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3D printed, and CAD/CAM milled indirect restorations from hybrid polymers. Mechanical properties. A Literature Review

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Abstract

This literature review examines the composite materials for making inlay, onlay, and overlay using Computer-aided design and computer-aided manufacturing (CAM) technologies (Subtractive manufacturing technologies (milling) and Additive manufacturing technologies (3D printing)). The chemical composition and mechanical properties of composite materials for making inlays, onlays, and overlays were described. The types of composite materials with ceramics were considered:1.Composite blocks with dispersed ceramic particles, and 2. Composite blocks with a ceramic network for milling and materials composed of monomers based on acrylic esters or filled hybrid material for 3D printing. From the mechanical properties, the following were compared: flexural strength, flexural modulus, hardness, Vickers hardness, hardness shore, and wear. These are important for determining the durability of future structures for the restoration of hard dental tissues and their wear in the conditions of the oral environment. The composition of the materials for computer-aided constructions determines their mechanical properties. The study of the mechanical properties of the materials has established that milling materials are suitable for permanent structures. In contrast, 3D printing materials are more suitable for temporary crowns, wax-up and mock-up models, and restorations in the oral cavity. Further laboratory and clinical studies are needed to explore the exact limits of their application.

Keywords: *CAD/CAM, composite blocks, 3D printing, mechanical properties*

Introduction

In the last two decades, computer-aided technologies (Computer Aided Design - CAD) have been established in dental practice. With these technologies, it is possible to elaborate a digital model and design of the future structure. The boundaries of the prosthetic field are outlined on the digital model, and the prosthetic restoration is modeled. The data is transferred to a manufacturing device (milling machine or 3D printer). The processes related to restoration manufacturing are divided into subtractive (milling) and additive manufacturing (1).

Milling machines are divided into 3-, 4-, and 5-axis machines depending on the direction of movement around the block/disk (1). The 5-axis machines are the most often used. Milling machines can operate in “dry” and “wet” modes (2). Seven types of additive technologies (3D printing) have been described: stereolithography (SLA), material jetting (MJ), material extrusion or fused deposition modeling (FDM), binder jetting, powder bed fusion, sheet lamination, and direct energy deposition (3, 4). In dentistry, SLA, the similar DLP (digital light processing), and MJ are the most often used (1, 5).

The first ceramic materials (in the form of blocks) were presented in 1985 [6] and had a tensile strength of approximately 120 MPa. Those were used for inlays, onlays, and veneers. Later in 1991, leucite ceramics were introduced (7). It had wear resistance close to enamel and was suitable for inlays, onlays, single crowns, and veneers (8). Ceramic materials demonstrate high aesthetic results, high fracture resistance, and good wear resistance (9). Other studies found that due to their fragile structure and potentially high abrasive effect on antagonists, these are unsuitable for restoring vital teeth with significant destruction (10, 11). The first composite blocks for mass use were offered in 2000. Initially, those were similar in composition to the corresponding direct composite material. However, they polymerized in the factory under the action of light (12, 13). These materials had significant wear, roughness, color instability, and fractures (14).

This review investigates the mechanical properties of composite resin materials with ceramic and PMMA materials for indirect restoration (inlay, onlay, overlay).

Classification and composition of Composite resin materials with ceramics materials and PMMA

Composite resin materials with ceramics materials used for CAD inlay, onlay, and overlay are two types (15, 16):

1. Composite blocks with dispersed ceramic particles – Lava Ultimate (3M ESPE, Seefeld, Germany), Cerasmart (GC Europe, Leuven, Belgium), Cerasmart 270 (GC Europe, Leuven, Belgium), Katana Avencia block (Kuraray Noritake, Ins, Tokyo, Japan);
2. Composite blocks with the ceramic network – polymer infiltrated ceramic network – Vita Enamic (Vita Zahnfabric, Bad Säckingen, Germany).

There are two options to affect the mechanical properties of the composite blocks: by changing their composition (17,18) or by the polymerization method. For the needs of CAD/CAM technologies, materials with a polymer matrix and dispersed ceramic particles have been introduced. Some authors define the latter as hybrid materials, although they are closer to composites. Significant advances in the mechanical properties of composite blocks have occurred after the introduction of their polymerization by heat and pressure (19).

Composite blocks with dispersed ceramic particles-types

Lava Ultimate was created in 2012 and was the first representative of nanohybrid composite blocks. It contains a combination of individually connected nanoparticles and nanoparticle agglomerates in clusters located in a polymer matrix. This material is a combination of 0.6-1.0 μm total zirconia/silica cluster (20 nm silica and 4-11 nm zirconia particles) and unbound 20 nm silicon particles and 4-11 nm zirconia nanoparticles. These are treated with a suitable silane-coupling agent for chemical bonding. This material's formulation uses nanoscale and nanocluster fillers, giving a filler composition of approximately 80% unit weight (10).

*CERASMART.*This was created in 2014. It consists of 71% silica weight units (20 nm) and barium (300 nm) glass particles bonded to a polymer matrix. In terms of composition, it is similar to conventional laboratory composites. In 2021, Cerasmart 270 was developed, which had the same composition, but through a unique technology ("full coverage silane coating"), a more even distribution of the filler was achieved.

Composite blocks with polymer-infiltrated ceramic network

VITA ENAMIC was introduced in 2013 and was the first material with a polymer-infiltrated ceramic network (PICN), called a hybrid ceramic. Manufactured with a double matrix structure, VITA ENAMIC consists of a dominant porous ceramic network reinforced with a polymer matrix. The two networks are completely interpenetrating each other. VITA ENAMIC offers significant advantages such as less tendency to fracture than conventional ceramics and higher wear resistance than composite. The ceramic structure occupies approximately 86% of the weight units (10).

Table 1. Composition of composite materials for milling and printing.

Material	***Manufacturer***	***Monomer***	***Filler***	***Filler weight %***	***Type of block composition***
Paradigm MZ 100	3M ESPE	Bis-GMA	Zr/Si particles of size 0.6 μm	85%	Composite material with ceramic particles
Lava Ultimate	3M ESPE	Bis-GMA, UDMA, Bis-EMA, TEGDMA	SiO2 (20 nm), ZrO2 (4-11 nm), ZrO2/SiO2 clusters (SiO2=20 nm, ZrO2=4-11 nm)	80%	Composite material with ceramic particles
Vita Enamic	Vita Zahnfabric	UDMA, TEGDMA	Feldspar ceramic reinforced with aluminum oxide	86%	Composite material with ceramic network
Cerasmart 270	GC	Bis-MEPP, UDMA, DMA	Silicon particles (20 nm), barium glass particles (300 nm)	71%	Composite material with ceramic particles
NextDent C&B	Vertex dental	PMMA	–	–	–

PMMA materials for inlay, onlay, and overlay used for– discs for milling machines and materials for additive manufacturing by 3D printing – Nextdent B&C Micro Filled Hybrid.3D printing machines ensure structures'

cheap and quick manufacturing from innovative nanofill composite materials. For the latter, there is also insufficient evidence of their strength properties (1). NextDent C&B Micro Filled Hybrid is a Class IIa biocompatible material. The balance between the inorganic fillers and organic matrix gives the material strength. Modern 3D printing materials are microfilaments and microfilament hybrid polymethyl methacrylates (PMMA). The manufacturer still needs to provide complete information regarding their exact composition (3).
The composition of materials for milling and 3D printing is presented in Table 1.

Mechanical properties

The research of some mechanical properties such as fatigue and impact strength of indirect dental restorations of different materials in the distal parts of the dentition, as well as their biological features regarding their interaction with the soft tissues in the oral cavity, will lead to the development of recommendations for their optimal application to the degree of load in the restoration area and the desired function and aesthetics (Table 2).

Table 2. Mechanical properties of composite materials for milling and 3D printing.

Material	Flexural strength	Flexural modulus	Wear	Hardness	Color change	Monomer separation
E-max	376.9 MPa (21)	67.2 GPa (12)	0.119 mm^3 (21)	452.9 HV (21)	–	Not established
Cerasmart 270	187 MPa (13) 219 MPa (12) 234.5 MPa (21)	9.55 GPa (13) 7.9 GPa (12) 12.10 GPa (21)	0.182 mm^3 (21)	62.2 HV (21)	Clinically acceptable	Not established
Lava Ultimate	207 MPa (13) 178 MPa (12) 248.4 MPa (21)	13 GPa (13) 10.8 GPa (12) 16 GPa (21)	0.152 mm^3 (21)	102.3 HV (21)	Clinically acceptable	–
VITA ENAMIC	149 MPa (13) 137 MPa (12) 202.1 MPa (21)	32.2 GPa (13) 22.1 GPa (12) 21.5 GPa (21)	0.21 mm^3 (21)	157.2 HV (21)	Clinically acceptable	Not established
Nextdent C&B	160 MPa (22)	2.62 GPa (25)	257 µm (5) 1.3 mm^3	181 MPa (25) 137 MPa (27)	–	–
Nextdent C&B MFH	91.8 MPa (23) 130 MPa (3) 107 MPa (3) 163.9 MPa (24)	2.37 GPa (23) 2.30-2.50 GPa (3) 2.40-2.60 (3)	1.11 mm^3 (26)	–	Clinically acceptable	Separateds depending on the polymeriza-tion

The *tensile strength* of materials is expressed in their ability to withstand a load. Materials with higher values of this parameter are less brittle and more flexible. Sismanoglu et al. investigated the tensile strength of composite and feldspar blocks (11). According to them, composites with ceramic particles have the highest values for this parameter, followed by composites with ceramic networks and feldspar. Awada et al. found that composite blocks with ceramic particles had significantly higher tensile strength and flexural modulus values than ceramic blocks(10). Lawson et al. investigated the microstructure, tensile strength, hardness, and wear of several CAD/CAM blocks (19). According to the authors, the lithium-disilicate blocks have a higher tensile strength than the composite blocks with ceramic particles. Composite blocks with ceramic particles have a higher tensile strength than those with a polymer-infiltrated ceramic network – E-max CAD 376.9 MPa, a Paradigm MZ 100 189.7 MPa, Cerasmart 234.5 MPa, Lava Ultimate 248.4 MPa, VITA ENAMIC 202.1 MPa (19).

Shim et al. investigated the tensile strength of Nextdent Base, a 3D printing material, at different positions relative to the surface of obtaining the item. The values they got, 160 MPa, were lower than those compared to the values from other studies of composite milling blocks (20).

Dentine flexural modulus is between 16 – 20.3 GPa, and that of enamel – 48 to 105.5 GPa (11). Composite cement has a flexural modulus similar to hard dental tissues (HDT). If the restorative material has a flexural modulus identical to that of HDT, the indirect restorative–cementing agent–HDT system acts as a monoblock that resists masticatory forces and redistributes stress evenly (13). When there is a difference in the values of this parameter, the more elastic material is more deformed than the less elastic one, which causes tension and rupture of the adhesive bonds (13). Sismaonoglu et al. investigated the flexural modulus of different CAD/CAM blocks: composite with ceramic particles, composite with a ceramic network, and feldspar (13). Both types of polymer blocks have values of this parameter closer to dentine than feldspar blocks. Similar are the results reported by Lawson et al. They reported that composite blocks had a flexural modulus similar to that of dentin, and lithium disilicate blocks had a higher flexural modulus (19). According to Alamoush et al., composite materials have a flexural modulus similar to hard dental tissues (26).

Digholkar et al. compared the flexural strength of materials for 3D printing, milling, and conventional materials containing polymethyl methacrylate (27). They reported significantly lower values for printing materials.

Mendonca et al. found that composite blocks have significantly lower stiffness and are more susceptible to fracture than ceramic materials (30). Alamoush et al. conclude from their research that material hardness is directly related to their composition (30). According to them, composite materials for CAD have a hardness close to that of HDT and combine the qualities of ceramic and composite materials, i.e., high resistance and low hardness (27).

Printing materials containing PMMA have significantly lower flexural modulus values than composite milling blocks (22). Lawson et al. investigated the material's hardness and wear to HDT (19). According to them, ceramic blocks cause enamel erosion, unlike composition blocks. Digholkar et al. found that 3D printing materials had significantly higher microhardness than conventional and milling materials (27). Composite blocks with ceramic particles (Cerasmart) have mechanical properties suitable for restoring significant defects. They have high tensile strength and a flexural modulus similar to dentin.

Wear resistance. Dental wear is the loss of hard dental tissue caused by factors other than dental caries and fractures (29). Composite blocks show less enamel wear compared to glass ceramics. Composite blocks with ceramic particles cause less abrasion of the antagonists (19). Lauvahutanon et al. investigated wear in composite with ceramic particles, composite with a ceramic network, and feldspar blocks (30). The authors found that the wear resistance of all indirect materials was increased compared to that of direct composite materials. They also reported that composite blocks with ceramic particles were the material of choice for single premolar crowns (30).

Xu et al. investigated the wear mechanism of composite blocks with ceramic networks compared to the wear mechanism of enamel (31). According to them, their Vickers hardness is similar to enamel's; however, their flexural modulus is significantly lower. The wear resistance of the blocks is considerably weaker, but the mechanism by which the wear takes place is similar to that of enamel. In the case of composite blocks with a ceramic network, the polymer part is changed first, then the ceramic piece as in the case of enamel – first the interprismatic spaces, then the enamel prisms, respectively (31). The wear resistance of the materials and preservation of the height of the finished structures determines their long-term use (5). The filler content of 3D printing materials has similar effects on other restorative materials (5). Modern 3D printing materials have low inorganic filler content and are suitable for temporary structures (5).
Park et al. investigated the wear resistance of various 3D printing materials, conventional and milling, containing PMMA. Materials for additive techniques demonstrated results comparable to the other two groups. However, wear was higher than similar' studies results in composite milling blocks – 1.22 mm3 (24). Based on the research data of composite blocks with ceramic particles (Cerasmart), a wear resistance close to that of HDT and conventional laboratory composites was established. There is no data on the wear resistance of the printed composites.

In the recent generations of nanoceramic hybrid materials, a stronger bond between the filler and the matrix has been achieved, with an increase of filler, resulting in a stronger material with improved aesthetic properties. With their improved strength and wear resistance, this group of materials creates very smooth and shiny surfaces, which is beneficial for the aesthetic appearance and limits the wear of the opposite tooth. The improved fracture toughness and flexibility of the material contribute to the buffering of masticatory forces. The application flexibility of these materials allows for their sandblasting or etching before cementation (9,15,16).
Hussain et al. investigated the release of monomers from several laboratory composite materials and composite blocks. No release of monomer was detected(6).

Color change. Acar et al. investigated the color change of different materials: nanofil composites for direct restoration (Filtek Supreme Ultra Universal), composite blocks with ceramic particles (Lava Ultimate), blocks with PICN (Vita Enamic), and lithium disilicate glass ceramics (IPS E- max CAD)[32]. Composite CAD/CAM materials demonstrated visible but clinically acceptable color change, making them a suitable material for fabricating esthetic structures.

Advantages and disadvantages of Computer-Aided Design Technologies

The advantage of CAD structures is related to the shorter time for elaborating the restoration (11). Introducing those into daily practice, it is possible to carry out complex treatment procedures (inlay/onlay/overlay) in one visit (3, 19). Therefore, the risk of contamination of the dentinal wound with microorganisms from the oral cavity is reduced. The quality of the structures is exceptionally high due to the precision of the digital printing and milling systems.
By analyzing the digital impression, the cavity elements on the computer screen are analyzed and can be corrected if necessary (33). Despite their advantages, milling techniques have disadvantages such as material loss, high cost of milling cutters for manufacturing, and generation of surface and subsurface defects in the finished structures (34). Additive manufacturing technologies are more economical and fast than milling technologies. They can easily reproduce complex structures, even those of a minimum thickness (35).

One of the disadvantages is the high cost of all the equipment and the need to train the dentist. There are difficulties in taking the digital impression and controlling the fluids (blood, saliva) in the operative field. Milling techniques are associated with disposing of a large amount of residual product. The details of the finished CAM structure depend on the size of the smallest milling machine (33).

Conclusion

The fast-developing digital technologies open up new perspectives for dentists. Milling and 3D printing materials are changing and improving. The knowledge of their chemical composition and mechanical properties assists clinicians in their selection of obturating materials. Additional laboratory and clinical studies are needed to establish the wear resistance of the composite materials for milling and printing and to determine the exact indications for their application.

DISCLOSURE STATEMENT

The authors deny any conflict of interest related to this study.

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