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Preparation of Bioactive Composite and Fibers for Dental Applications

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Abstract: The ultimate goal of restoring tooth structure and bone regeneration depends on using durable and biocompatible material. Recently, bioactive materials have been widely used in hard tissue repair and regeneration and recently gained interest in dental sciences. The term bioactive materials generally refers to biomaterials which have the capability to induce and conduct the response to the biological system upon interacting.

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I. Introduction:

The ultimate goal of restoring tooth structure and bone regeneration depends on using durable and biocompatible material. Recently, bioactive materials have been widely used in hard tissue repair and regeneration and recently gained interest in dental sciences. The term bioactive materials generally refers to biomaterials which have the capability to induce and conduct the response to the biological system upon interacting (1).

There are two classes of bioactive materials; class B bioactive materials bond to hard tissue (bone) and stimulate bone growth along the surface of the bioactive material (osteo-conduction). Examples of class B bioactive materials are synthetic HA and tricalcium phosphate ceramics. Class A bioactive materials not only bond to bone and are osteoconductive but they are also osteo-inductive, that is, they stimulate the growth of new bone on the material away from the bone/implant interface by stimulating the differentiation of undifferentiated mesenchymal cells. Examples of class A bioactive materials are bioactive glasses (2). As a result of their valuable properties, bioactive materials have been introduced into various dental applications and there is extensive ongoing research to optimize and tailor their properties according to each specific use.

Applications of bioactive composites in dentistry:

Bioactive scaffold materials:

Synthetic bioactive and bioresorbable composite materials are becoming increasingly important as scaffolds for tissue engineering. Certain bioactive ceramics such as tricalcium phosphate and hydroxyapatite as well as bioactive glasses, react with physiologic fluids to form tenacious bonds with hard (and in some cases soft) tissue. However, these bioactive materials are relatively stiff, brittle, and difficult to form into complex shapes. Conversely, synthetic bioresorbable polymers are easily fabricated into complex structures, yet they are too weak to meet the demands of surgery and the in vivo physiologic environment. Composites of tailored physical, biologic, and mechanical properties as well as predictable degradation behavior can be produced combining bioresorbable polymers and bioactive inorganic phases (3).

Bioactive resin composite:

The incorporation of bioactive materials into resin composites is advantageous in many ways (4):

a) Remineralizing effect:

- Bioactive restorative materials can release calcium and phosphate ions to remineralize dental hard tissues (4).

b) Marginal gap sealing:

- The dissolution of bioactive materials provide nucleation sites for apatite formation, favoring its precipitation almost immediately after the start of dissolution (4).
- This feature can be used to form HA layer on the restoration surface which is thick enough to hinder bacterial penetration into the marginal gap (4).

c) Improving the longevity of the hybrid layer:

- By inhibiting the matrix metalloproteinase activity via the increase in the local pH and depositing the HA precipitate within the demineralized collagen network. This will result in decreasing the nanoleakage and protecting the hybrid layer from hydrolytic degradation (4).

d) Treatment of post operative sensitivity:

- Precipitation of HA can occlude Dentinal tubules and reduce dentinal fluid flow thus reducing dentin postoperative sensitivity after placing composite fillings (4).

Bioactive materials used in dental applications:

Calcium Orthophosphate materials:

Hydroxyapatite (HA):

HA is a highly crystalline form of calcium phosphates. It is classified as bioactive due to its osteoconductive ability and formation of hard tissues and remineralization of enamel and dentin. Since it is highly crystalline, it is highly stable and has low dissolution rates and high acid resistance (5).

Amorphous Calcium phosphates (ACP):

ACP [$Ca_9(PO4)_6$] is one of the calcium orthophosphate compounds. it has a much higher degradability than any other calcium phosphates. The ACP is readily converted into crystalline HA, which is desirable during hard tissue maturation. The crystalline HA is more acid-resistant and has better mechanical properties. ACP had shown better cell adhesion with hard and soft tissues, biocompatibility, bioactivity, and osteoconduction properties. Based on its bioactive properties, the ACP is applied as a transient phase that could be readily utilized as a precursor in apatite growth (6).

Tri Calcium Phosphates (TCP):

TCP exists in three polymorphic forms, the ultra-high temperature α'-TCP, high-temperature α- TCP, and the low-temperature ⊚-TCP. The α-TCP only exists at very high temperatures (around 1500°C) and is not generally used. The ⊚-TCP is unstable at high temperatures and changes into α-TCP (1125–1200°C) and reverts to the original single ⊚ phase if it cools properly. The α-TCP is safe at high temperatures and single-phase powder can be achieved successfully. TCPs are bioactive, biocompatible, bioresorbable and osteo-inductive materials. TCPs had been used in dental surgery, however, due to their poor mechanical properties, low cohesion, brittleness, and no microporosity, their clinical applications were limited to non-load bearing areas (6).

As pure HA had a low dissolution rate and pure TCP had a very high dissolution rate. Therefore, biphasic apatites (HA/TCP) could affect the dissolution tendency and bone-bonding. The reported dissolution order of calcium phosphate members was: α -TCP > ⊚-TCP > HA (1).

Bioactive glass:

1969, Larry Hench and co-workers laid the first stone of bioactive ceramics by bringing chemically bone-alike Hench's 45S5 Bioglass® into the market. This first Bioglass was based on 45% SiO_2, 24.5% Na_2O, 24.5% CaO, and 6% P_2O_5. The first generation of bioglass was biologically inert, while the second generation of bioglass concept changed from bioinert

to bioactivity. The third generation led to the development of resorbable bioactive bioglass. Recently, bioactive glass particles, micro-, and nano-sizes had been introduced, combined with polymers, to form a composite for diverse applications (7).

Calcium Silicates:

Calcium silicate based bio-ceramics are commonly used in various load bearing biomedical applications. They also possess chemical similarities to bone with osteoconduction properties (1).

There were two crystalline modifications of stoichiometric calcium silicate ($CaSiO_3$), i.e., low-temperature (◎-$CaSiO_3$) and (α-$CaSiO_3$). Dicalcium silicate (Ca_2SiO_4) had four different modifications: γ phase, which was stable at room temperature; α' and α- phases, which were stable at high temperatures; and ◎ -phase, which was not thermodynamically stable. Tricalcium silicate (Ca_3SiO_5) was a phase stable between 1250°C and 1900°C (1).

With all the advantages of biocompatibility, limitations of CSs are high brittleness, and insufficient bioactivity compared to calcium phosphates-based materials. To overcome these limitations, other components such as magnesium (Mg), zinc (Zn), and zirconium (Zr) could be added to form ternary compounds (1).

Commercial calcium silicates based dental biomaterials include MTA and Biodentine.

Preparation methods of bioactive fillers:

Preparation of calcium phosphates (CP) materials.

Dry synthesis:

Stoichiometric and well-crystallized CP can be prepared by solid-state reactions of calcium orthophosphates with calcium oxide or related salts such as Ca $(OH)_2$ (e.g. $CaHPO_4$ + CaO). at a stoichiometric Ca/P mixing ratio for each CP material formation at high temperatures (typically above 700 ◦C) (8).

Mechano-chemical processing (or mechanical alloying) through direct ball milling for the above mixtures (that is, calcium orthophosphates and calcium oxide) is another way to fabricate CP nanoparticles in a dry state (8)

These CPs materials are generally obtained in the bulk form, and therefore grinding or milling is necessary to obtain micro or nanoparticles (8).

Wet synthesis:

Calcium phosphates can be fabricated under milder conditions in solutions via several ways, such as wet chemical precipitation, sol–gel method, emulsion method. The morphology (shape and size) of HAp nanoparticles can be widely varied by adjusting the reaction conditions. However, highly crystallized HAp can be obtained only at elevated temperatures, by hydrothermal treatment in a wet condition or calcination in a dry state (8).

Wet chemical precipitation:

Wet chemical precipitation has been widely used because of its simplicity. Mixing of two aqueous solutions of calcium and orthophosphate (at pH > 7) results in the formation of highly supersaturated solutions for CP. The type of the formed CP compound is controlled by the reaction and precipitation conditions which induces a fast precipitation of nanoparticles according to the following reaction (8):

$$10\ Ca(OH)_2 + 6H_3PO_4 \rightarrow Ca10(PO_4)_6(OH)_2 + 18H_2O$$

The morphology (shape and size) of the nanoparticles depends on precipitation conditions such as concentration of reactants, ionic strength, pH and temperature. The mixing condition for two (calcium and orthophosphate) aqueous solutions is also important. A microreactor is a device that has microchannels on the order of micrometers and that enables chemical reactions to be performed in a space several orders of magnitude smaller than conventional batch reactors (8).

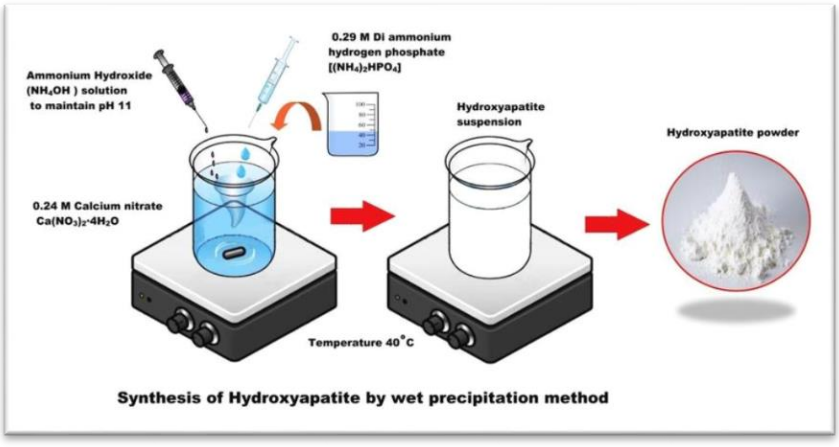

Figure (1) is a schematic representation for wet synthesis of HA.

Hydrothermal process:

Hydrothermal processes include several techniques for crystallizing materials in aqueous media at high temperatures (typically 100–250 ◦C, and hence under high vapor pressure when the temperature is above 100 ◦C). Microwave irradiation can be used instead of conventional heating in pressure-resistant vessels, shown in figure (2) (8).

The hydrothermal process usually produces particles with larger size (up to millimeter range), higher degree of crystallinity and a Ca/P ratio close to the stoichiometric value compared with those obtained by the precipitation processes at lower temperature. However, the size distribution of the produced particles is usually broad (8).

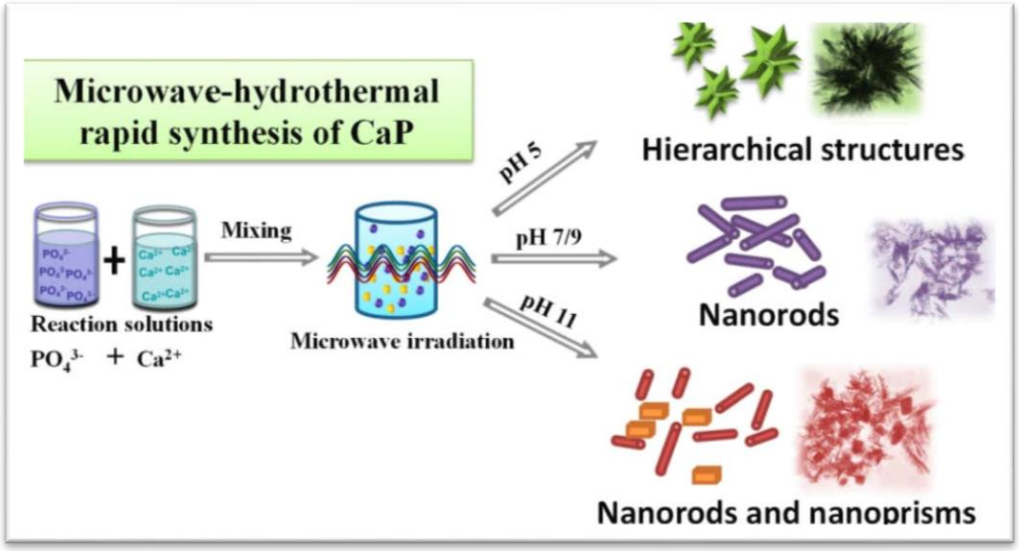

Figure (2) Schematic representation for hydrothermal process

Homogenous precipitation:

The homogeneous precipitation starts with a homogeneous, acidic calcium phosphate solution, and nucleation/growth of CP compound is induced by thermal decomposition (hydrolysis) of:

Urea: $((NH_2)2CO + H_2O \rightarrow CO_2 + {}_2NH_3)$

or acetamide ($CH_3CONH_2 + H_2O \rightarrow CH_3COOH + NH_3$).

The resultant NH_3 raises the solution pH (and degree of supersaturation for CP), leading to the formation (precipitation) of CP particles. Slow hydrolysis of the molecules at a high temperature leads to the formation of large and well-crystallized particles (8).

Sol-Gel method:

The sol–gel method has been used for fabricating fine ceramics in wet conditions for a long time. The precursor combinations (calcium alkoxides and phosphorus alkoxides) undergoes hydrolysis and polycondensation reactions to form a solid phase. In this process, the sol (i.e., solution) dissolving precursors evolves gradually towards the formation of a gel-like network of the solid phase, as shown in figure (3). The solid phase can also be deposited on a substrate to form a film. By controlling the reaction parameters, the solid phase can also be obtained as nanoparticles dispersed in media (8).

In the sol-gel method for CP preparation, the as-obtained solid phase is generally amorphous Ca–P intermediates and hence a thermal treatment (typically at 400–500 ◦C, which is lower than the sintering temperature of CP powder, ~800–1000 ◦C) is necessary to obtain well-crystallized CP. The products are obtained in a sintered polycrystalline form and hence grinding or milling is usually necessary to obtain micro or nanoparticles (8).

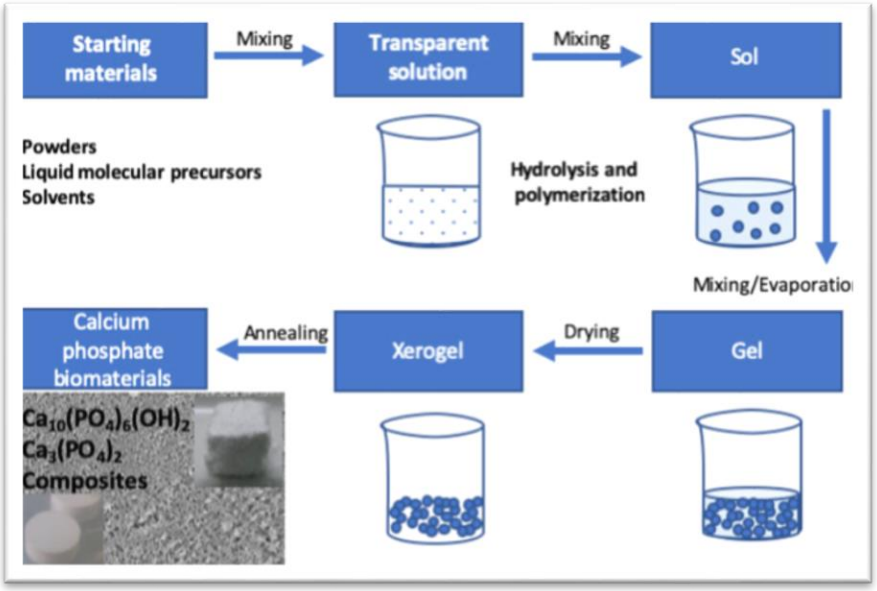

Figure (3) Schematic representation for Sol-Gel process

Preparation of calcium phosphates fibers:

CaP fibers can be produced through several routes including spinning, extrusion, sol–gel and pyrolysis, and electrospinning, shown in figure (4). Electrospinning is frequently used because it is a simple technology that allows the production of nano- and micro-fibers by applying a high voltage to a polymer solution. It has been used to produce different

types of ceramic fibers using chemical precursors mixed to the polymer solution and by performing a thermal treatment on the resulting fibers (9).

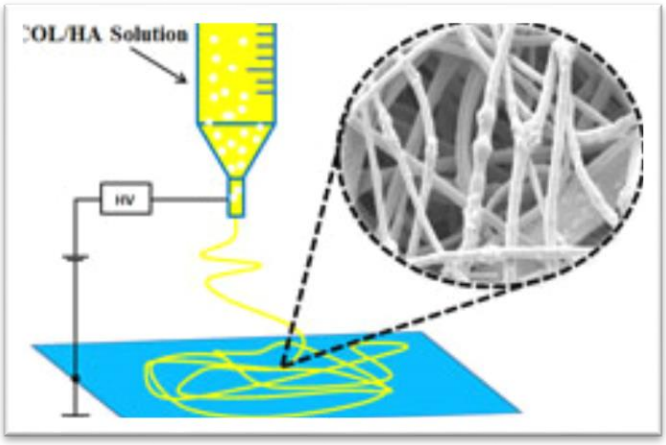

Figure (4) Schematic representation for preparation of HA fibers

Preparation of bioactive glass:

The most common techniques to produce bioactive glasses are traditional melt quenching routes and the sol–gel technique.

Melt-Quenching technique:

In melt quenching technique, glass is prepared by taking required stoichiometric amounts of different constituent oxides or carbonates of high purity (99.9%). These constituents are first mixed together by ball-mill in an acetone medium. The powder obtained after ball milling is melted at high temperatures in a high resistance furnace depending upon the composition chosen. The melt is then poured into molds to produce rods/cylinders or any other desired shape of interest. The melt can also be quenched in air using copper plates to obtain frits. The quenched glass is then annealed at 500◦C to remove the internal stresses from the glasses (7). Figure (5) is a schematic representation of melt-quenching processing.

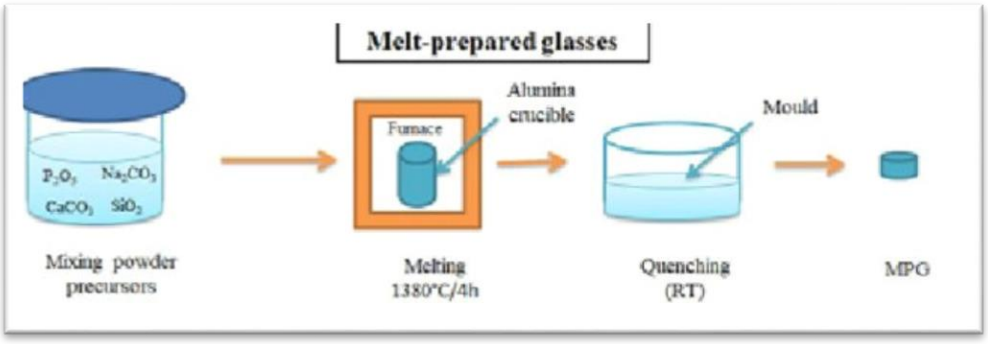

Figure (5) Schematic representation for melt-quenching method

Sol-Gel technique:

A sol–gel process has been used to prepare porous scaffolds of bioactive glasses. The process involves hydrolysis, polymerization, gelation, drying, and a dehydration process. Sol (or solution) evolves towards the formation of a gel-like diphasic system (with the aid of surfactant) containing both a liquid phase and solid phase. Its morphology can range from discrete particles to continuous polymer networks. Nano pores present in the glass prepared from a sol–gel method yield a high surface area. Consequently, this leads to degradation and a faster conversion of these glasses to HA than scaffolds of melt-derived glass with the same composition (7).

In addition, the sol-gel method provides high purity glasses with more homogeneity. Moreover, a lower processing temperature is required. However, these sol–gel-derived scaffolds have low strength (2–3 MPa) and consequently they are suitable for substituting defects in low-load sites only (7).

Preparation of Bioactive glass fibers:

Bioactive glass is first prepared by one of the previously mentioned methods (melt-quenching or sol-gel) then fibers are prepared by drawing or electrospinning as shown in figure (6) (10).

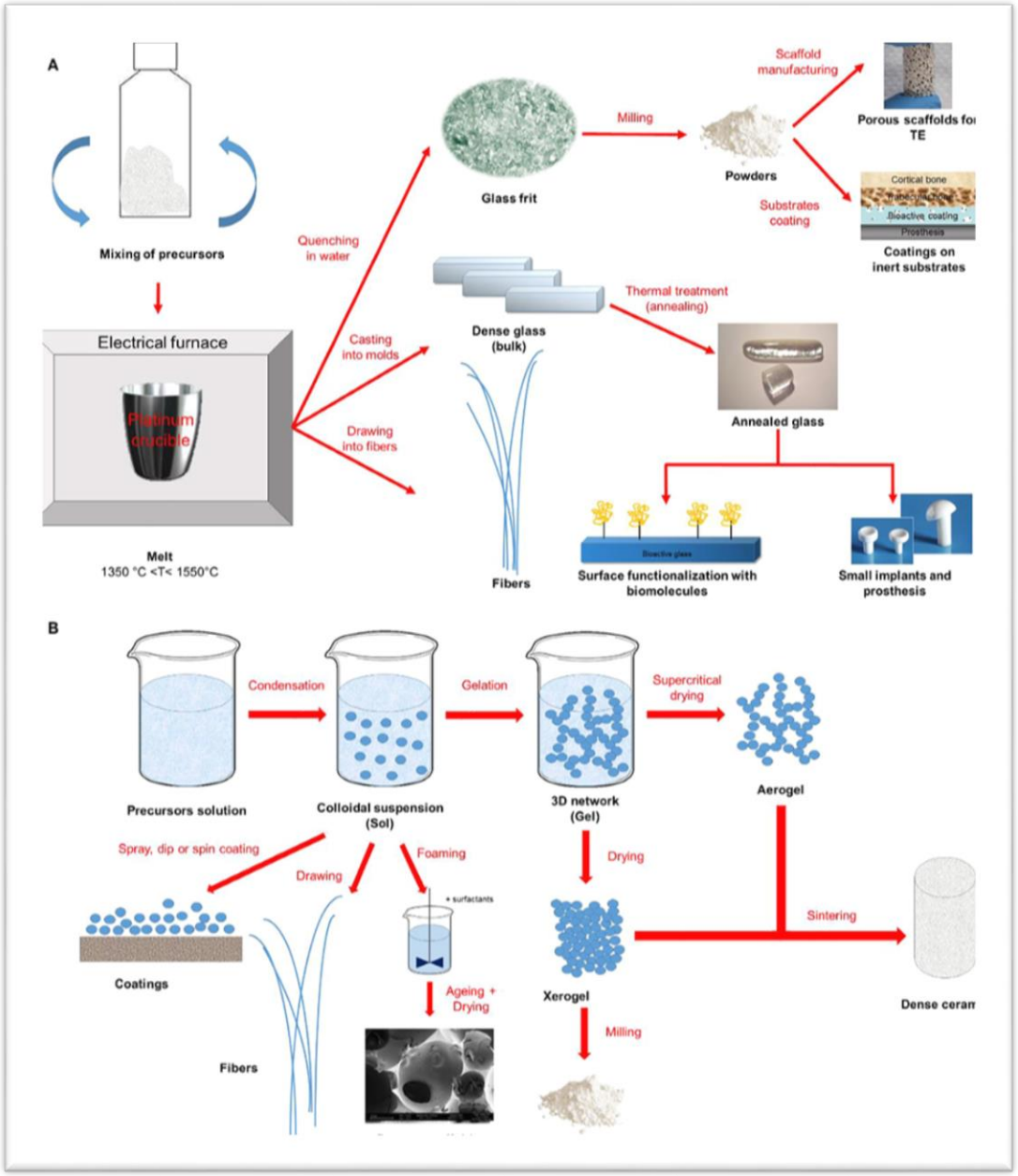

Figure (6) Preparation of bioactive glass fillers and fibers

Surface modifications of bioactive fillers:

The major issue during preparation of a composite material is to ensure proper bonding between the matrix and the fillers, and to ensure proper dispersion of the inorganic fillers within the matrix. Therefore, surface modifications for the bioactive fillers are done (11).

Chemical treatments:

The surface modification of nanoparticles by chemical treatments (such as the absorption of silane coupling agents) is a useful method to improve the dispersion stability of nanoparticles in various liquid media and to improve the compatibility between the particle and polymer surfaces, consequently the properties of composite materials (11). Figure (7) demonstrates silanization of HA fillers.

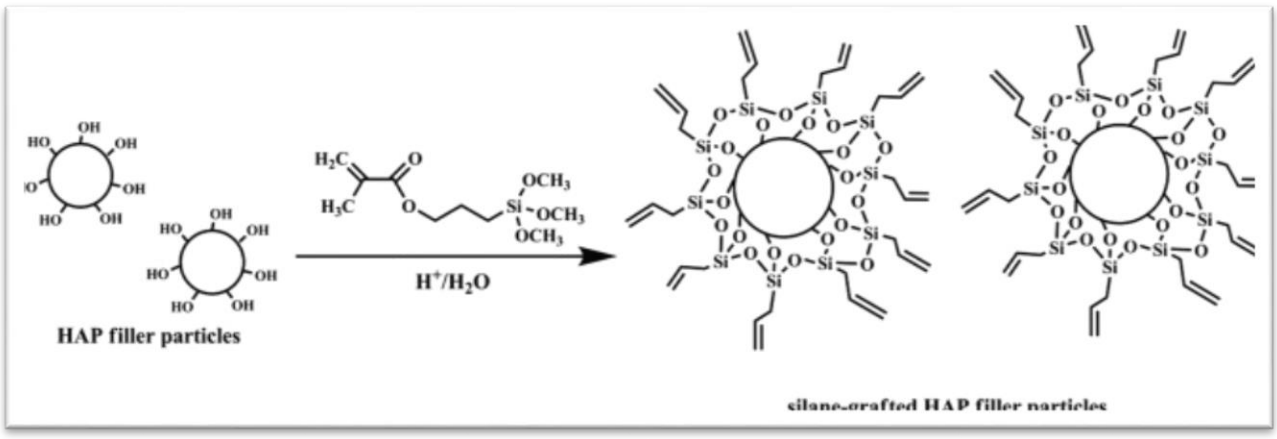

Figure (7) Silanization of HA fillers particles

Grafting of synthetic polymers:

Another approach to modify the surfaces of inorganic and organic materials is based on grafting synthetic polymers to the substrate surface, which enhances the chemical functionality and alters the surface topology of the native inorganic and organic materials. Such polymer-grafted inorganic nanoparticles are considered to be organic–inorganic nanocomposite particles (11).

Because monomers usually have a low molecular weight by their nature, they can penetrate the aggregated nanoparticles and react with the activated sites on the nanoparticle surface. The interstitial volume inside the nanoparticle aggregates becomes partially filled with grafted macromolecular chains, and the aggregated nanoparticles become further separated. In addition, the surfaces of the nanoparticles become hydrophobic, which is important for the miscibility of the filler and matrix. Figure (8) shows the dispersion behavior of bare and polymer-grafted nanoparticles in a polymer matrix (11).

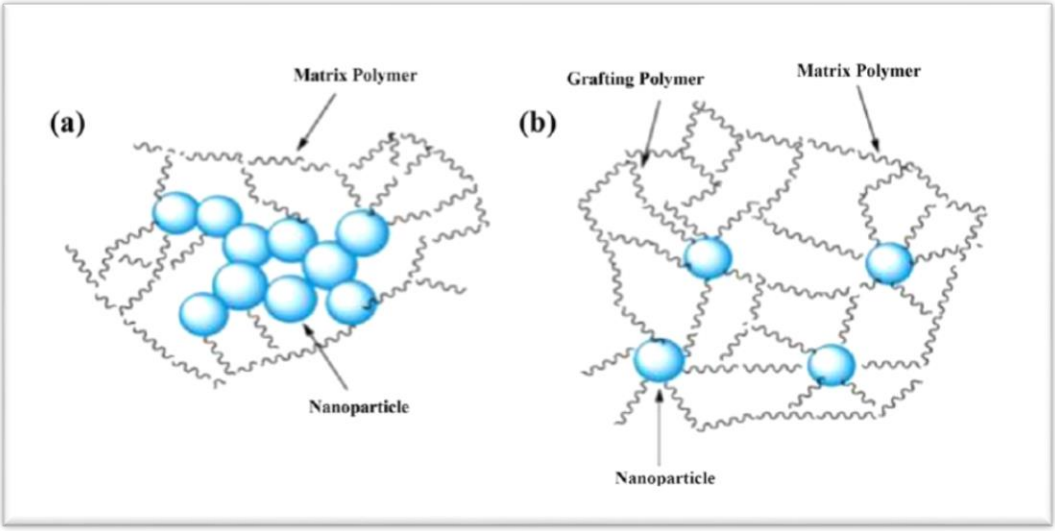

Figure (8) Schematics of: (a) agglomerated nanoparticles in the matrix polymer in the case without grafting polymer and (b) separation of particles due to the grafting polymer.

Adsorption of dispersants:

Other methods for surface modification of inorganic nanoparticles have been reported, including adsorption of polymeric dispersants and in situ surface modification. Surface modification by adsorption of polymeric dispersants is one of the simplest methods to improve the dispersion behavior of nanoparticles in aqueous systems. The hydrophilic nanoparticles can be dispersed in highly polar organic solvents by using anionic or cationic polymer dispersants. These dispersants generate steric repulsive forces among the polymer chains and increase the surface charge, which results in better dispersibility of the nanoparticles, shown in figure (9) (11).

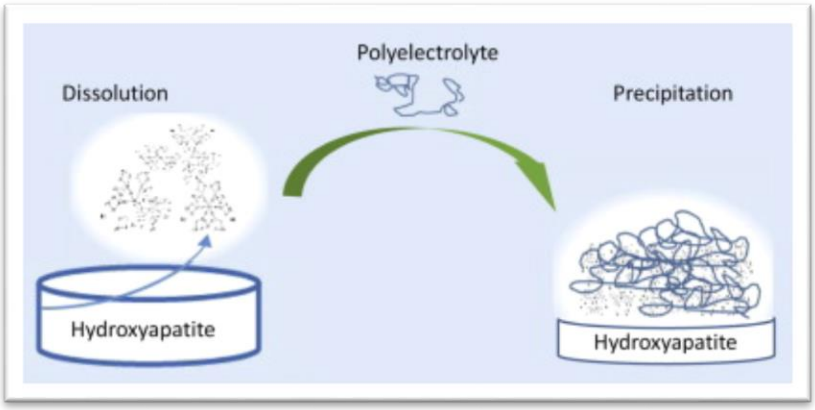

Figure (9) Adsorption of dispersants on HA fillers particles

Etching of fillers surfaces

Surface pores can be easily obtained through an etching process. The surface of glass-ceramic fillers can be chemically etched with hydrofluoric acid. Resin monomers will be forced into the porous fillers by high pressure or vacuum before polymerization, which will enable micromechanical interlocking in the cured composites. The idea of porous fillers is advantageous over using silane coupling agent due to the hydrolysis of silane coupling agents that can reduce the lifetime of dental composites (12).

Effect of surface modifications of bioactive fillers on properties:

Influence on dispersion of fillers in organic solvents/matrices:

The dispersion stability of ultrafine inorganic particles in organic solvents or polymer matrices is known to be remarkably improved after being silanized or when polymers have been grafted on their surfaces. The chemical surface modification of the fillers prevents aggregation of the particles and increase the affinity of the surface for the solvent or polymer matrix and consequently enhancing the cellular adsorption on its surface, as illustrated in figure (10) (13).

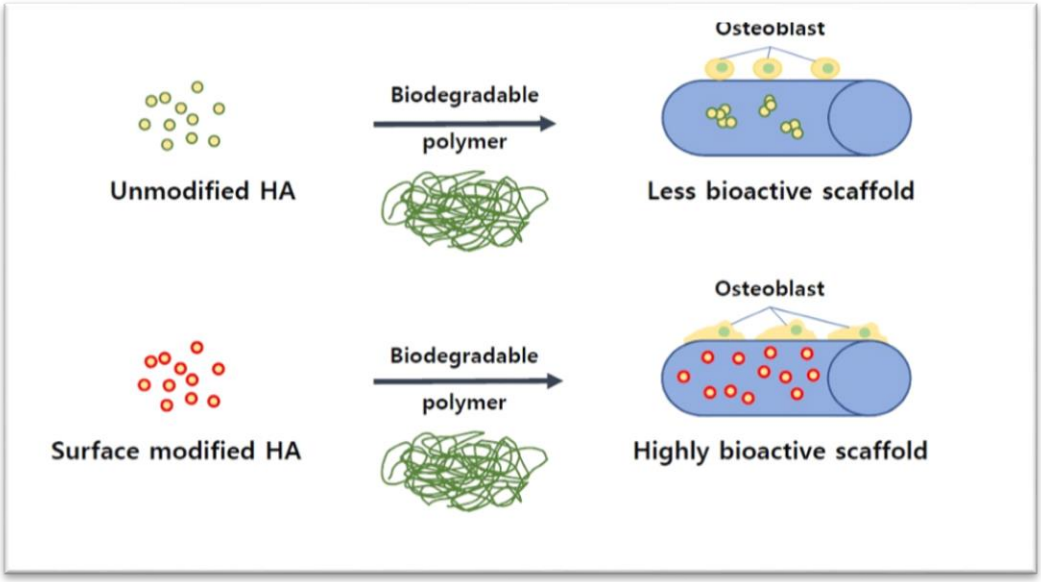

Figure (10) Schematic showing the effect of surface modification on Cellular adsorption of on HA fillers particles

Influence on mechanical properties:

The surface modified particles produced an increase in elastic modulus and impact strength of the resin matrix. The reverse effect was found for yield stress and tensile strength of the composites. These effects are explained by proper

interfacial bonding between the fillers and the matrix which lead to proper stress transfer from the matrix to the fillers (13).

However, the interfacial bond in case of using fiber fillers should not be very strong that it prevents fiber pull-out mechanisms. Fiber pull out is considered as one of the main toughening mechanisms in fiber-reinforced composites (13).

Influence on degree of conversion:

The main limiting factor for reaching high degrees of conversion is an immense increase in viscosity in the composite during polymerization. High viscosity impairs mobility of free radicals and monomers, causing the polymerization reaction to stop well before all available reactants are consumed (4).

Studies have shown that silanized bioactive fillers in resin composite showed lower degree of conversion compared to unsilanized fillers. Also, for polymer grafting; it was shown than increasing the grafting ratio significantly decreases the degree of conversion due to increased viscosity (14).

Influence on ion release and bioactivity:

The bioactivity is essentially a dissolution/reprecipitation process. As the initial ACP particles are gradually dissolved, calcium and phosphate ions are solubilized and subsequently precipitated in the form of HA (4).

Since solubility is decreased by silanization, the bioactivity is substantially decreased. Some studies reported that bioactivity is not affected by graft polymerization unlike silanization (14). Also, bioactivity is better for fillers with porous structure that provide high surface area (for example; those fabricated by sol-gel method) with micromechanical interlocking interaction at the filler-matrix interface that can also increase mechanical properties (15).

References

1. Almulhim KS, Syed MR, Alqahtani N, Alamoudi M, Khan M, Ahmed SZ, et al. Bioactive Inorganic Materials for Dental Applications: A Narrative Review. Materials (Basel). 2022;15(19).

2. Jones JR. Acta Biomaterialia Review of bioactive glass : From Hench to hybrids. Acta Biomater [Internet]. 2013;9(1):4457–86. Available from: http://dx.doi.org/10.1016/j.actbio.2012.08.023

3. Boccaccini AR, Blaker JJ. Bioactive composite materials for tissue engineering scaffolds. 2005;303–17.

4. Tarle Z, Par M. Bioactive dental composite materials. Med Sci. 2018;45:83–100.

5. Qidwai M, Sheraz MA, Ahmed S, Alkhuraif AA, Ur Rehman I. Preparation and characterization of bioactive composites and fibers for dental applications. Dent Mater. 2014;30(10):e253–63.

6. Al-Sanabani JS, Madfa AA, Al-Sanabani FA. Application of calcium phosphate materials in dentistry. Vol. 2013, International Journal of Biomaterials. 2013.

7. Kaur G, Pandey OP, Singh K, Homa D, Scott B, Pickrell G. A review of bioactive glasses: Their structure, properties, fabrication and apatite formation. J Biomed Mater Res - Part A. 2014;102(1):254–74.

8. Okada M, Furuzono T. Hydroxylapatite nanoparticles: Fabrication methods and medical applications. Sci Technol Adv Mater. 2012;13(6).

9. Mouthuy P, Crossley A, Ye H. Fabrication of calcium phosphate fi bres through electrospinning and sintering of hydroxyapatite nanoparticles. Mater Lett [Internet]. 2013;106:145–50. Available from: http://dx.doi.org/10.1016/j.matlet.2013.04.110

10. Kargozar S, Montazerian M, Fiume E, Baino F. Multiple and Promising Applications of Strontium (Sr) -Containing Bioactive Glasses in Bone Tissue Engineering. 2019;7(July).

11. Kango S, Kalia S, Celli A, Njuguna J, Habibi Y, Kumar R. Surface modification of inorganic nanoparticles for development of organic–inorganic nanocomposites—A review. Prog Polym Sci [Internet]. 2013; Available from: http://dx.doi.org/10.1016/j.progpolymsci.2013.02.003

12. Chen H, Wang R, Qian L, Ren Q, Jiang X, Zhu M. Dental Restorative Resin Composites : Modification

Technologies for the Matrix / Filler Interface. 2018;1800264:1–16.

13. Rong MZ, Zhang MQ, Ruan WH. Surface modification of nanoscale fillers for improving properties of polymer nanocomposites : a review. Mater Sci Technol. 2006;22(July).

14. Liu F, Jiang X, Bao S, Wang R, Sun B, Zhu M. Effect of hydroxyapatite whisker surface graft polymerization on water sorption , solubility and bioactivity of the dental resin composite. Mater Sci Eng C [Internet]. 2015;53:150–5. Available from: http://dx.doi.org/10.1016/j.msec.2015.04.043

15. Aminoroaya A, Esmaeely R, Nouri S, Panahi P, Das O, Madry H, et al. A review of dental composites : Challenges , chemistry aspects , filler influences , and future insights. Compos Part B [Internet]. 2021;216(September 2020):108852. Available from: https://doi.org/10.1016/j.compositesb.2021.108852