materials that are different from conventional glasses and are used in dentistry. Bioactive glasses are composed of calcium and phosphate, which are present in a proportion that is similar to the bone hydroxyapatite. These glasses bond to the tissue and are biocompatible. They have a wide range of medical and dental applications and are currently used as bone grafts, scaffolds and coating material for dental implants. This article reviews various properties of bioactive glasses and their applications and also reviews the changes that can be made in their composition according to a desired application.

A material is said to be bioactive, if it gives an appropriate biological response and results in the formation of a bond between material and the tissue. Bioactive glasses are silicate based, containing calcium and phosphate. Hench was the first to develop bioactive glasses and these glasses were able to bond to tissues[3]. Safety of these bioactive glasses was a concern, so various studies were performed to ensure that bioactive glasses are safe for clinical applications. Bioactive glasses have different families and each family has a different composition. Bioacitve glasses were initially obtained via melting at higher temperatures. Two common processes for the formation of bioactive glasses are melting and sol-gel process. By sol-gel processing and it was observed that glasses made from the sol-gel process required lower temperatures as compared to conventional melting method. Glass transition temperature (T_g) is a range of transformation when an amorphous solid is changed into a super cooled liquid on heating. Properties like dissolution rate and strength of different glasses can be compared with the help of T_g. A linear relationship exists between T_g and hardness of a bioactive glass. A decreased T_g of a bioactive glass predicts that the glass has reduced hardness.

Bioactive glasses have a wide range of applications. Bioglass also known as 45S5 is most commonly used for bone grafts. Bioactive glasses help in the repair of hard tissues and various compositions are being used nowadays for preparation of scaffolds[4] and as coating material for implants. In addition to remineralization, bioactive glasses have antibacterial effects as they can raise the pH of aqueous solution. Bioactive glasses when used for air polishing yielded better results in terms of stain removal and patient comfort as compared to traditional sodium bicarbonate powder. Bioactive glass can also be utilized for cutting cavities in teeth by air abrasion. Bioactive glasses are a group of biomaterials, which are used in the fields of dentistry and orthopedics. Forty five years ago, these glasses modified the functions and capabilities of biomaterials from bioinert to bioactive by stimulating a strong response after implanting in the human body. A material can be classified as bioactive if the above-mentioned biological response results in formation of a strong chemical bond between the implanted material and a soft or hard tissue[5]. Certain compositions of the silicate-based glasses, with calcium and phosphorus in proportions identical to those of natural bone, can form such a strong bond without an intervening fibrous layer. When the glass contains more than 60 % SiO_2, bonding to tissues is no longer observed. On the other hand, it is expected that bioactivity increases with the amount of CaO in the composition, because the dissolution of the calcium ion from the glass plays an important role in formation of the chemical bond[6].

Composition of bioactive materials

Bioactive materials, including bioactive glasses and glass-ceramics[7], are special compositions made typically from the Na_2O-CaO-MgO-P_2O_5-SiO_2 system. All of the compositions form a mechanically strong bond with bone. The rate of bone bonding depends upon composition of the material. Glass compositions with the fastest rates of bone bonding also bond to soft tissues. Bioactive materials are used as bulk implants to replace bones or teeth, coatings to anchor orthopaedic or dental devices or in the form of powders, as bone grafts, to fill various types of bone defects. When a particulate of bioactive glass is used to fill a bone defect the rate and quantity of bone regeneration depend on the material's composition. The glass composition contained 45% SiO_2, in weight % with network modifiers of 24.5% Na_2O and 24.5% CaO. In addition 6% P_2O_5 was added to the glass composition to simulate the Ca/P constituents of hy-droxyapatite (HA), the inorganic mineral phase of bone, Table 1. The glass composition was denoted as 45S5 to signify the weight % of silica (S) as the network former and a 5-fold ratio of Ca/P. The glasses did not form interfacial scar tissue isolating them from the host femoral bone, and could not be removed from their implant site[8]. This discovery led to the development of a new class of biomaterials, called bioactive materials, for use in implants or prostheses and repair or replacement of bones, joints and teeth.

Table 1: Composition of bioactive glasses and glass-ceramics used for medical and dental applications

Composition (wt %)	45S5 Bioglass (NovaBone)	S53P4 (AbminDent1)	A-W Glass-ceramic (Cerabone)
Na_2O	24.5	23	0
CaO	24.5	20	44.7
CaF_2	0	0	0.5
MgO	0	0	4.6
P_2O_5	6	4	16.2
SiO_2	45	53	34
Phases	Glass	Glass	Apatite beta-wollastonite glass
Class of bioactivity	A	B	B

The most recent modification in bioactive chemically bonded cements with a predominant use in restorative dentistry has been the introduction of a calcium aluminate–glass ionomer luting cement (CM Crown & Bridge, originally named Xera Cem). The luting cement is actually a hybrid composition combining both calcium aluminate and glass ionomer chemistry. The setting mechanism of Ceramir C&B is a combination of a glass ionomer reaction and an acid base reaction of the type occurring in hydraulic cements. Glass ionomer component contributes to: Low initial, short-duration pH, improved flow and setting characteristics, early adhesive properties to tooth structure, early strength properties. Calcium aluminate component in the cement contribute to: increased strength and retention over time, biocompatibility, sealing of tooth material interface, bioactivity-apatite formation, stable, sustained long-term properties, lack of solubility/degradation, ultimate development of a stable basic cement pH.

Phosphate-based glasses show unique features such as low melting (T_m) and glass transition (T_g) temperatures and high coefficients of thermal expansion that extend their applications in various technological fields. Phosphate glasses have attracted huge interest recently as degradable biomaterials. These glasses have the unique property of being completely soluble in aqueous media and more importantly, this degradability can be controlled, with solubility times ranging from a few hours to several months, to suit the end application via changes in the glass chemistry. This ability to dissolve and to be able to control the rate is seen as a very desirable property, particularly for tissue engineering applications, in which the presence of a device is only required to support the cells/tissue in the short term. The main constituent of phosphate glasses is phosphorus pentoxide, which acts as the primary network former. However, pure vitreous P_2O_5 is very difficult to obtain in a glassy form. This is due to the fact that P_2O_5 is very hygroscopic and volatile; hence, a mixture of oxides including network modifiers and network intermediates are added to the phosphate glass system to stabilize the glass network[9].

Technological and clinical applications

Metal oxides play a very important role in many areas of chemistry, physics and materials science. The metal elements are able to form a large diversity of oxide compounds. In technological applications, oxides are used in the fabrication of microelectronic circuits, sensors, piezoelectric devices and fuel cells, coatings for the passivation of surfaces against corrosion and as catalysts[10-32]. Rao et al.[33-49] presented our results on different oxide materials in our earlier studies. The potential range of biomedical applications of glass fibers encompasses the fields of muscle and ligament tissue engineering and nerve regeneration; this is mainly because the morphology and chemistry of glass fibers can be conducive to the growth of muscle tissue or neuronal cells along the longitudinal axis of the fiber. Several studies have investigated the production of phosphate glass fibers containing metallic oxides such as Fe_2O_3 and CuO as dopants. In these studies, the glass fibers are prepared by drawing from a melt of specific viscosity at a high temperature onto a rotating steel drum. Very few studies, however, have investigated the fabrication of glass fibers made from phosphate glasses incorporating titanium oxide. The similarities between the matrices and cortical bone in terms of bending strengths and elastic moduli and the favorable biocompatibility of the matrices as evidenced by in vitro cell culture studies demonstrated the promise of these fiber composites for use in bone fixation devices.

Glass microspheres show considerable potential for use in a whole host of biomedical applications, including cancer radiotherapy and thermotherapy, drug and protein delivery and bone filler materials. Microspheres can be prepared from melt–quenched glasses by a flame spheroidization process wherein glass powders are introduced into a horizontal or vertical gas/oxygen flame and then collected at specific distances from the flame. Alternatively, bioactive glass microspheres can be prepared from sol–gel glasses by an emulsion technique and potentially by electro spraying as well. We envisage the application of these microspheres as an effective bone filler material; another possible application could be as a substrate in bioreactors for cell growth and differentiation. There is a large literature describing the mechanical properties of different types of glass ceramics. However, effects of the crystallized volume fraction at constant grain size and of varying grain size with constant crystallized volume fraction on mechanical properties of glass-ceramics have seldom been investigated. There are only a few studies of mechanical properties of bioactive glass ceramics. Several papers compare the mechanical behavior of the parent glass with (almost) fully crystallized glass-ceramics but do not consider partially-crystallized glass-ceramics of varied microstructure. Some studies compared the mechanical behavior of glass-ceramics, varying the crystal size for a fixed volume percentage of crystal phases, whereas others describe the effect of volume fraction of crystal phase, but neglect the crystal size effect.

Borosilicate glasses are of technological interest because they have many and diverse applications. They generally have lower thermal expansion values, good chemical resistance, high dielectric strength and higher softening temperatures than other commercial glasses. For these reasons they are used for many applications such as glassware, industrial piping, bulbs for hot lamps and also they are recently investigated as for immobilization of nuclear wastes, possible materials that could perform bioactivity. The mechanism of bonding of bioactive glasses with living tissues has been reported to be associated with the development of a layer consisting of carbonate containing hydroxyapatite (HCAp) similar to that of bone on the surface of the materials. Series of reactions with their kinetics that take place on the surfaces of these glasses after immersion in tissues or experimental fluids are responsible for the onset of the apatite formation.

CONCLUSION

The interaction between restorative dental materials and tooth tissue encompasses multiple aspects of dental anatomy and materials science. Thus, the field of biomaterials has become an imperative area, as these materials are helpful in improvement of the quality and the longevity of human life. Bioactive glasses are novel dental materials that are different from conventional glasses and are used in dentistry. Bioactive glasses are composed of calcium and phosphate which are present in a proportion that is similar to the bone hydroxyapatite. These glasses bond to the tissue and are biocompatible. Bioactive glasses are novel dental materials that are different from conventional glasses and are used in dentistry. Bioactive glasses have a wide range of applications. Bioglass also known as 45S5 is most commonly used for bone grafts. The potential range of biomedical applications of glass fibers encompasses the fields of muscle and ligament tissue engineering and nerve regeneration.

REFERENCES

1. L. L. Hench, J. Am. Ceram. Soc., **74(7),** 1487 (1991).
2. Hench, Biomaterials, **19(16)**, 1419 (1998).
3. L. L. Hench, J. Mater. Sci.: Mater. Med., **17**, 967 (2006).
4. J. R. Jones, E. Gentleman and J. Polak, Elements, **3(6)**, 393 (2007).
5. L. L. Hench, R. J. Splinter and W. C. Allen, J. Biomed. Mater., **5**, 117 (1971).
6. G. Laudisio and F. Branda, Thermochim. Acta., **370**, 119 (2001).
7. L. L. Hench and H. A. Paschall, J. Biomed. Mater. Res., **5**, 49 (1974).
8. C. A. Beckham and T. K. Greenle, Cal. Tis. Res., **8(1)**, 165 (1971).
9. J. R. van Wazer and K. A. Holst, J. Am. Chem. Soc., **72**, 639 (1950).
10. M. C. Rao, Int. J. Chem. Sci., **10(2)**, 1111 (2012).
11. M. C. Rao and K. Ramachandra Rao, Int. J. Chem. Tech. Res., **6(7)**, 3931 (2014).
12. S. M. Begum, M. C. Rao, R. V. S. S. N. Ravikumar, J. Inorg. Organometa. Poly. Mater., **23(2)**, 350 (2013).
13. S. M. Begum, M. C. Rao and R. V. S. S. N. Ravikumar, J. Mol. Struct., **1006(1)**, 344 (2011).
14. S. M. Begum, M. C. Rao and R. V. S. S. N. Ravikumar, Spectrochim. Acta Part A: Mol. & Biomol. Spec., **98**, 100 (2012).
15. K. Ravindranadh, M. C. Rao, R. V. S. S. N. Ravikumar, J. Mater. Sci: Mater. Elect., **26**, 6667 (2015).
16. K. Ravindranadh, M. C. Rao and R. V. S. S. N. Ravikumar, Appl. Mag. Reson., **46(1)**, 1 (2015).
17. K. Ravindranadh, M. C. Rao and R. V. S. S. N. Ravikumar, J. Luminesce., **159**, 119 (2015).
18. M. C. Rao, J. Crys. Growth, **312(19)**, 2799 (2010).
19. M. C. Rao, Optoelect. & Adv. Mater., (Rapid Commu.), **5**, 85 (2011).
20. M. C. Rao and O. M. Hussain, IOP Conf. Series: Mater. Sci. Eng., **2**, 012037 (2009).
21. M. C. Rao, Optoelect. & Adv. Mater., (Rapid Commu.), **5(5-6)**, 651 (2011).

22. M. C. Rao, J. Optoelect. & Adv. Mater., **13**, 428 (2011).
23. M.C. Rao and O. M. Hussain, Optoelect. & Adv. Mater., **13(2-4)**, 1109 (2011).
24. M. C. Rao, Optoelect. & Adv. Mater., (Rapid Commu.), **6**, 511 (2012).
25. M. C. Rao and O. M. Hussain, Eur. Phys. J. Appl. Phys., **48(2)**, 20503 (2009).
26. M. C. Rao and O. M. Hussain, Ind. J. Eng. Mater. Sci., **16**, 335 (2009).
27. M. C. Rao, J. Optoelect. & Adv. Mater., **12**, 2433 (2010).
28. M. C. Rao, Optoelect. & Adv. Mater., (Rapid Commu.), **4**, 2088 (2010).
29. M. C. Rao, J. Optoelect. & Adv. Mater., **13**, 78 (2011).
30. M. C. Rao, K. Ravindranadh, Sk. Muntaz Begum and G. Nirmala, AIP Conf. Proc., 1349, 641 (2011).
31. M. C. Rao and O. M. Hussain, Optoelect. & Adv. Mater., (Rapid Commu.), **6**, 245 (2012).
32. M. C. Rao, Sk. Muntaz Begum, E. Sivanagi Reddy and O. M. Hussain, AIP Conf. Proc., **1447**, 613 (2012).
33. M. C. Rao and S. M. Begum, Optoelect. & Adv. Mater., (Rapid Commu.,), **6**, 508 (2012).
34. M. C. Rao and O. M. Hussain, J. Alloys Compd., **491(1)**, 503 (2010).
35. M. C. Rao and K. Ravindranadh, Der Pharma Chemica, **8**, 243 (2016).
36. M. C. Rao, K. Ravindranadh and M. S. Shekhawat, AIP Conf. Proc., **1536**, 215 (2013).
37. K. Ravindranadh, M. S. Shekhawat and M. C. Rao, AIP Conf. Proc., **1536**, 219 (2013).
38. M. C. Rao, K. Ravindranadh and M. S. Shekhawat, AIP Conf. Proc., **1728**, 020077 (2016).
39. K. Ravindranadh, R. V. S. S. N. Ravikumar and M. C. Rao, AIP Conf. Proc., **1728**, 020079 (2016).
40. K. Ravindranadh, D. Sridhar Kumar, K. Durga Venkata Prasad and M. C. Rao, Int. J. Chem. Tech. Res., **9(4),** 598 (2016).
41. Ch. Srinivasa Rao, M. C. Rao and T. Srikumar, Int. J. Chem Tech Res., **6(7)**, 3931 (2014).

42. T. Srikumar**,** Ch. Srinivasa Rao and M. C. Rao, Int. J. Chem. Tech. Res., **6(11)**, 4697 (2014).

43. Ch. Srinivasa Rao, T. Srikumar and M. C. Rao, Int. J. Chem Tech Res., **7(1)**, 420 (2014).

44. Ch. Srinivasa Rao and M. C. Rao, Int. J. Chem. Tech. Res., **8(2)**, 524 (2015).

45. M. C. Rao and K. Ravindranadh, Der. Pharm. Che., **8(7)**, 74 (2016).

46. K. ParameswaraRao, B. V. Ramesh, Ch. Siva Prasad and M. C. Rao, Der Pharm. Lett., **8(9)**, 341 (2016).

47. Sk. Muntaz Begum, K. Ravindranadh, M. C. Rao and R. V. S. S. N. Ravikumar, AIP Conf. Proc., **1536**, 27 (2013).

48. M. C. Rao, Int. J. Chem. Tech. Res., **6(3)**, 1904 (2014).

49. K. Parameswara Rao, B. V. Ramesh, Ch. Siva Prasad, G. V. Ramana and M. C. Rao, Der Pharm. Lett., **8(10)**, 222 (2016).

Accepted : 17.07.2016