

Dental Ceramics: Part I – An Overview of Composition, Structure and Properties

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Abstract Over the last decade, it has been observed that there is an increasing interest in the ceramic materials in dentistry. Esthetically these materials are preferred alternatives to the traditional materials in order to meet the patients' demands for improved esthetics. Dental ceramics are usually composed of nonmetallic, inorganic structures primarily containing compounds of oxygen with one or more metallic or semi-metallic elements. Ceramics are used for making crowns, bridges, artificial denture teeth, and implants. The use of conservative ceramic inlay preparations, veneering porcelains is increasing, along with all-ceramic complete crown preparations. This article is a review of dental ceramics; divided into two parts such as part I and II. Part I reviews the composition, structure and properties of dental ceramics from the literature available in PUBMED and other sources from the past 50 years. Part II reviews the developments in evolution of all ceramic systems over the last decade and considers the state of the art in several extended materials and material properties.

Keywords: ceramics, porcelains, feldspar, silica, glass, firing

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1. Introduction

In dentistry, ceramics represents one of the four major classes of materials used for the reconstruction of decayed, damaged or missing teeth. Other three classes are metals, polymers, and composites. The word Ceramic is derived from the Greek word "keramos", which literally means 'burnt stuff', but which has come to mean more specifically a material produced by burning or firing [1]. A ceramic is an earthly material usually of silicate nature and may be defined as a combination of one or more metals with a non-metallic element usually oxygen. The American Ceramic Society had defined ceramics as inorganic, non-metallic materials, which are typically crystalline in nature, and are compounds formed between metallic and nonmetallic elements such as aluminum & oxygen (alumina - Al_2O_3), calcium & oxygen (calcia - CaO), silicon & nitrogen (nitride- Si_3N_4) [2]. Ceramics are characterized by their refractory nature, hardness, chemical inertness, biocompatibility [3,4,5] and susceptibility to brittle fracture [6,7]. Ceramics are used for pottery, porcelain glasses, refractory material, abrasives, heat shields in space shuttle, brake discs of sports cars, and spherical heads of artificial hip joints [1,8]. In dentistry, ceramics are widely used for making artificial denture

teeth, crowns, bridges, ceramic posts, abutments, and implants and veneers over metal substructures [1,9]. This article in part I; reviews the composition, structure and properties of dental ceramics from the literature available in PUBMED and other sources from the past 50 years. Part II reviews the developments in evolution of all ceramic systems over the last decade and considers the state of the art in several extended materials and material properties.

Dental ceramics are usually referred to as nonmetallic, inorganic structures primarily containing compounds of oxygen with one or more metallic or semi-metallic elements like aluminum, calcium, lithium, magnesium, phosphorus, potassium, silicon, sodium, zirconium & titanium [1,10]. The term porcelain is referred to a specific compositional range of ceramic materials made by mixing kaolin, quartz and feldspar in proper proportioning and fired at high temperature [1,10,11]. Porcelain is essentially a white, translucent ceramic that is fired to a glazed state. [5] Dental porcelains may be classified based on their fusion temperature, microstructure, and processing technique [1,12,13]. According to their fusion temperature, porcelains are classified as high fusing, medium fusing, low fusing and ultra-low fusing porcelains. The fusion temperature ranges of dental porcelains and their clinical recommendations are detailed in Table 1.

Table 1. Fusion temperature ranges of various dental porcelains and their clinical applications

Porcelain Type	Fusion temperature range	Clinical Applications
High fusing	> 1300°C	Denture Teeth
Medium Fusing	1000°C- 1300°C	Jacket Crowns, Bridges and Inlays
Low Fusing	850°C - 1000°C	Veneers over cast metal crowns
Ultra-low fusing	< 850°C	Used with Titanium and its alloys

2. Structure

Ceramics can appear as either crystalline or amorphous solids [1,10] (also called glasses). Thus, ceramics can be broadly classified as non crystalline (Amorphous Solids or glasses) and Crystalline ceramics. The mechanical and optical properties of dental ceramics mainly depend on the nature and the amount of crystalline phase present. More the glassy phase more the translucency of ceramics; however, it weakens the structure by decreasing the resistance to crack propagation. On the other hand, more the crystalline phase better will be the mechanical properties which in turn would alter the aesthetics [1,11]. Conventional or feldspathic porcelains are usually non-crystalline ceramics. These conventional porcelains are very weak and brittle in nature leading to fracture even under low stresses. Recent developments in the processing technology of dental ceramics have led to the development of crystalline porcelains with suitable fillers such as alumina, zirconia and hydroxy apatite [1,14,15].

2.1. Non- Crystalline Ceramics

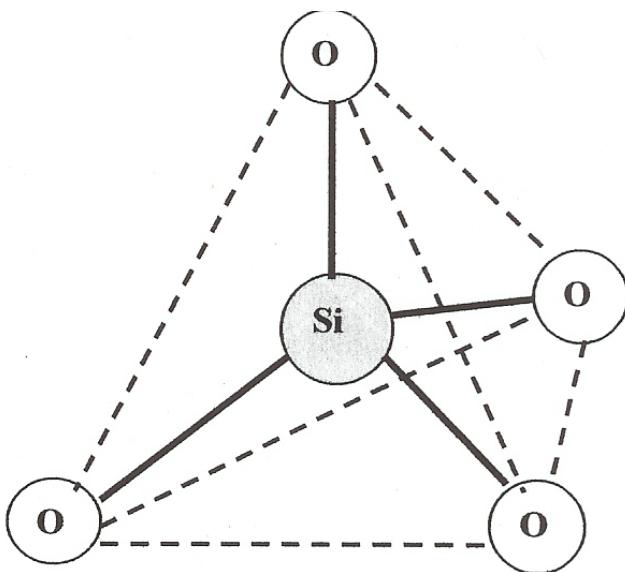


Figure 1. Tetrahedral configuration of Silica

These are a mixture of crystalline minerals (feldspar, silica and alumina) in an amorphous (non-crystalline matrix of glass) vitreous phase. The glass-forming matrix of dental porcelains uses the basic silicone oxygen (Si-O) network with the silicon atom combining with 4 oxygen atoms, forming a tetrahedral configuration [Figure 1] in which the larger oxygen atoms serve as a matrix, with the smaller metal atoms such as silicone inserted into spaces between the oxygen atoms. Thus each silica unit consists of a single silicone atom (Si) surrounded by four oxygen atoms (O). The atomic bonds in this glass structure have both a covalent and ionic character thus making it stable and also make silica units to link with each other to form a

chain configuration. Several such linked silicate unit chains form the continuous SiO_4 (tetrahedral network) in glass [Figure 2]. This stable structure, with strong atomic bonds and no free electrons imparts some important qualities like excellent thermal and optical insulating characteristics, inertness translucency to the glass matrix. However, these strong dual bonds may also impart brittleness to the glass matrix leading to the fracture even at low tensile stress applications [16,17,18,19].

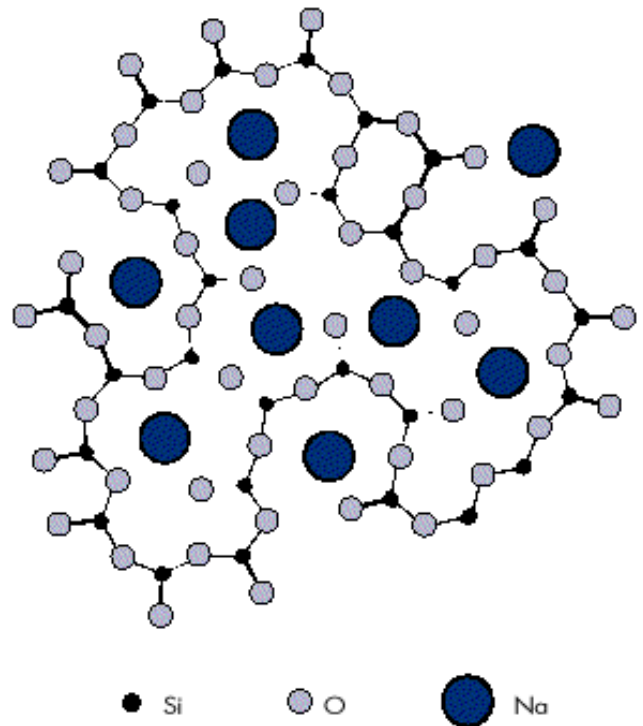


Figure 2. Glass structure with the presence of large alkali cations

2.2. Crystalline Ceramics

Ceramics are reinforced with crystalline inclusions such as alumina and leucite into the glass matrix to form crystal glass composites as a part of strengthening the material and improving its fracture resistance (dispersion strengthening). McLean and Hughes (1965) introduced the first generation of reinforced porcelains for porcelain jacket crowns, which are generally referred to as "Aluminous porcelains" [16]. Covalent crystals are very hard and have a very high melting point, e.g. Silicone Carbide.

3. Composition

Dental ceramics are mainly composed with crystalline minerals and glass matrix. Crystalline minerals include feldspar, quartz, and alumina and perhaps kaolin as glass matrix [1,10,11]. The detailed composition of dental ceramics was discussed in Table 2.

Table 2. Composition of Dental Ceramics¹

Ingredient	Functions
Feldspar (naturally occurring minerals composed of potash [K ₂ O], soda [Na ₂ O], alumina and silica).	It is the lowest fusing component, which melts first and flows during firing, initiating these components into a solid mass.
Silica (Quartz)	<ul style="list-style-type: none"> • Strengthens the fired porcelain restoration. • Remains unchanged at the temperature normally used in firing porcelain and thus contribute stability to the mass during heating by providing framework for the other ingredients.
Kaolin (Al ₂ O ₃ .2 SiO ₂ . 2H ₂ O - Hydrated aluminosilicates)	<ul style="list-style-type: none"> • Used as a binder. • Increases moldability of the unfired porcelain. • Imparts opacity to the finished porcelain product.
Glass modifiers, e.g. K, Na, or Ca oxides or basic oxides	They interrupt the integrity of silica network and acts as flux.
Color pigments or frits, e.g. Fe/Ni oxide, Cu oxide, MgO, TiO ₂ , and Co oxide.	To provide appropriate shade to the restoration.
Zr/Ce/Sn oxides, and Uranium oxide	To develop the appropriate opacity.

Feldspar is responsible for forming the glass matrix [1]. Feldspar is the lowest melting compound and melts first on firing. Feldspar is a naturally occurring mineral and composed of two alkali aluminum silicates such as potassium aluminum silicate (K₂O-Al₂O₃-6SiO₂); also called as potash feldspar or ortho clase and soda aluminum silicate (Na₂O-Al₂O₃-6SiO₂); also called as soda feldspar or albite [1,10,20]. Most of the currently available porcelains contain potash feldspar as it imparts translucency to the fired restoration. Potash fuses with kaolin and quartz to form glass when heated from 1250°C to 1500°C [20]. Soda feldspar lowers the fusion temperature of the porcelain that results in pyroplastic flow [1,10]. This material did not attract the porcelain manufacturers as it does not influence the translucency of the porcelain.

Quartz has high fusion temperature and provides the framework as it remains same at the firing temperature of the porcelain. Quartz also acts as filler in the porcelain restoration [1,10,16,17].

Kaolin is a type of clay material which is usually obtained from igneous rock containing alumina. Kaolin acts as a binder and increases the moldability of the unfired porcelain. Kaolin also imparts opacity to the porcelain restoration so; dental porcelains are formulated with limited quantity of kaolin [21]. Glass modifiers are used as fluxes and they also lower the softening temperature and increase the fluidity [1,17]. Color pigments or frits are added to provide the characteristic shade [1].

4. Properties

Dental ceramics exhibit excellent biocompatibility with the oral soft tissues and are also chemically inert in oral cavity. They possess excellent aesthetics. The structure of porcelain restoration is probably the most important mechanical property. The physical and mechanical properties are described in Table 3. The structure of porcelain depends upon its composition, surface integrity and presence of voids. The strength is also depends on the presence of surface ingredients. The nature, amount, particle size and coefficient of thermal expansion of crystalline phases influence the mechanical and optical properties of the materials [14]. Dental ceramics possesses very good resistance to the compressive stresses, however, they are very poor under tensile and shear stresses [1,11,22]. This imparts brittle nature to the ceramics [23,24,25] and tend to fracture under tensile stresses. Various modes of clinical fractures of ceramic structures

include cracks initiating from the contact zone at the occlusal surface [25,26], from the cementation surface beneath the contact [25,27], and from the margins of crowns and connectors in fixed partial dentures. [28,29,30,31,32] Structural defects lead to the failure in dental ceramic prostheses. Defects may arise in the form of micro-cracks of sub-millimeter scale; during fabrication of ceramic prostheses and also from application of masticatory forces in the oral cavity [33].

Table 3. Physical and Mechanical properties of Dental Ceramics¹

Compressive strength	330 MPa
Diametral tensile strength	34 MPa
Transverse strength	62 - 90 MPa
Shear strength	110 MPa
MOE	69 GPa
Surface hardness	460 KHN
Specific gravity	2.2–2.3 gm/cm ³
Thermal conductivity	0.0030 Cal/Sec/cm ²
Thermal diffusivity	0.64 mm ² /sec
Coefficient of Thermal expansion	12 × 10 ⁻⁶ /°C

Fatigue strength plays an important role in the durability and longevity of dental ceramic restorations. Fatigue can be accounted for by chemically-enhanced, rate-dependent crack growth in the presence of moisture [34-41] and cyclic application of stresses [42-50]. Water enters incipient fissures and breaks down cohesive bonds holding the crack walls together and results in initiation of slow crack growth which progresses steadily over time, accelerating at higher stress levels and ultimately leading to failure [25].

Surface hardness of ceramics is very high hence they can abrade the opposing natural or artificial teeth [1,11,22]. Ceramics are good thermal insulators and their coefficient of thermal expansion is almost close to the natural tooth [22,51]. During firing any residual water is lost from the material accompanied by loss of any binders that results in volume shrinkage of about 30–40%, due to elimination of voids during sintering. Therefore, a precise control of the condensation and firing technique is required to compensate for such shrinkage value during the construction of porcelain restoration [1].

Adhesion of ceramic restoration to the natural tooth also plays a significant role in the durability of the restoration. The success of a fixed restoration depends on the use of the luting agent and cementation technique [52]. Various luting agents have been discussed in the literature [53,54,55]. Glass ionomer cements and resin cements are most commonly used for luting of ceramic restorations

[53,54,56,57]. The ceramic surface must be altered to provide adequate bonding with the luting agent and also with orthodontic bracket either by mechanical or chemical or by combined approaches [58,59]. Mechanical approaches include use of air abrasion/sand blasting [60,61,62], a diamond stone bur [62,63], sand paper disks and LASERS [64,65,66,67]. However, excessive roughening of the surface should be avoided since it may induce the crack initiation and propagation within ceramic that results in fracture of the ceramic restoration during service. Chemical alteration of the ceramic surface can be introduced by either etching the surface to increase the mechanical retention of the adhesive or by changing the ceramic surface affinity to the adhesive materials [68,69,70,71]. Studies have shown that chemical conditioning methods such as silanation increases the adhesion of the composite resin bond to the ceramic [72,73,74]. The silica of the dental ceramic is chemically united with the acrylic group of the composite resin through silanation [75]. To

improve the bond strength of adhesive resins to ceramics, combination of mechanical and chemical conditioning methods are recommended [59].

5. Strengthening of Dental Ceramics

The major drawbacks of ceramics are brittleness, low fracture toughness and low tensile strength. Methods used to overcome the deficiencies of ceramics fall into two categories including methods of strengthening brittle materials and methods of designing components to minimize stress concentration and tensile stress [1,10,76]. Methods to strengthen the brittle materials include the development of residual compressive stress within the surface of the material and interruption of crack propagation through the material. Methods of strengthening of brittle materials are illustrated in Figure 3 [1,10,76,77].

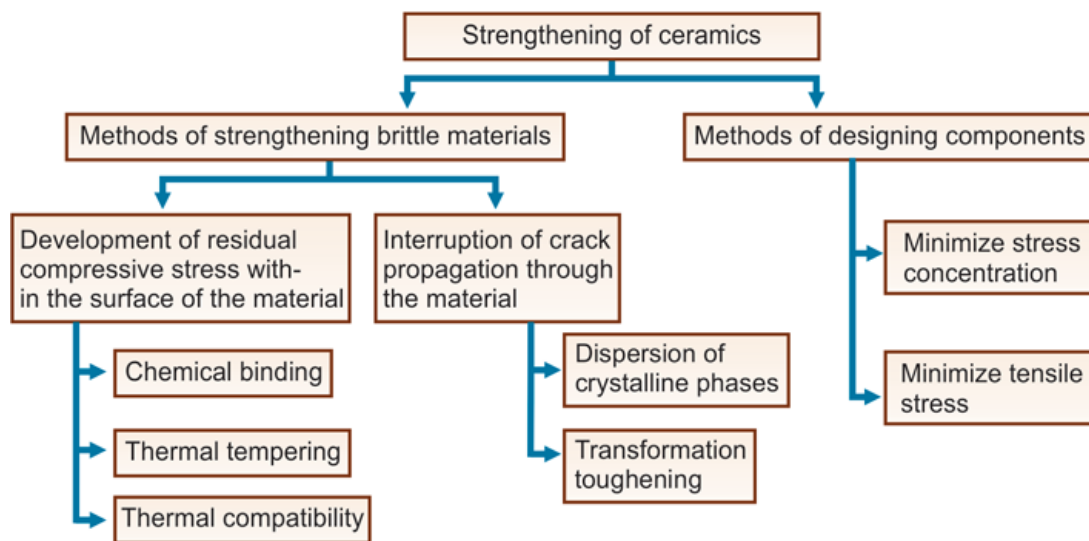


Figure 3. Methods of strengthening dental ceramics

Residual compressive stresses are introduced within the surface of glass and ceramic objects in order to gain strength. These introduced compressive stresses help in neutralizing the tensile stresses developed during service. Compressive stresses can be introduced by either of the three mechanisms such as chemical tempering, thermal tempering and thermal compatibility [1]. Chemical tempering involves replacement of smaller Na^+ ions (a common constituent of variety of glasses) with the larger K^+ ions. Replacement of these ions create larger residual compressive stresses (700 MPa) in the surface of the glass subjected to this treatment as the K^+ ions are 35% larger than the Na^+ ions. This surface compression which results in increased strength of porcelain is also called as ion exchange [1,76,78,79]. Thermal tempering involves rapid cooling of the restorations' surface from the molten state which introduces residual compressive stresses. The rapid cooling produces skin of glass surrounding soft (molten) core, which will shrink later during solidification which creates the residual tensile stress in the core and residual compressive stresses within the outer surface [1,10,17,80]. Thermal compatibility method applies to porcelain fused metals. The metal and porcelain should be selected with slight mismatch in their thermal contraction coefficient. Usually the difference of $0.5 \times 10^{-6}/^\circ\text{C}$ in thermal

expansion between metals and porcelain causes the metal to contract slightly more than does the ceramic during cooling after firing the porcelain which results in development of residual compression in the ceramic surface [1,10].

A dispersed crystalline phase is reinforced into the glasses or ceramics to strengthen them by interrupting the crack propagation through the material. Two different types of dispersions are used to interrupt the crack propagation such as alumina (Al_2O_3) or Partially Stabilized Zirconia' (PSZ) [1,10,14,76]. Al_2O_3 is a tough crystalline material, which can prevent the crack propagation through them and strengthen the glass [1,10,14,76,81,82]. PSZ is capable of undergoing change in crystal structure when placed under stress and can improve the strength [1,10,14,76,83].

6. Conclusion

It is apparent that ceramics as a material group would continue to play a vital role in dentistry owing to their natural aesthetics and sovereign biocompatibility with no known adverse reactions. However, there will always remain a compromise between aesthetics and

biomechanical strength. In order to achieve adequate mechanical and optical properties in the final porcelain restoration, the amount of glassy phase and crystalline phase should be optimised. Good translucency requires a higher content of the glassy phase and good strength requires a higher content of the crystalline phase. Hence, the two material phases need to be balanced. Eventhough the material is high abrasion resistant, fracture toughness and resistance to the tensile stresses are inherent disadvantages. Some attempts have been made to overcome these shortcomings. However, resistance to fracture toughness and tensile stresses is further needed to be addressed.

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