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Review article

MODERN COMPOSITES WITH CERAMIC FILLINGS FOR FIXED ADDITIVE PROSTHETIC CONSTRUCTIONS - ARE THEY RELIABLE FOR PERMANENT APPLICATION?

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ABSTRACT

Purpose: Based on a review of the latest materials for additive technologies in fixed prosthodontics, the authors aim to critically analyse the current scientific information on the mechanical and physical properties of composites with ceramic fillings for 3D printing.

Material/Methods: A keyword search of scientific sources was conducted in Google Scholar, PubMed, EBSCOhost, MDPI, Wiley online library without fixing a period. Study selection was based on specific eligibility criteria, incorporating both the inclusion and exclusion criteria.

Results: Initially, the literature sources identified by keywords consisted of 3,653 items. Of these, 693 were removed due to duplicate records, 956 records marked as ineligible by automation tools were also excluded. 1,237 were excluded for other reasons: 369 short communications, 471 case reports and 397 other documents. Of the remaining papers, 305 abstracts were excluded. Of the 462 reports sought for retrieval, 140 were removed due to irrelevance to the topic. The reports assessed for eligibility were 322, of which 251 articles were excluded. After this selection of the literature sources, 71 scientific publications relevant to the specific topic of this literature review remained.

Conclusions: The rapid introduction of 3D printing into dentistry on a global scale has led to a justifiable need for new, in-depth studies of composite materials with ceramic fillings.

Keywords: composites with ceramic fillings**,** dental ceramics, dental composites, dental materials for 3D crowns,

INTRODUCTION

The application of 3D printing in dentistry dates back to 2000 when it was used to fabricate implants and prosthetic constructions [1]. According to Oberoi G, et al. [2], literature data related to 3D printing in dentistry prove and confirm its wide application in the fields of oral and maxillofacial surgery, prosthetic dentistry, implantology, endodontics, orthodontics and periodontics. Other scientific studies describe the successful application of additive manufacturing with different materials through prototyping [3, 4, 5]. Barazanchi A, et al. [6] take note of the difficulties in working with some materials commonly used in dental practice, such as ceramics, for application with 3D printers. Rangelov [7], Vlahova and Zlatev [8], in their research papers, also focus on the introduction and development of additive manufacturing in prosthetic dentistry. In his PhD thesis, Rangelov [9] takes notice of the success of the use of 3D printing in the fabrication of reinforced prefabricated fixed constructions. Dikova et al. [10] present the advantages of additive manufacturing for removable and fixed prosthodontic purposes, summarising the possibilities of using a range of materials, such as polymers, composites, waxes, metal alloys and even ceramics.

It has been shown that dental materials in aesthetic fixed prosthodontics must meet the requirements for mechanical and physical properties [11, 12, 13] that are the same or similar to those of the tissues they restore [14]. The presence of biocompatibility and the ability to maintain their shape and volume in the conditions of the oral cavity allows optimal satisfaction of the medico-biological indicators: prophylaxis, function and aesthetics [15, 16, 17].

Conventional ceramics, which have established their undisputed place in crown and bridge prosthodontics, have been extensively studied with respect to all mechanical and physical characteristics, biocompatibility and wear resistance [18, 19, 20, 21]. According to Höland W, et al. [22] and Svanborg P [23], the indications for their application are wide ranging from inlay to bridge fabrication.

Tian et al. [24] compared conventional methods of fabricating constructions with 3D printing, favouring additive manufacturing as a faster and more accurate method. As a result of the specific characteristics of the technology, the final product is fabricated with high precision, accuracy, and individual conformability.

According to a publication by Oberoi G, et al. [2], there are scientific studies on metal- and polymer-based materials in additive manufacturing, while information on materials incorporating ceramics in their composition is scarcer. In their study, the authors also note that milled ceramic constructions show CAD/CAM system deficiencies, expressed in microscopic cracks and serious material loss. The authors conducted a study showing that ceramics produced by lithography yield similar mechanical properties to milled ceramics, according to which 3D printing technology has serious potential in fabricating constructions from materials incorporating ceramics in their composition [2].

Over the last decade, the advent of new technologies in dentistry, driven by the high demands for precision, accuracy and short-term results, has necessitated the use of advanced materials for additive manufacturing of fixed prosthetic constructions [25, 26, 27, 28].

The aim of the authors is, based on a review of the latest materials for additive technologies in fixed prosthodontics, to critically analyse the current scientific information on the mechanical and physical properties of composite materials with ceramic fillings for 3D printing available on the dental market in the last three years.

MATERIALS AND METHODS

The layout, analysis, and reporting of this literature review conformed to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) [29].

Scientific studies

A comprehensive literature search was conducted by three independent reviewers using scientific Google Scholar, PubMed, EBSCOhost, MDPI, Wiley online library, without fixing a period. The keywords encompassed various aspects as follows: “dental materials for additive manufacturing for permanent crowns”, “dental composites with ceramic fillings for 3D permanent crowns”; “dental ceramics for additive technologies”; “permanent additive prosthetic crowns”.

Eligibility Criteria

Study selection was based on specific eligibility criteria, incorporating both the inclusion and exclusion criteria. The inclusion criteria included articles, case reports applying 3D printing for permanent crown, reviews, systematic reviews or meta-analyses, and full-text articles. All articles were in English. The exclusion criteria comprised abstracts, short communications, letter to the editor, and studies lacking fundamental information about the physical and mechanical properties of the composites with ceramic fillings.

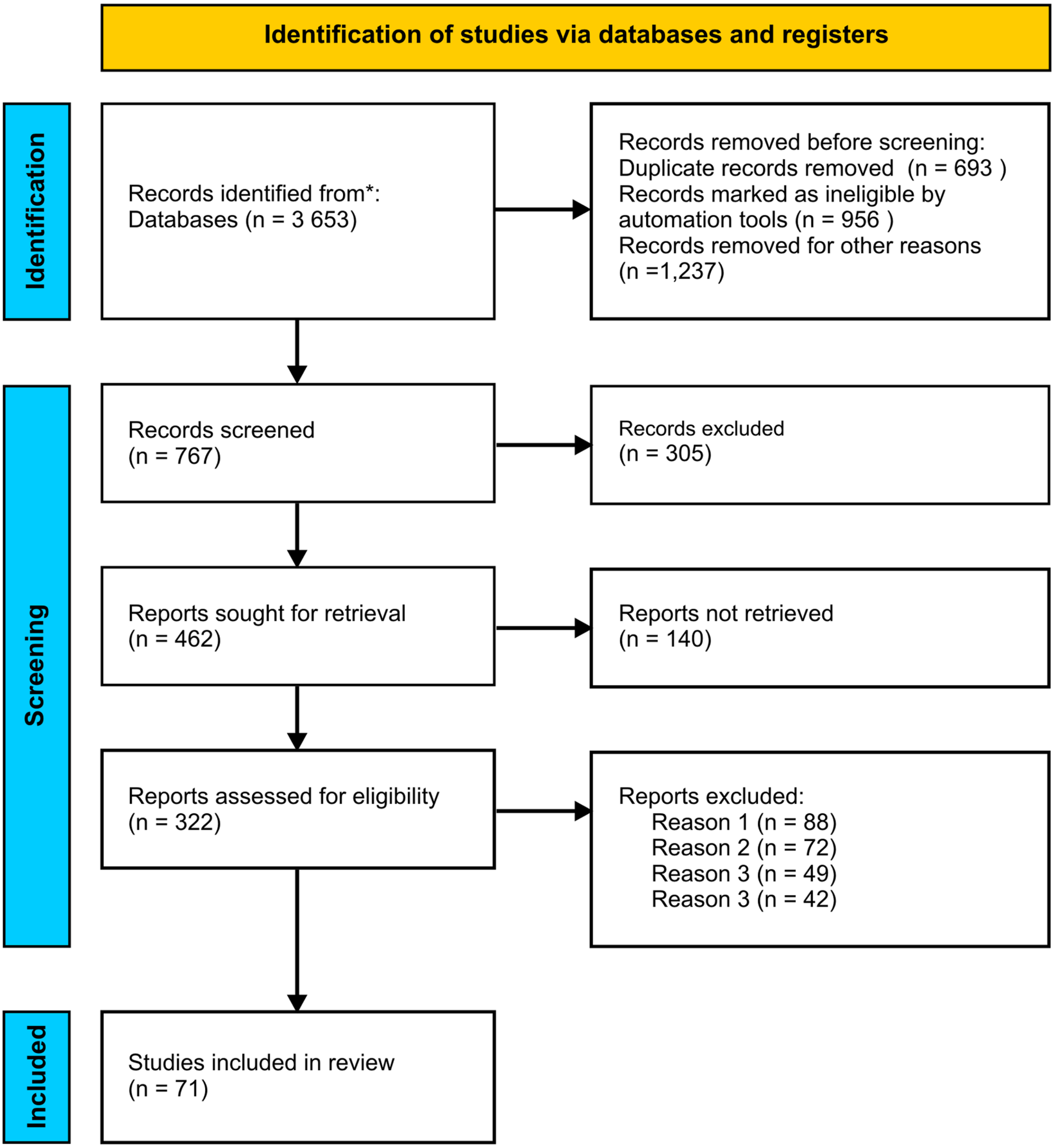
Analysis

The data regarding the mechanical and physical properties of modern composite materials with ceramic fillings intended for three-dimensional printing in prosthodontics were critically analysed A tabular system was formed using Microsoft Office Excel 2019 to establish the accuracy and analyse the data. Duplicate entries were eliminated from the research articles thus systematised. Due to the extremely recent advent of ceramic filling materials for fixed permanent prosthodontics, a limited number of experimental studies were identified. Technical characteristics of some materials shared by the manufacturer companies were added to supplement missing information.

RESULTS

Figure 1 is depicted in the PRISMA flow chart, mirroring the research article selection process, from initial identification to final inclusion in the study.

Fig. 1. The PRISMA flow chart for the selection process of the articles.



Initially, the literature sources identified by keywords consisted of 3,653 items. Of these, 693 were removed due to duplicate records, 956 records marked as ineligible by automation tools were also excluded. 1,237 were excluded for other reasons: 369 short communications, 471 case reports and 397 other documents. Of the remaining papers, 305 abstracts were excluded. Of the 462 reports sought for retrieval, 140 were removed due to irrelevance to the topic. The reports assessed for eligibility were 322, of which 251 articles were excluded. After this selection of the literature sources, 71 scientific publications relevant to the specific topic of this literature review remained.

Contemporary scientific sources explore new materials indicated for additive manufacturing of fixed constructions [30, 31, 32, 33, 34]. Vlahova and Zlatev [8] note that the addition of ceramic particles to a polymer structure intended for 3D printing of constructions increases the abrasion resistance of the final product. In 2023, Cai et al. [20] summarised that the most commonly used ceramic materials for additive manufacturing in fixed prosthodontics are glass-ceramics, zirconia ceramics and alumina ceramics.

1. Glass-ceramics

Glass-ceramics are described as “bioactive glass-ceramics” [35, 36], which have the ability to stimulate specific biological responses at the material-tissue interface, and “restorative glass-ceramics” [37, 38].

Bioactive glass-ceramics are used in implant treatments and promote bone regeneration. Restorative glass-ceramics have indications in the fabrication of inlays, onlays, full crowns, partial crowns, bridges and veneers [30, 39, 40].

Höland et al. [41] note the most important types of glass-ceramics for clinical application: leucite-, lithium disilicate- and apatite-containing ceramics. According to Galante et al. [31] and Fu et al. [42], lithium disilicate-based glass-ceramics have good mechanical properties: modulus of elasticity of 90-100 GPa, flexural strength of 250-365 MPa and fracture strength of 2-3. 5 MPa.m$^{1/2}$, while leucite-based ceramics have the following parameters: modulus of elasticity of 65-67 GPa, flexural strength of 55-134 MPa and fracture strength of 0.8-1.3 MPa.m$^{1/2}$ or 2.31 ± 0.17 MPa.m$^{1/2}$.

Apatite-containing glass-ceramics have the lowest indices: modulus of elasticity of 70-88 GPa, flexural strength of 140-180 MPa and fracture strength of 1.2-2.1 MPa.m$^{1/2}$ [17].

The application of glass-ceramics by means of 3D printing methodology is a subject of active scientific interest [43-45]. Baumgartner et al. [46] describe the “outstanding mechanical properties” of glass-ceramics fabricated by stereolithography (SLA). The research team reported mechanical flexural strength index values of more than 400 MPa for the additively fabricated one, while it is around 200 MPa for the conventional one [15].

According to Yang et al. [47], the additively manufactured glass-ceramics have a microhardness of 772.05 HV, flexural strength of 205.97 MPa and modulus of elasticity of 97.06 GPa. Conventionally fabricated glass-ceramics in experimental studies are described with a hardness or the hardness of 731.63 ± 30.64 HV [48], flexural strength of 443.63 ± 38.90 MPa and modulus of elasticity of 70.44 ± 1.97 GPa [49]. These data relative to the results from other scientific sources [43, 49] direct the analysis to consider the superiority of 3D printed glass-ceramics over conventional ones in relation to the above mechanical parameters [48].

In 2020, Baumgartner et al. [46] summarised that a material that has been additively manufactured is characterised by “excellent mechanical properties”, fully meeting the requirements for fixed prosthodontics.

2. Zirconia ceramics

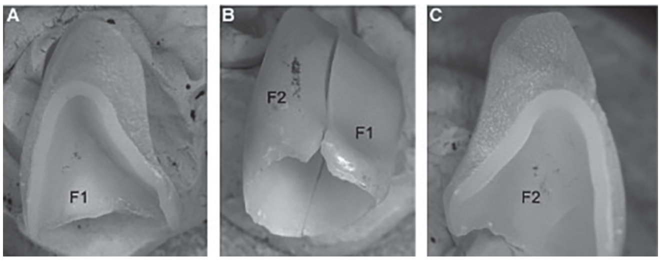
Zirconia ceramics (ZrO2) are now increasingly used in dentistry [50, 51, 52]. Barazanchi A, et al. [6] and Cai et al. [20] describe this material as highly suitable for prosthodontic purposes due to its biocompatibility and easy adaptation to surrounding soft tissues. The authors note that “zirconium has high strength” (150 MPa) and describe it as suitable for use with stereolithography (SLA) and selective laser sintering (SLS) technology. According to some literature sources, zirconia ceramics can also be fabricated by pushing a suspension through a nozzle (direct inkjet printing) [8, 54, 55].

Regarding the mechanical properties of zirconia ceramics, Galante et al. [31] consider that it has a fracture trength of 1.8 MPa.m$^{1/2}$, high hardness of 5-15 GPa, flexural strength of 177-1,000 MPa, modulus of elasticity of 100-250 GPa and tensile strength of 115-711 MPa. Cai et al. [20] and Aragón-Duarte et al. [56] note that the material is also referred to as “ceramic steel” precisely because of its good mechanical properties.

The zirconia ceramics commonly used in dentistry are stabilised with 3 mol% yttrium tetragonal zirconia polycrystal (3Y-TZP), and this type of ceramic contains a stable tetragonal phase and is tempered by the martensitic phase transformation of the t-phase, making it suitable for processing with various technologies [57-60].

Ebert et al. [54] report an average fracture strength of 6.7 MPa.m$^{1/2}$ for the material produced by using the direct inkjet printing technology. In the study of Xing et al. [55], additively manufactured zirconia ceramics are characterised by the following mechanical properties: fracture strength of 6.37 ± 0.25 MPa.m$^{1/2}$, hardness of 13.90 ± 0.62 GPa, and flexural strength of 1,154 ± 182 MPa.

Fig. 2. Fracture of an upper-incisor zirconia crown. (A) Overview over the fracture surface of fragment 1. (B) Repositioned fragments, lingual view, one small piece is missing. (C) The fracture surface of fragment 2 [39].



The mentioned literature data allow the generalisation that zirconia ceramics produced by means of additive technologies are characterised by impressive mechanical performance, which determines a significant potential for its use in the fabrication of fixed restorations with high precision and minimal material consumption [54, 61].

3. Alumina ceramics

Alumina ceramics (Al2O3), also called aluminium oxide, has found its application in dentistry for the fabrication of endodontic pins, dental implants, single crowns, inlays, onlays, veneers, and bridges [62, 63, 64]. The research of Al-Sanabani et al. [64] confirms these indications, describing the application of alumina ceramics in different fields of dentistry.

According to a 2022 publication by Sarker et al. [62], alumina (Al_2O_3)-based ceramics have low fracture strength (3.3-5 MPa.m$^{0.5}$). To reduce the possibility of fracture, zirconia particles are added to produce zirconia-toughened alumina ceramics, which have a higher hardness of 10-18 GPa, modulus of elasticity of 350-450 GPa, and fracture strength of 4-10 MPa.m$^{0.5}$ [62].

Some authors [31, 65] describe alumina ceramics as suitable for application with stereolithography (SLA) technology. Chugunov et al. [65] argue that the mechanical and physical properties of alumina ceramic samples produced by stereolithography are comparable to those produced by conventional methods. According to Ndinisa et al. [66], additively fabricated alumina ceramics are characterised by satisfactory mechanical properties close to those of conventional ceramics. The authors reported similar results in terms of hardness and fracture strength. The results presented for additively manufactured alumina ceramics in terms of hardness, flexural strength, and fracture strength are as follows: 18 GPa; 374 MPa and 3.8 MPa.m$^{1/2}$, respectively. According to Sarker et al. [62], conventionally fabricated alumina ceramics have a mechanical hardness of 17.65 GPa, a modulus of elasticity of 380 GPa and a fracture strength of 3.3-5 MPam$^{0.5}$.

The above data show that ceramic materials, regardless of the fabrication technology, exhibit very good mechanical and physical properties, making them suitable and preferred for fixed prosthodontics. The growing interest in 3D printing of fixed prosthetic constructions and their increasing use in clinical practice has led to the development and improvement of materials for this technology [67, 68, 69].

One of the newest composites for additive fabrication of fixed permanent constructions are ceramic-reinforced composites. According to information from companies producing dental materials, three extremely new hybrid materials for additive fixed permanent constructions have entered laboratory and clinical practice in the last three years [70, 71, 72]. The results obtained refer to three qualitatively new hybrid materials for 3D printing that contain ceramic fillings. These materials are designed to create fixed permanent restorations. Their indications are related to the fabrication of single crowns, inlays, onlays and veneers. The application of this new generation of composite materials in bridge treatment has not yet been explored.

In the methodology for fabrication of single crowns, inlays, onlays and veneers, the recommended minimum thickness indicated by BEGO (Bremen, Germany) is 1 mm [70]. The measurement indicated by SAREMCO (Switzerland) is as follows: occlusal 1.5 mm, marginal 1.0 mm, and for onlays, the thickness in the tubercular area is recommended to be 2.0 mm. For SprintRay material (Los Angeles, CA, USA) is as follows: crown wall and occlusal surface e” 1.0 mm, marginal edge e” 0.5 mm, veneer e” 0.5 mm. Ceramic Crown (SprintRay, Los Angeles, CA, USA) is described as a photopolymerisable polymer material with more than 50% inorganic ceramic content in its composition [72].

According to the available scientific data from experimental studies of the materials considered in the literature review, the investigated mechanical properties are presented and compared below in the following sequence: hardness, flexural strength, modulus of elasticity, wear resistance and adhesive bond [73, 74].

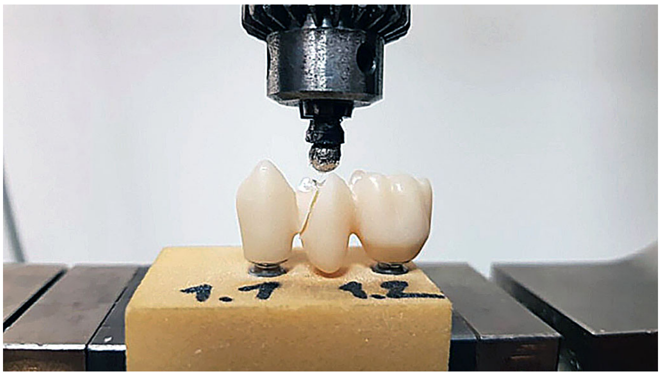
The established scientific data from the literature study of Grzebieluch W, et al. [75] in 2021 concerning this mechanical indicator for VarseoSmile Crown plus (BEGO, Bremen, Germany) revealed that the Vickers hardness of this material was 25.8 (±0.7) HV01 when tested using a Vickers intender (Shimadzu HMV-2T, Japan) with a load of 980.7 mN (HV 0.1). In another study by Alkandary (Boston University) [74] for VarseoSmile Crown plus (BEGO, Bremen, Germany), CROWNTEC (SAREMCO, Switzerland) and Ceramic Crown (SprintRay, Los Angeles, CA, USA), the reported Vickers microhardness values were, as follows: 22.66 HVN, 26.31 HVN and 44.07 HVN, respectively. During the study, the author used a Micromet 2003 microhardness tester (Buehler, Illinois, USA), subjecting the test bodies to 50 g of loading for 15 seconds.

In a comparative study by Schulz [19], fracturing results showed fairly close values for temporary (VarseoSmile Temp A2) and permanent resin material (VarseoSmile Crown Plus A2) containing 30 to 50% inorganic fillers, table 1 and figure 3.

Table 1. Mean Values of VarseoSmile Temp (Group VST) and VarseoSmile Crown Plus (Group VSCP) according to Schulz [19]:

	Force Break in IN	Displacement Force Break in mm
Mean values (VST)	311,80 ± 96,77 N	**1**.47 mm
Mean values (VSCP)	306.50 ± 94.68 N	1.46 mm

Fig. 3. Fracture line according to Schulz research [19].



According to the research data of Grzebieluch et al. [75], the flexural strength of VarseoSmile Crown plus (BEGO, Bremen, Germany) was 119.85 MPa after a three-point test with a support range of 12 mm and a speed of 1 mm/min using a LabTest 5.030S machine (LaborTech, Opava, Czech).

In a publication by Alkandary [74], the values recorded after a three-point flexural strength test with a support range of 20 mm on the three materials were as follows: VarseoSmile Crown plus (BEGO, Bremen, Germany) - 91.16 MPa; CROWNTEC (SAREMCO, Switzerland) - 126.38 MPa; Ceramic Crown (SprintRay, Los Angeles, CA, USA) - 160 MPa. The author also conducted tests regarding biaxial flexural strength on the materials and observed the following results: VarseoSmile Crown plus (BEGO, Bremen, Germany) - 120.24 MPa; CROWNTEC (SAREMCO, Switzerland) - 134.21 MPa; Ceramic Crown (SprintRay, Los Angeles, CA, USA) - 170.76 MPa. The tests were conducted with the Instron 5566 universal test system (Instron, USA) apparatus using a plunger-equipped device, and the samples were positioned on three balls.

In a scientific study performed in 2022, Pablo J. Atria et al. [68] also conducted biaxial flexural strength tests on CROWNTEC (SAREMCO, Switzerland) using the same methodology and apparatus. From the results denoted in the paper, the value for the material was 208.03 MPa.

In a scientific paper, Grzebieluch et al. [75] reported the modulus of elasticity of VarseoSmile Crown plus (BEGO, Germany) with a value of 4.37 GPa.

According to a study conducted by Alkandary [74] on the modulus of elasticity of the materials, the results were as follows: Ceramic Crown (SprintRay, Los Angeles, CA, USA) - 7.8 GPa, followed by VarseoSmile Crown plus (BEGO, Germany) - 6.2 GPa and CROWNTEC (SAREMCO, Switzerland) - 4.5 GPa. The two research teams recorded significantly different results in terms of the modulus of elasticity mechanical indicator for the VarseoSmile Crown plus material (BEGO, Germany). There is a need for further studies to clarify the modulus of elasticity mechanical indicator for the three materials under equal experimental conditions.

The keyword review allows the selection of only two scientific sources presenting experimental studies on the wear resistance mechanical indicator. In a technical leaflet, BEGO (Bremen, Germany) [70] describe a test on the wear resistance of VarseoSmile Crown plus (BEGO, Bremen, Germany) by scanning the occlusal surfaces of the studied crowns subjected to 10 years of *in vivo* masticatory loading. The reported material loss was 0.275 mm.

Studies were also conducted on abrasion and scratching of the material by simulating tooth brushing using electric brushes with a lateral movement of 5 mm, a speed of 10 mm/sec and a pressure force of 1.5 N. In the results, a mass loss of 0.08 mg for the 1-year simulation, 0.32 mg for the 3-year simulation, and 0.56 mg for the 5-year simulation was observed. The average roughness (Ra) on the surface of the experimental objects was Ra of 0.09 ìm after 1-year simulation, Ra of 0.10 ìm after 3-year simulation, and Ra of 0.11 ìm after 5-year simulation [75].

In 2023, Jockin et al. [73] published two clinical cases prosthetised with single crowns of Ceramic Crown material (SprintRay, Los Angeles, CA, USA) printed using a SprintRay 55 3D printer (SprintRay, Los Angeles, CA, USA). After a follow-up of 6 months, based on the results, the authors defined the material as suitable for crown prosthodontics, as no clinical wear was observed on the constructions and on the natural antagonist teeth.

The physical properties of their colour and translucency were investigated and reviewed.The conducted keyword search did not provide any scientific sources investigating or questioning other physical properties of the materials. One scientific experiment conducted by Intralawan et al. [69] in 2022 was found to relate only to VarseoSmile Crown Plus (BEGO, Germany). The authors investigated the colour and translucency of experimental objects manufactured from the material by immersing them in water, coffee and cola for a period of one month in an incubator at 37ºC, with the solutions being renewed every day. Calculations were performed duringthe first week, the second week and after one month using the VITA Easyshade spectrophotometer (VITA, North America). Changes in colour and translucency were determined by numerical comparison using a formula.In conclusion, the authors noted that the materials are prone to colour and transparency change.

Table 2 presents a synthesis of the scientific data regarding additive manufacturing in prosthodontics. This table provides research directions in this area, making it a valuable reference for readers seeking an overview of the current state of research in this area.

Table 2. Synthesis of scientific data regarding additive manufacturing in prosthodontics.

Topic	Area of Application/Significance	References
Additive manufacturing	Introduction and application	Gross et al., 2014 [1]
		Oberoi et al., 2018 [2]
	Application in prosthodontics	Rangelov, 2023 [7]
		Vlahova, 2021 [8]
		Rangelov, 2021 [9]
		Dikova et al., 2015 [10]
	Types of materials for additive manufacturing	Katreva et al., 2016 [3]
		Bagheri et al., 2019 [4]
		Rangelov, 2021 [5]
		Barazanchi et al., 2016 [6]
		Dikova et al., 2015 [10]

Materials	Requirements to materials in aesthetic fixed prosthodontics	Vlahova, 2021 [8]
		Liu et al., 2008 [11]
		Mahmood et al., 2015 [12]
		Manappallil, 2016 [13]
		Anastasov, 2013 [14]
		Magne et al., 1999 [15]
		Ritzberger et al., 2010 [16]
		Pavloviæ et al., 2017 [17]
	Conventional VS additive ceramics	Conrad et al., 2007 [18]
		Schulz et al., 2023 [19]
		Cai et al., 2023 [20]
		Naji et al., 2018 [21]
		Höland et al., 2008 [22]
		Svanborg et al., 2020 [23]
		Tian et al., 2021 [24]
	Introduction of advanced materials for additive manufacturing	Vlahova, 2021 [8]
		Cai et al., 2023 [20]
		Alharbi et al., 2016 [25]
		Schweiger et al., 2020 [26]
		Hartmann et al., 2019 [27]
		Dilling, 2018 [28]
		Monmaturapoj et al., 2013 [30]
		Galante et al., 2019 [31]
		Lakhdar et al., 2021 [32]
		Schonherr et al., 2020 [33]
		Nötzel et al., 2018 [34]
Glass-ceramics	Application	Monmaturapoj et al., 2013 [30]
		Montazerian et al., 2017 [35]
		Höland et al., 2006 [36]
		Saint-Jean et al., 2014 [37]
		Chatzistavrou et al., 2010 [38]
		Oilo et al., 2014 [39]
		Wildgoose et al., 2004 [40]
		Höland et al., 2008 [41]
	Mechanical properties of conventional glass-ceramics	Anastasov, 2013 [14]
		Ritzberger et al., 2010 [16]
		Galante et al., 2019 [31]
		Fu et al., 2016 [42]
		Sun et al., 2017 [43]
		Li et al., 2019 [44]
		Zhang et al. 2022 [45]
		Baumgartner et al., 2020 [46]
		Elsaka et al., 2016 [49]
	Mechanical properties of additive glass-ceramics	Anastasov, 2013 [14]
		Baumgartner et al., 2020 [46]
		Yang et al., 2021 [47]
		Leung et al., 2015 [48]
		Elsaka et al., 2016 [49]

Zirconia ceramics	Application	Vlahova, 2021 [8]
		Cai et al., 2023 [20]
		Nakai et al., 2021 [50]
		Yin et al., 2023 [51]
		Agustín-Panadero et al., 2014 [52]
		Chaudhary et al., 2021 [53]
		Ebert et al., 2009 [54]
		Xing et al., 2017 [55]
	Mechanical properties of conventional zirconia ceramics	Cai et al., 2023 [20]
		Galante et al., 2019 [31]
		Aragón-Duarte et al., 2017 [56]
		Pandoleon et al., 2017 [57]
		Zhang et al., 2019 [58]
		Trunec et al., 2008 [59]
		Kontonasaki et al., 2020 [60]
	Mechanical properties of additive zirconia ceramics	Ebert et al., 2009 [54]
		Xing et al., 20177 [55]
		Alves et al., 2020 [61]
Alumina ceramics	Application	Galante et al., 2019 [31]
		Sarker et al., 2022 [62]
		Hashiguchi et al., 1999 [63]
		Al-Sanabani et al., 2014 [64]
	Mechanical properties of conventional alumina ceramics	Sarker et al., 2022 [62]
		Hashiguchi et al.1999 [63]
		Al-Sanabani et al., 2014 [64]
	Mechanical properties of additive alumina ceramics	Sarker et al., 2022 [62]
		Chugunov et al., 2020 [65]
		Ndinisa et al., 2020 [66]

DISCUSSION

The available literature data with respect to the investigated hardness of ceramic materials in the context of the methodology used, either additive manufacturing or conventional methodology, allow the construction of a working hypothesis for further new experimental studies. Existing data to date indicate a higher hardness of additive glass-ceramics (772.05 HV) [47] than conventional ceramics (731.63 ± 30.64 HV) [48]. It can be expected that additive manufacturing technology will improve the mechanical hardness property of glass-ceramics. Zirconia ceramics fabricated by 3D printing also demonstrated significant hardness (13.90 ± 0.62 GPa) [55], which falls within the hardness range of conventional zirconia ceramics (5-15 GPa) [31]. Similar conclusions can be drawn for alumina ceramics, where the additively manufactured ceramic has a hardness of 18 GPa [66] and the conventional one - 17.65 GPa [62]. These results direct the literature analysis to the generalisation that in terms of quality, 3D printing is not inferior but probably superior to conventional techniques in terms of the hardness mechanical indicator of the material.

It could be found that additively manufactured ceramics are characterised by better microhardness compared to conventional ones. Such results would highlight the potential of additive manufacturing in dentistry.

The results of this review show that additively manufactured ceramic materials demonstrate significant mechanical advantages in terms of flexural strength compared to conventional materials. Glass-ceramics fabricated by 3D printing have been noted to have flexural strength values in excess of 400 MPa, which is twice that of conventional glass-ceramics, which are around 200 MPa [14]. This suggests that additive manufacturing can significantly improve the mechanical performance of glass-ceramics. Zirconia ceramics produced by additive manufacturing possess flexural strength values of 1154 ± 182 MPa [55], which exceed those of conventional ones of 177-1,000 MPa [31]; therefore, it can be expected that additive manufacturing will produce zirconia ceramics with very high flexural strength. Additive alumina ceramics also demonstrate a high flexural strength of 374 MPa, making them competitive with other materials [66].

Based on the data, we can summarise that additively manufactured ceramic materials exhibit excellent flexural strength, which in many cases exceeds that of conventional ceramics. The results support the potential of additive manufacturing in dentistry to create high-quality ceramic components that are resistant to mechanical stresses. The studied ceramic materials with ceramic fillings have good flexural strength exceeding that of conventional ceramics. However, the paucity of scientific evidence in this direction should be borne in mind, which is probably justified by the fact that the materials are recent entrants to the dental market.

From the present study, we can compare the modulus of elasticity of different types of ceramic materials, both conventional and additively manufactured. Conventional lithium disilicate-based glass-ceramics show the highest modulus of elasticity of 9-100 GPa, which makes it extremely strong and durable. It is followed by apatite glass-ceramics with values between 70-88 GPa and leucite glass-ceramics with a modulus of elasticity of 65-67 GPa [31].

According to the study, the additively manufactured glass-ceramics have a modulus of elasticity of 97.06 GPa [47], which is comparable to the highest values of conventional lithium disilicate-based glass-ceramics. This indicates that additive manufacturing can create glass-ceramics with very high mechanical properties, making it suitable for choice in dentistry.

CONCLUSIONS

Biocompatibility and the ability of the materials to retain their shape and volume in the oral cavity allow optimal meeting of the medico-biological requirements: prevention, function and aesthetics. All the requirements for the mechanical and physical properties of the materials used in conventional methods for fixed restoration in dental practice are also applicable to the materials used in additive manufacturing.

Physical properties of ceramic materials, especially their colour and translucency, are essential for the aesthetics of prosthetic constructions. The analysis of the scientific literature showed a lack of experimental studies, allowing a comparative characterisation between the three materials in terms of their mechanical properties.

Finally, there is a need for further mechanical and physical studies, conducted under equal experimental conditions, involving the materials to ensure a full assessment of their properties. Such studies would contribute to a better understanding and selection of the most appropriate material for the specific needs in clinical practice.

LIMITATIONS

1. Mechanical Properties:

• Strength and Durability: While composites with ceramic fillings have improved strength and wear resistance, they may still not match the mechanical properties of traditional materials like metal alloys or fully ceramic restorations. This can lead to reduced longevity, particularly under high occlusal loads.

• Fracture Risk: Composites with ceramic fillers can be more prone to fracture or chipping compared to metal or ceramic prosthetics, especially if not properly fabricated or used in high-stress areas.

2. Adhesion and Bonding:

• Bond Strength: The bond between the composite material and the tooth or implant substrate may not be as strong as desired, potentially leading to debonding or microleakage over time.

• Surface Treatment: The effectiveness of surface treatments and bonding protocols can vary, affecting the overall longevity and stability of the prosthetic construction.

3. Aesthetic Limitations:

• Color Stability: Over time, the resin matrix in composites can discolor or stain, particularly when exposed to foods, beverages, or habits like smoking. Ceramic fillers improve this but may not entirely prevent it.

• Wear and Polishability: While ceramic-filled composites can achieve a good initial polish, maintaining this luster over time can be challenging, and wear patterns may differ from natural tooth enamel, affecting aesthetics.

4. Complexity in Fabrication:

• Technique Sensitivity: The fabrication of these composites is technique-sensitive, requiring precision in layering, curing, and finishing processes. Errors in these steps can compromise the final product's quality.

• Additive Manufacturing Limitations: The current state of additive manufacturing (3D printing) for composites with ceramic fillings may not always achieve the precision or material properties required for highly detailed or load-bearing prosthetics.

5. Biocompatibility and Long-Term Performance:

• Material Interaction: The interaction between the composite and the surrounding biological tissues is crucial. While generally biocompatible, some patients may have adverse reactions to certain resin components.

• Longevity: The long-term performance of these materials under varying oral conditions (e.g., pH, temperature changes, enzymatic activity) is still under study, and more clinical data is needed to confirm their efficacy over decades.

FUTURE PERSPECTIVES

1. Material Advancements:

• Nanotechnology: The integration of nanotechnology could lead to the development of composites with even finer ceramic particles, improving mechanical properties, wear resistance, and aesthetics.

• Self-Healing Materials: Future composites may incorporate self-healing properties that could extend the lifespan of prosthetics by automatically repairing minor cracks or fractures.

2. Improved Additive Manufacturing Techniques:

• Precision 3D Printing: Advances in 3D printing technology could allow for more precise control over the placement of ceramic fillers, optimising the mechanical properties and aesthetics of prosthetic constructions.

• Hybrid Printing: The development of hybrid printing techniques that combine different materials in a single process could lead to prosthetics with graded properties, where different areas have different strengths and aesthetics tailored to their specific functional needs.

3. Enhanced Adhesion and Bonding Protocols:

- New Adhesives: The development of new adhesive systems specifically designed for ceramic-filled composites could improve bonding strength and reduce the risk of debonding or microleakage.
- Surface Functionalisation: Advances in surface functionalisation of both the tooth/implant and the composite material could lead to more durable and stable bonds, enhancing the longevity of the prosthetic.

4. Customised Solutions:

- Personalised Prosthetics: With advances in digital dentistry and materials science, future composites could be tailored to the specific needs of individual patients, considering factors like occlusal forces, aesthetic preferences, and biological compatibility.
- Smart Materials: The incorporation of smart materials that can respond to changes in the oral environment, such as pH or temperature, could lead to prosthetics that adapt to the conditions of the mouth, potentially improving comfort and performance.

5. Clinical and Long-Term Studies:

- Evidence-Based Improvements: As more long-term clinical data becomes available, it will be possible to refine composite formulations and prosthetic designs to maximise performance and patient outcomes.
- Regenerative Approaches: The future may also see the integration of regenerative medicine techniques, where composites are combined with biologically active materials that promote tissue regeneration or healing.

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