Composition and mechanical properties of contemporary CAD/CAM glass ceramics

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KEYWORDS

Ceramics, Dental materials, CAD/CAM, Mechanical properties.

ABSTRACT

Aim: *In the field of dentistry, the demand on aesthetics is ever increasing and therefore new glass ceramic materials are being developed for computer aided design/computer aided manufactory (CAD/CAM) technology. The aim of the manuscript is to help dental practitioners make informed decision of the choice of dental material, based on the relevant mechanical properties.*

Methods: *This paper overviews basic mechanical properties of materials, followed by a review of the mechanical properties of some popular CAD/CAM ceramic materials used by dentists. The mechanical properties are distilled from a comprehensive literature review and are then compared to mechanical properties of dentin and enamel.*

Results: *The new glass ceramic materials come in different optical, mechanical, and color properties. The flush of this new information can be sometimes confusing for the dental professional.*

Conclusion: *Lithium disilicate glass ceramics is not only aesthetic, but also durable due to good mechanical properties such as fracture toughness, flexural strength, and elastic modulus. It appears to be a very suitable material in CAD/CAM technology in the production of the reconstruction, which will then be luted by adhesive resin.*

Introduction

The word ceramic comes from the Greek word keramos, which means potter/pottery (1,2). Porcelain was known already in the 7th century BC in China. Ceramics as we know it today was discovered in the 7th century AD. In Europe, interest in porcelain can be observed in the 17th century when rich rulers brought porcelain from China and Japan. The largest collection owned by Augustus III. from Saxon, is exhibited in the Zwinger castle in Dresden (3). Due to its aesthetic properties, ceramics began to be used in dentistry in the 18th century. The main pioneer and pathfinder in the use of ceramics in this field was the Parisian pharmacist Alexander Duchateau, who made the first dental prosthesis made all of ceramics (4).

Ceramics are aesthetic materials that help us to restore natural smiles for our patients. It is a biocompatible and aesthetic material, but hard and brittle. It consists of two basic components: glass and crystalline phases. The ratio of these influences the properties of the material and the resulting prosthetic reconstruction (2).

Ceramics is usually classified not only based on the composition and its clinical use, but also based on microstructure and the processing techniques. Nowadays, modern technologies and increasing demand for processing time of dental products makes ceramics that are processed by CAD/CAM (computer aided design/computer aided manufactory) technology more and more desirable.

This paper first overviews basic mechanical properties of materials such as hardness, flexural strength, fracture toughness and modulus of elasticity. These mechanical properties are reviewed for glass CAD/CAM ceramics used in contemporary dentistry. The mechanical properties are distilled from a comprehensive literature review, and are then compared to mechanical properties of dentin and enamel.

The aim of the manuscript is to help dental practitioners make informed decision of the choice of dental material, based on the relevant mechanical properties.

Description of physical properties

Vickers hardness

Vickers hardness is the most common hardness test for dental ceramics. The method consists of pushing the indenter (the extruded body) into the material under a pressure. The indenter is a diamond four-sided pyramid with a top angle of 136° (Fig. 1) (5). The Vickers hardness can then be calculated from the ratio of the force applied by the indenter to the surface (Fig. 2), where F is impression force, A is surface of indentation and d is diagonal imprint. The resulting value is denoted as VHN (Vickers Hardness Number) (6).

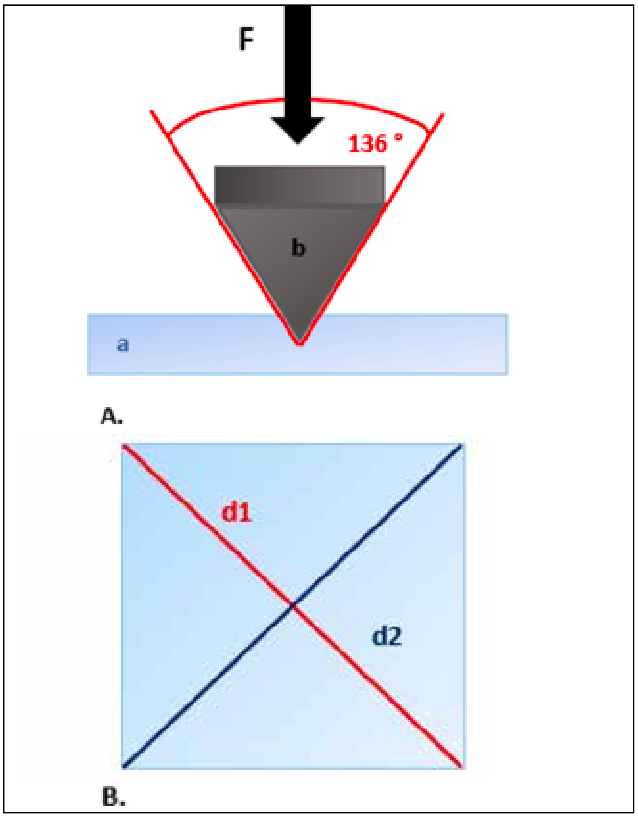

Figure 1 A: Vickers hardness test illustration. Where a is ceramic sample, b is Vickers indenter, F is indentation force.
B: Upper view of indentation, d1 and d2 are diagonals.

$$HV = \frac{F}{A} = \frac{2F\sin(136°/2)}{d^2}$$

Figure 2 Vickers hardness equation

Flexural strength

Flexural strength is defined as the maximum stress in the body that a material can withstand (caused by external bending forces before it breaks). The test is usually performed using a three-point flexural/bending test, where the beam is laid on two cylinders and the third cylinder is pushed against the centre of the beam (Fig. 3). The bending strength can be calculated using the equation described in Figure 4, where F is the force acting on the beam, L is the distance between the lower cylinders, b is the width of the beam and d is the height of the beam. The resulting force is often expressed in Pa (5,7).

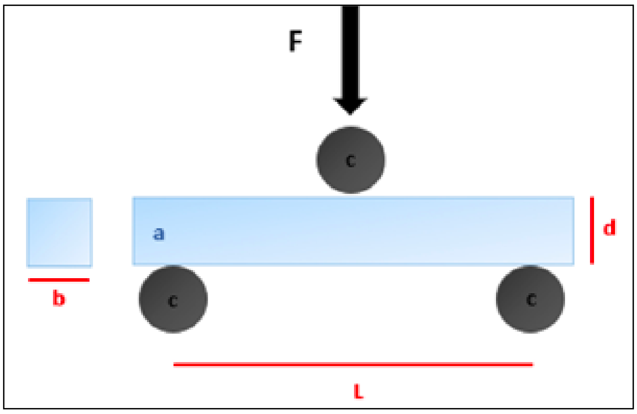

Figure 3 Three points bending test illustration. Where a is ceramic beam sample, c are cylinders, L is the distance between the supporting cylinders, b is the width of the beam and d is the height of the beam, F is acting force

$$\sigma = \frac{3FL}{2bd^2}$$

Figure 4 Flexural strength equation

Fracture toughness

Fracture toughness represents an energy that is necessary for a formation of a fracture. It describes the ability of a material to resist propagation of cracks. The mathematical equation used to calculate this property is presented in Figure 5, where σ is the internal stress in the material, a is the crack length and Y is the dimensionless shape coefficient of the body and crack. The value is denoted in $\text{MPa}\sqrt{m}$ (5,7).

Elastic/Young Modulus

Elastic/Young Modulus describes the stiffness of material within the elastic region. It can be described by the mathematical equation given below (Fig. 6), where σ is the stress (pressure acting on the inner surface perpendicular to the direction of external deformation forces) and ε is the relative deformation (extension of the body to the original length of the body). The Elastic modulus is measured in Pa (5–7).

Distribution of glass CAD/CAM ceramics

Ceramics are widely used in dentistry due to their biocompatibility, chemical stability, high abrasion and compression resistance, low plaque accumulation (due to high polishing), high aesthetics and color stability.

CAD/CAM glass ceramics can be divided (based on the McLaren classification) into:

i) mainly glass ceramics;
ii) leucite reinforce glass ceramics;
iii) lithium di silicate glass ceramics.

Ceramics consist of a certain proportion of glass and crystalline phases, and this ratio determines the properties of the final reconstruction. The glass adds aesthetics, natural appearance, translucency, but reduces the mechanical resistance of the material. Crystals increase mechanical resistance, but the more crystals the ceramics contains, the more opaque and less aesthetic it is (1,2,8).

Mostly glass ceramics

The ceramics, which best mimic the optical properties of enamel and dentine, are mostly glass ceramics. A well-known representative of this group of CAD/CAM processing is Vita Mark II (Vita Zahn Fabric, Bad Sakingen, Germany) (Fig. 7). It is a glass ceramics with homogeneously distributed fine grain feldspar particles in raw stage (30%, 3-4 um) undergoing a sintering process at 1170 °C under vacuum that can produce a homogenous microstructure ceramic block for the milling process (9–11). The mechanical properties found in the literature are the following.

1. Flexural strength: 106.67±18 (10) 112.4±3.2 (12) 102.77±3.6 (13) 137.83±12.4 (14) 128.87±5.41 (11) 113-154 (15) 100 (16) 97±8 (17) 122±13 (18) 154 (19) 113 (20) MPa.
2. Vickers hardness: 594.74±25.22 (10) 502.4 (6) 647.00±12.95 (11) 640±20 (21) VHN.
3. Elastic modulus: 57.2±3.6 (14) 47.7 (6) 68 (16) 63 (22) 45±0.5 (21) 65 (20) GPa.
4. Fracture toughness: 2.34±0.04 (12) 1.25 (14) 1.18±0.17 (20) 0.9 (16) 0.73±0.13 (23) MPa√m.

Indication for this ceramic are inlay, onlay, veneers, and frontal crown (12). Table 1 shows examples of other commercial names of mostly glass ceramic blocks.

Leucite reinforced glass ceramics

A well-known representative of this group is IPS. Empress CAD (Ivoclar Vivadent, Schaan, Liechtenstein) (Fig. 8). It is a glass ceramic reinforced with leucite crystals (KAlSi2O6), which promotes better mechanical properties. The crystal content is about 30- 45% and size of the crystals is 1-10 microns. Leucite is formed by adding potassium oxide to silica glass (1,8,24).

Leucite crystals can inhibit the propagation of cracks and thus enhance the mechanical properties of ceramics (2). The mechanical properties found in the literature are the following.

Flexural strength: 134.5±3.3 (12) 160 (8) 106±17 (18) 127 (16) 154.62±6.66 (11) 157.1±14.9 (25) 160 (13) MPa.

Vickers hardness: 565.8 (26) 610.16±4.55 (11)

$$K1 = Y\sigma a^{1/2}$$

Figure 5 Fracture toughness equation

$$E = \frac{\sigma}{\varepsilon}$$

Figure 6 Elastic modulus equation

Figure 7 Ceramic block of Vita Mark II

Figure 8 Ceramic block of IPS Empress CAD

Figure 9 Ceramic block of IPS e.max CAD – partially crystalized form

Ceramic category	Brand name (manufacturer)
Mostly glass ceramics	Vita Mark II, Vita TriLuxe forte Vita RealLife (Vita Zahnfabrik); Cerec blocs (Sirona Dental Systems)
Leucite reinforced glass ceramics	IPS Empress CAD (Ivoclar -Vivadent); Initial LRF Block CEREC/InLab Blocks, Initial LRF Block Universal (GC)
Lithium disilicate glass ceramics	IPS e.max CAD (Ivoclar-Vivadent); Obsidian (Glidewell Laboratories); Amber Mill, Rosetta SM (Hass)

Table 1 Examples of ceramic commercial names available on market

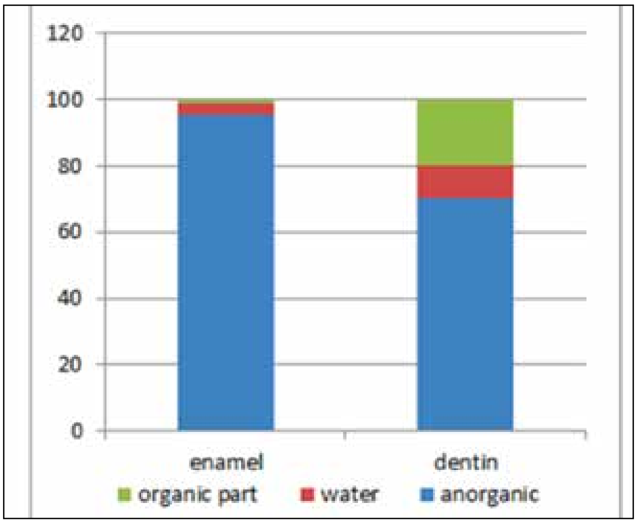

Figure 10 Composition of enamel and dentin (w/w%)

525.6±21.3 (27) VHN.

Fracture toughness: 1.90±0.03 (12) 1.3 (28) 1.3 (16) 1.28±0.19 (29) MPa√m.

Elastic modulus: 62 (28) 62 (21) 70 (16) 65 (30) 65 (31) GPa.

Indications for this ceramic are inlay, onlay, veneers, and frontal crown (12).

Table 1 shows examples of other commercial names of leucite reinforced glass ceramic blocks.

Lithium disilicate glass ceramic

The most widely used ceramics in this group is the well-known ceramic material under its corporate name IPS e.max CAD (Ivoclar Vivadent, Schaan, Liechtenstein) (Fig. 9). IPS e.max CAD is a ceramic-reinforced with lithium disilicate crystals (Li2SiO5). It contains 70% volume of lithium di silicate crystals of 1.5-5 microns in diameter (2,8,9). This ceramic has good aesthetic and mechanical properties. The ceramics is sold in a partially crystalized form (blue form) because it is easier to machine, less time consuming and causes less wear of diamond milling burs. The partially crystallized phase consists of meta silicate crystals (Li2SiO3) and some lithium disilicate (Li2SiO5) crystals (8,9,32,33). After milling, the restoration needs to undergo crystallization process (850°C in vacuum, 20-30 min). During this process, the bluish color change to natural color of the teeth, also the microstructure is changed. The metasilicates dissolve, and new lithium disilicate crystals are formed (8,24,33,34). Crystallization process includes 0,2% linear shrinkage which is accounted in the designer software (24,33).

Flexural strength of 130±30 (8) 130 (33) 130 (35) MPa and fracture toughness 0.9-1.25 (33) MPa√m. After crystallization of the ceramic, it gains more flexural strength as it is stated: 359.2±4.2 (12) 334.1±54.3 (23) 341.88±40.25 (10) 210.2 (36) 350-450 (8) 360-400 (9) 262-360 (33) 360-400 (37) 360-400 (2) 262±88 (35) 262±88 (18) 376.99±6.24 (11) 376.9±76.2 (38) 415±26 (17) 348.33±28.69 (39) 245.3±23.5 (25) 289±20 (32) 450-500 (40) MPa.

Vickers hardness: 731.63±30.64 (10) 617±44 (41) 452.9±16.2 (38) 602.79±6.38 (11) 645.5 (26) 606.917 (42) 596±18 (32) 539.7±16.4 (27) VHN.

Fracture toughness 1.67±0.03 (12) 1.8±0.29 (36) 2-2.5 (33) 2.5 (35) 2-2.5 (28) 2.01±0.13 (39) 1.23±0.26 (43) 2-2.5 (34) 1.88±0.62 (23) 1.83-2.76 (44) 2-2.5 (40) MPa√m.

Elastic modulus 95 (45) 100 (30) 90-100 (28) 95 (22) 67.2±1.3 (38) 60.61±1.64 (39) 63.9±4.8 (43) 95±5 (21) 95±5 (34) 58.97-02 (44) 100-110 (40) GPa.

Indications for this ceramic material are inlay, onlay, veneer, anterior and posterior crowns, three-unit bridges up to premolars, anterior and posterior implant abutments (12).

Table 1 shows examples of other commercial names of lithium disilicate glass ceramic blocks.

Co-operation of the basic properties of ceramic with enamel and dentin

Enamel

Enamel is the surface layer of the crown of a tooth. It is ectodermal in origin and is produced by cells called ameloblasts. It has a blue-white to sometimes translucent color. It is the best mineralized tissue of human body and consists of 95% w/w inorganic tissue, predominantly hydroxyapatite (Fig. 10). It contains a small amount of water as compared to bone, dentin or cement. Organic tissue consists predominantly of soluble and insoluble proteins and lipids whose distribution differs from area to area

	VM II	Emp	Emx	Enamel	Dentin
Flexural strength (MPa)	97 ±8 - 154	106 ± 17 - 160	210,2 - 500	60 - 90	137.9 - 280
Vickers hardness (VHN)	502,4 - 647.00±12.95	525,6±21,3 - 610.16±4.55	452.9±16.2 - 731,63±30,64	274.8±18.1 - 408	60 - 65.6±3.9
Fracture toughness (MPa√♏)	0.73±0.13 - 2.34±0.04	1.28±0.19 - 1,90±0,03	1.23±0.26 - 2,5	0,4 - 2,2	1 - 3,08
Elastic modulus (GPa)	45 ± 0.5 - 68	62 - 70	60.61±1.64 - 110	50 - 120	11 - 25

Table 2 Overview of mechanical properties of – Vita Mark II (VM II), IPS Empress CAD (Emp), IPS e.max CAD (Emx), enamel and dentin

(46). The properties of the enamel are particularly important because the choice of suitable ceramics should mimic these properties.

Flexural strength: 60-90 (5) MPa.

Vickers hardness: 313.3 (6) 274.8±18.1 (47) 343 (48) 352.5±13.8 (49) 395.01 (50) 350 (51) 408 (52) VHN.

Fracture toughness: 0.4-1 (53) 0.7-2.2 (54) 0.4-1.5 (55) MPa√♏.

Elastic modulus: 59.7 (6) 84 (5) 50 (51) 84.1 (52) 80 (56) 84.1 (30) 84 (55) 70-120 (53) GPa.

Dentin

Dentin is the basic internal tissue of a tooth. It is of mesodermal origin and its composition is very different from enamel, being closer to bone. Both primary and secondary dentin possesses yellow to ochre color, tertiary discolored to brownish brown. Dentin is produced by odontoblasts throughout the life of the dentin-pulpal border. This process occurs during the formation of a tooth on the dentin-enamel boundary. First, the odontoblasts produce a collagen matrix called the predentin, which is subsequently mineralized. Dentin consists of 70% inorganic tissues, 10% water, 20% organic tissue whose main representative is collagen type (Fig. 10) (46).

Flexural strength: 137.9-220.63 (48) 212.9 (31) 245-280 (5) 142.41±46.79 (57) MPa.

Vickers hardness: 62.3 (6) 65.6±3.9 (47) 64.75±73.75 (48) 60 (51) 60 (52) VHN.

Fracture toughness: 2 (54) 1-2 (58) 3.08 (55) MPa√♏. Elastic modulus: 11-19 (45) 16.5 (6) 18.6 (56) 18.6 (31) 18.6 (30) 17 (5) 12 (51) 18.5 (52) 20-25 (58) 17 (55) GPa.

Discussion

Table 2 reports the range of mechanical properties of glass ceramics, enamel and dentine. The ideal mechanical properties of dental material should match or be close to the mechanical properties of replacement dental tissues as dentin or enamel. The disadvantage of ceramic is its high hardness in comparison to dental hard tissues - this was confirmed for all three types of ceramics.

Comparing all values, the elastic modulus, fracture toughness and hardness of these glass ceramics are closer to enamel, while the values of flexural strength are closer to dentin. The highest values of the reported mechanical properties are mostly achieved by lithium disilicate glass ceramics.

Conclusion

Lithium disilicate glass ceramics is not only aesthetic, but also durable due to good mechanical properties such as fracture toughness, flexural strength, and elastic modulus. It appears to be very suitable material in the CAD/CAM technology indication in the production of the reconstruction, which will then be luted by adhesive resin.

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