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REVIEW

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Glass fiber-reinforced composites in dentistry

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Abstract

Background: Enormous improvements in dental materials' manufacturing for the aim of producing durable dental materials without compromising the aesthetic properties were developed. One of the approaches that fulfill this aim is the use of reinforcing glass fibers as fillers into dental materials, typically resin polymers, in order to obtain glass fiber-reinforced composites. Glass fiber-reinforced composite offered many advantages to the dental materials though some limitations were recorded in many literature.

Methods: In this review, a study of the glass fibers' types, factors affecting the properties and the properties of glass fibers reinforced materials was carried out; in addition, research papers that experimentally studied their applications in dentistry were presented.

Conclusion: The success of glass fibers reinforced composites in dentistry depends on glass fibers' composition, orientation, distribution, amount, length and adhesion; these factors once employed according to the required clinical situation would provide the essential reinforcement to the dental restorations and appliances.

Keywords: Glass fibers, Resin polymers, Reinforced composite, Properties, Dental application

Background

Glass fibers are thin strands, silica-based glass, that are extruded into small-diameter fibers. These fibers are enclosed into resin matrix to produce glass fiber-reinforced composites.

Glass fiber-reinforced composites are polymerized monomer matrix that is filled by fine thin glass fibers, chemically bonded to that matrix using silane coupling agents. The concept of the reinforcing effect of the fiber fillers depends on the transfer of stress from the polymer to the fibers as well as the role of each fiber in preventing crack propagation.

Glass fibers are existing in different compositions, namely A-glass, C-glass, D-glass, AR-glass, S-glass and E-glass, they have different properties and uses, but generally, all glass fibers are amorphous, and they are formed of three-dimensional network of silica, with oxygen and other atoms arranged randomly.

Glass fibers are employed in different fields, such as engineering, plastic industries, electronic boards, radar housing and in dentistry. They are applied in the manufacturing of different dental products such as fixed partial denture, endodontic post systems and orthodontic fixed retainers.

Glass fiber-reinforced composite offers many advantages to the dental materials, as they provide acceptable aesthetics, non-corrosiveness, high toughness, metal free, non-allergic effect, applicable chair side handling, biocompatibility and ability to be tailored to meet the specific requirement of many dental applications (Ferracane and Condon 1992; Ramakrishna et al. 2001).

Methods

Different types of reinforcing fibers exist, such as carbon/epoxy, polyaramide, ultra-high molecular weight polyethylene (UHMWPE) and glass fibers. Each has their own advantages and disadvantages; for instance, carbon/

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epoxy fibers have high tensile, fatigue strength and modulus of elasticity, but poor esthetics, while polyaramide fibers are difficult to handle and polish; on the other hand, UHMWPE fibers have poor adhesion to polymer matrix; meanwhile, glass fibers have enhanced adhesion to the polymer matrix with better esthetics; that's why glass fibers have gained wide-spread in dentistry (Khan et al. 2015).

Glass fibers types (Khan et al. 2015).

1. A-Glass fibers: they are high-alkali glass with 25% soda and lime. They are used as filler in plastic industry as they are cheap and easy to manufacture though they have poor chemical resistance to water and alkaline media.
2. C-Glass fibers: they have high chemical resistance to corrosion so they are used in contact with acidic materials; however, they have low strength properties.
3. D-Glass fibers: they have greater electrical properties and low dielectric permittivity so they are used in electronic boards as a reinforcing material. However, they have low strength and poor chemical resistance.
4. S-Glass fibers: they have high strength, modulus of elasticity, corrosion resistance with low dielectric permittivity. Unfortunately, they are difficult to manufacture and thus are expensive.
5. AR-Glass fibers: they have high resistance to crack propagation and great impact strength due to the presence of zirconium; however, they have high melting temperature that restricts their application.
6. E-Glass fibers: they are electric grade glass fibers and are the most used type of glass fibers (50% of the glass fiber market) (Kolesov et al. 2001), due to their low cost, high electrical insulation and high water resistance. Unfortunately, boron oxide and fluorine are volatile elements that might disturb the glass chemical homogeneity and pollute the environment.

Of all these types, only E-glass and S-glass fibers have used in dentistry. Many dental products reinforced with glass fibers are available commercially such as pre-impregnated E-glass fiber-reinforced composite (Vectris Pontic, Ivoclar Vivadent, Schaan, Liechtenstein), pre-impregnated S-glass fiber-reinforced composite (FiberKor, Pentron Corporation,Wallingford, CT, USA) and PMMA-impregnated E-glass fiber-reinforced composite (Stick Tech, Turku, Finland) (Khan et al. 2015).

Factors affecting the properties of glass fiber-reinforced dental materials

Chemical composition of glass fibers

The content of alkali metals (Li, Na, K, etc.) and alkaline earth metals (Mg, Ca, etc.) in glass fibers plays an important role in their physical and mechanical properties. The chemical composition and the properties of the most used glass fibers in dentistry, S-glass and E-glass, are listed in Table 1. It is well documented that the constitutional elements of glass fibers are critical factors for the hydrolytic stability of the glass fibers. Boron oxide (B_2O_3), for example, could react with saliva in oral cavity with the subsequent leaching of B_2O_3; this reaction induces corrosion effects on glass fibers causing negative impact on glass strength. E-glass fibers contain 6–9 wt% B_2O_3 and S-glass fibers contain less than 1 wt% B_2O_3 (Li et al. 2014; Miettinen et al. 1999). This problem was overcome by pre-impregnating (Prepreg) the glass fibers with polymer matrix, or the use of impregnated fibers, which are glass fibers impregnated with highly porous PMMA during manufacturing (Takahashi et al. 2006).

Table 1 A comparison between S-glass and E-glass fibers, composition and properties. (Meriç et al. 2005; Chong and Chai 2003; Vallittu 1998)

Point of comparison	S-glass fibers	E-glass fibers
Structure	Amorphous (not crystalline)	Amorphous (not crystalline)
Chemical composition	SiO_2 (62–65 wt%), Al_2O_3 (20–25 wt%), MgO (10%), B_2O (< 1 wt%)	SiO_2 (53–55 wt%), CaO (20-24 wt%), MgO (20–24 wt%), B_2O (6–9 wt%), Al_2O_3 (14-16 wt%)
Density	2.485–2.495 g/cm^3	2.55–2.6 g/cm^3
Tensile strength	4700–4800 MPa	1950-2050 MPa
Elastic modulus	86–93 GPa	72–85 GPa
Hardness	5000–6000 MPa	3000–6000 MPa
Endurance limit	4050–4410 MPa	2970–3110 MPa
Fracture toughness	0.5–1 MPa m^{½}	0.5–1 MPa m^{½}

Orientation of glass fibers in the polymer matrix

Glass fibers are present in different orientations in the polymer matrix; these orientation provide different properties and strengthening effect. They could have **random** or **longitudinal orientation**; the random (chopped) oriented fibers give isotropic properties, i.e., same mechanical properties in all directions, while the longitudinal orientation in the form of *(a) unidirectional continuous fiber laminates*, which provide anisotropic effect, i.e., they have different properties in different direction; it shows the highest strength and stiffness in composite, but only in the one direction of the fibers. *(b) bidirectional discontinuous short and long fiber* or *textile fabrics* (woven, knitted and braided fabrics) laminates which present orthotropic effect, i.e., same properties in two directions with different properties in the third, orthogonal direction. A combination of two or more types of orientations in a composite is called hybrid fiber composites (Tezvergil et al. 2003).

In general, the parallel orientation of the glass fibers to the applied force results in strength reinforcement, while those perpendicular to the applied force yield low reinforcement (Khan et al. 2015).

A composite with the longer fibers displays higher wear resistance (Callaghan et al. 2006), higher ultimate strength and fracture resistance (Xu et al. 2000). Garoushi et al. (2007b) and Manhart et al. (2000) stated that short glass fibers can be detached readily from the matrix resulting in high wear.

In addition, glass fiber orientation affects thermal behavior and polymerization shrinkage of the composites as well (Tezvergil et al. 2006).

Distribution of fibers

The distribution of glass fibers, whether evenly distributed or concentrated in a particular site, affects its mechanical properties. If they are evenly distributed, fatigue strength increases, and if they are concentrated at one area, then the stiffness and strength increase (Khan et al. 2015). Usually, distribution of glass fibers is controlled by its application; however, in most dental literature, glass fibers were positioned in the center of the specimens (Dos Santos et al. 2000).

A study conducted by Alander et al. in 2021 proved that FRC reinforcement positioning is very importance in cantilever fixed partial denture; they suggested that glass fibers should be within the tension side which is near the occlusal surface of the cantilever bridge (Alander et al. 2021).

Amount of glass fibers

Glass fiber should be covered with a sufficient layer of polymer composite to avoid wear; therefore, very high concentration of glass fibers is not preferred. It was found that more than 7.6 wt% glass fiber loading may result in a cluster of fibers with diminutive matrix in-between, resulting in a poor fiber bonding. The ultimate fiber loading for superior wear resistance is from 2.0 to 7.6 wt% (Lassila and Vallittu 2004).

Critical fiber length and fiber aspect ratio

In order to transmit the stress from the matrix to the fibers, fibers should have a sufficient length that is equal or greater than the so-called critical fiber length (Landel and Nielsen 1993). Critical fiber length could be calculated using a fiber fragmentation test. It was estimated that the critical lengths of E-glass with Bis-GMA polymer matrix are from 0.5 to 1.6 mm (Cheng et al. 1993). Weak adhesion between the fibers and polymer matrix could be compensated by increasing the critical length of glass fibers (Karacaer et al. 2003).

Additionally, a certain length to diameter ratio of the fiber called "fiber aspect ratio" needs attention to achieve optimum properties. Several studies examined a range of fiber aspect ratios added to dental composites and concluded that dental composites reinforced with a range of 50–500, i.e., low fiber aspect ratio, are the best range for reinforcing dental composites (Shouha et al. 2014).

In an experimental conducted by Behl et al. in 2020, flowability, mechanical properties and degree of conversion were tested for a variety of experimentally prepared GFRCs containing low fiber aspect ratio of 50, 70 and 100, micro-sized fibers (5 µm diameter). They concluded that micro-sized fibers can enhance flexural and compressive properties without significantly affecting flowability and degree of conversion and that the best composition is 5% of 70 fiber aspect ratio (Behl et al. 2020).

Bond between glass fibers and polymer matrix

Glass fiber reinforcement is achieved merely when load is transferred from the matrix to the glass fibers; therefore, fibers should have strong bond to the matrix to attain good reinforcement (Lastumäki et al. 2003). To achieve this, impregnation of the glass fibers, as well as their adhesion to polymer matrix, should have the ultimate concern.

Poor impregnation creates voids between the matrix and the fiber resulting in poor flexural strength, low elastic modulus and high water sorption that cause hydrolytic degradation of polysiloxane network and subsequent discoloration (Miettinen and Vallittu 1997; Lassila et al. 2002). Good impregnation can be obtained through pre-impregnated of fibers with monomers and/or, polymers, such as light polymerizable bifunctional acrylate or methacrylate monomers (Lastumäki et al. 2002).

On the other hand, poor adhesion results in stress concentration at the glass fiber's interface (Kallio et al. 2001; Cheikh et al. 2001). It is worth mentioning that the attraction force between glass fibers and polymer matrix is the result of many factors, for instance, van der Waals forces, chemical bond, electrostatic attraction and mechanical interlocking (DiBenedetto et al. 1995). Chemical adhesion between glass fiber and polymer matrix is obtained using 3- (trimethoxysilyl) propyl methacrylate (TMSPMA) silane coupling agent (Rosentritt et al. 2001).

Silanization and impregnation of fibers with a resin improve the hydrolytic stability and prevent water sorption of the composite. Multiple studies concluded that water sorption causes reduction in flexural strength and load bearing capacity of denture base polymers, causing plasticizing effect (Garoushi et al. 2007a).

Many commercially available glass fibers, such as S-glass fibers, are coated with lubricants, antistatic agents, polymeric binders and dust; this coating should be removed to enable appropriate bond to resin (Tomao et al. 1998). In addition, glass fibers should be etched using hydrochloric acid or sulfuric acid to selectively remove Al_2O_3 and MgO on the surface of the fibers without destroying SiO_2; this selective atomic level etching technique increases the surface roughness of the fibers and thus provides mechanical interlocking. Moreover, etching exposes plentiful hydroxyl groups thus provides strong chemical bonding with silane coupling agents. This treatment showed 11 ~ 40% increases in interfacial shear strength, and it improves the flexural strength and modulus of composites filled with modified S-glass fibers (Cho et al. 2019; Wang et al. 2020).

Properties of reinforced glass fiber materials

Mechanical properties

Geometry of the reinforcement fibers as well as fiber–resin interfaces in GFRC system affects dramatically many mechanical properties, such as strength, stiffness, toughness, static, impact and fatigue properties (Table 2). Additionally, silanization of glass fibers increases the hardness and diametric tensile (Debnath et al. 2004). The efficiency of the fiber reinforcement varies according to fiber orientation (Tuusa et al. 2007). Krenchel (Krenchel 1964) suggested that the efficiency of the fiber reinforcement (Krenchel's factor; value 0 to 1) estimates the strength of FRCs. As shown in Fig. 1, if fibers are oriented in continuous unidirectional manner, then the reinforcing efficiency will be 1 (100%), but are only gained in one direction (Murphy 1998), while continuous bi-directional (woven, weave) fibers have reinforcing efficacy of 0.5 (50%) or 0.25 (25%) and are equal in two directions. Yet, woven fibers are advantageous in many clinical situations, where the direction of the load is unknown or where there is no space for unidirectional fibers; woven fibers also provide additional toughness to the polymer, as it prevents crack propagation. On the other hand, random chopped short FRCs provide Krenchel's factor of 0.38 (38%) in two dimensions and 0.2 (20%) in three dimensions, where the mechanical properties are the same (isotropic) three-dimensionally (Chong and Chai 2003).

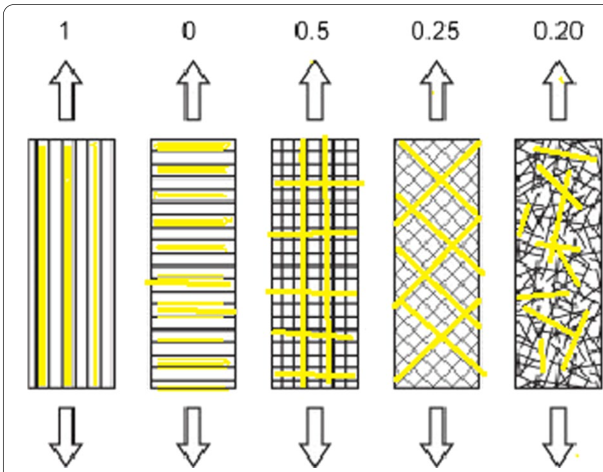

Fig. 1 Krenchel's factor of fibers according to their orientation in plane

Table 2 Mechanical properties of some experimentally tested glass fiber-reinforced composites (Ylä-Soininmäki et al. 2013)

Mechanical property	Average values of experimental GFRCs
Static fracture load	195.80 N
Dynamic fracture load	190.57 N
Flexural strength	297–426 MPa (according to degree of monomer conversion)
Elastic modulus	3–6 GPa (according to fiber quantity)
Compressive strength	965 MPa
Tensile strength	18.9 MPa to 43.4 MPa (increase with the addition of resin)

Optical properties
Glass fibers possess similar refractive index to that of resin; therefore, they allow light transmittance efficiently (Khan et al. 2015). Accordingly, addition of glass fibers to dental composite will improve their mechanical properties without affecting the degree of conversion of resin matrix, unlike opaque colored kelvin, carbon or zirconia fibers (Behl et al. 2020).

Viscoelastic properties
Studies revealed that the viscoelastic behavior of polymers reinforced using glass fibers was 15.32 GPa which is comparable to dentin (17GPa) (Khan et al. 2008).

Adhesive properties
Adhesion is an important property in dental practice, as the success of different restorative systems depends on adhesion. In a study conducted by La Bell et al., on the adhesion of titanium post, carbon fiber-reinforced posts and glass fiber-reinforced post to cements, they found that only GFRC posts showed no adhesive failure, while titanium and carbon fiber-reinforced composites posts showed 70% and 55% failure rate, respectively (Le Bell et al. 2005).

Thermal properties
The orientation of glass fibers has an impact on the linear coefficient of thermal expansion; linear coefficient of thermal expansion for unidirectional glass fiber was found to have an average of 5.0×10^{-6} °C^{-1} (Tezvergil et al. 2003). Interestingly, studies revealed that continuous unidirectional reinforced fibers have two coefficients of thermal expansion values, a lower value, in the direction parallel to the fibers, and a higher value, in the direction perpendicular to the fibers, as the rigidity of the fibers inhibits expansion of the matrix longitudinally and allows expansion in the transverse direction.

Biocompatibility
Many studies revealed that glass fiber-reinforced filling materials have low microbial adhesion to Streptococcus mutans compared to dentin and enamel (Murphy 1998). For instance, in a study conducted on Candida albicans adhesion to GFRC, it was observed that the impregnated hydrophobic resins with E-glass fibers reduced microbes adhesion (Assif et al. 1993).

Biocompatibility of BisGMA/TEGDMA reinforced with E-glass fibers evaluation revealed good proliferation and differentiation of cultured cells (Waltimo et al. 1999); in another study on fiber-reinforced oral implant, inspected using micro-CT scans, bone trabeculae was observed between the FRC implant's threads, which prove their excellent biocompatibility (Ballo et al. 2014).

Dental applications of glass fibers as reinforcing agent

Prosthodontic applications
The application for glass fibers as reinforcement agent in denture base may be the earliest application of GFRC in dentistry (1960s.) (Khan et al. 2015), and it proved successful influence on mechanical properties. Stress transfer can be reduced by adding glass fibers to the denture base (Duraisamy et al. 2019). Results revealed that denture base reinforced using 6-mm chopped glass fibers resulted in an increase in transverse strength, elastic modulus & impact strength (Selvan and Ganapathy 2016). Conversely, other studies mentioned that the use of GFRC as removable dentures provides high fatigue resistance but low flexural modulus (Karmaker et al. 1997). Meanwhile, most researches consider GFRC to be an excellent option for making denture base, due to their high fatigue resistance, the ability of resisting extremely high temperature, moisture and oil, as well as the property of polishing (Subasree and Murthykumar 2016).

In a study that compared the bonding strength of polymer matrix with denture base polymers enclosing either carbon, aramide, woven polyethylene or glass fibers, results revealed that glass fibers yielded the best esthetics and ease of bonding to the polymer matrix (Freilich et al. 1998).

Glass fiber-reinforced autopolymerizing resin can be utilized for repairing a broken denture, with a 45° bevel joint design of the broken surfaces and surface pretreatment; it proved to minimize stress concentration and to improve the transverse strength of the repaired denture base (Mamatha et al. 2020).

Glass fiber-reinforced composites are also utilized in the fabrication of fixed partial denture instead of the conventional cast metal resin-bonded fixed partial denture; they present adhesive, esthetic, metal-free, high elastic modulus, high fracture strength, low risk of allergy and low-cost option for tooth replacements (Van Heumen et al. 2009a). Studies reported that GFRC FPDs had 71% success rate and 78% survival rate after 5 years in the posterior area (van Heumen et al. 2009b).

Additionally, FRC CAD/CAM composite was evaluated for the fabrication of fixed dental prostheses; FRC consisted of parallel glass fibers dispersed in a multi-layer bi-direction manner into resin matrix. Results confirmed high reliability to the expected physiological masticatory load in the molar region (Bergamo et al. 2021).

Another study investigated the mechanical properties of short GFRC fabricated as temporary crown and bridge and found high flexural strength (117 MPa) and compressive load bearing capacity (730 MPa) compared to the conventional temporary crowns and bridges (Garoushi et al. 2008).

Endodontic applications

GFRC endodontic posts are another option introduced to endodontic dentistry; they are either prefabricated posts or individually polymerized GFRC ones.

Individually polymerized GFRC posts show higher flexural strengths and better bond to composite resin luting cement than the prefabricated posts (Le Bell et al. 2005; Biały et al. 2020).

Studies revealed that glass fibers oriented parallel to the long axis of the post, provided high strength and elastic modulus in this direction (Chieruzzi et al. 2014).

GFRC endodontic posts have the advantage of allowing light transmitted deep into the root canal and thus increase bonding of the cement to the post and dentin (Vieira et al. 2021).

Tooth restoration applications

One of the applications of glass fiber-reinforced composite is dental restorations, short glass fibers have positive impact on polymerization shrinkage stresses of composite resin and, accordingly, on marginal microleakage; therefore, it is an ideal choice in posterior and bulk composite restorations. Experimental studies on short GFRCs displayed high fracture toughness, flexural strength and flexural modulus (Garoushi et al. 2012).

Short GFRC (everX Posterior, GC, Tokyo, Japan) is a dental restorative composite resin product that was introduced into markets as dentin replacement in large cavities below conventional composite, to reinforce it and prevent fracture (Fallis and Kusy 1999). It consists of 8.6 wt% randomly orientated short E-glass fibers and 67.7 wt% barium glass fillers and resin matrix; this composite restoration showed high load bearing capacity, flexural strength and fracture toughness (Säilynoja et al. 2013).

Another impressive glass fiber-reinforced resin disk (TRINIA, SHOFU, Kyoto, Japan) that utilizes CAD/CAM technique for tooth restoration was introduced. It contains 55 wt% multi-directionally interlaced glass fibers, aligned as woven layers, parallel to the top surface of the disk. The size of E-glass fibers was 1.2–1.5 mm in width and 0.1–0.4 mm in thickness, respectively. It demonstrated high flexural strength (254.2- 248.8 MPa) and fracture toughness (9.1 ± 0.4 MPa/m$^{1/2}$), but these properties are anisotropy; therefore, this material can be used only in specific directions recommended by the manufacturer (Suzaki et al. 2020).

Novel dental composite filler, composed of nano-hydroxyapatite (nHA) and E-glass fibers, was created using the microwave irradiation technique; these fillers combine the advantages of bioceramic (nHA) and the high strength of E-glass fiber. The degree of conversion, flexural strength and micro-hardness results were very promising; however, flexural strength and water sorption behavior of the experimental composites decreased with increasing nHA/E-glass fibers (Syed et al. 2020).

Orthodontic applications

An esthetic orthodontic retainer was presented as a new clinical use of GFRC. It provides high fracture strength and high adhesive bond strength to enamel and to orthodontic attachments (Meiers et al. 2003).

A study compared the bond strength of glass fibers and stainless steel bonded lingual orthodontic retainers, to maxillary and mandibular teeth, for six years, revealed that detachment rate and breakage rate of glass fibers retainers are lower than stainless steel retainers (Rosenberg 1980).

First-generation GFRC retainers presented by Burstone and Kuhlberg (2000) were too rigid to allow tooth movement; recently, glass fiber (EverStick Ortho*) pre-impregnated with PMMA polymer was introduced; they offered micromechanical and chemical adhesion (Lastumäki et al. 2002). Alternatively, GFRC space maintainers placed on primary teeth are prone to failure, either due to presence of prismless enamel or due to moisture contamination (Zachrisson 1977).

Periodontal applications

Periodontal splints made of fiber-reinforced resin have provided clinicians the sufficient mechanical strength of metal splints with the satisfactory aesthetics of resins; in addition, they are simple in design, durable (Meiers et al. 1998), don't interrupt the occlusion and facilitate keeping good oral hygiene (Kumbuloglu et al. 2011).

Limitations of glass fibers reinforced materials

Though glass fibers have been investigated as reinforcing agent in dental polymers for almost forty years, still some of these materials may have limitations, for example,

1. It is not always applicable to include sufficient glass fibers.
2. Some GFRCs can only be used in the particular direction, recommended by the manufacturer, due to the anisotropy property.
3. Overlying veneering composite is prone to wear.
4. Deficient rigidity for use in long-span bridges.
5. Handling requires adequate moisture control for adhesive technique.
6. Posterior occlusal situations should have sufficient space to allow enough room for the glass fibers and

   the overlying veneering composite (Butterworth et al. 2003).
7. Relatively higher density of glass fibers compared to other fibers as carbon and organic fibers.
8. Self-abrasive if not treated and the tensile modulus would be prone to decrease.
9. Relatively low fatigue resistance (Zhang and Matinlinna 2012).
10. The S-glass is very costly though their service life is short.

Conclusions

The interest in using glass fiber-reinforced dental materials is growing; these materials offer strength and toughness equivalent to dental tissues, with very satisfactory aesthetics.

In this review, types of glass fibers and factors affecting the properties of fibers reinforced materials were revealed, and the properties and the applications of fiber-reinforced composites were discussed. This extensive research proved the effectiveness of glass fiber reinforcement in many dental restorations, as long as glass fibers' composition, orientation, distribution, amount, length, and adhesion are well performed in accordance with every clinical situation. In conclusion, the reported success of glass fibers as reinforcing material surpasses their limitations.

Abbreviations
UHMWPE: Ultra-high molecular weight polyethylene; PMMA: Polymethyl methacrylate; Al_2O_3: Aluminum oxide; B_2O: Barium oxide; MgO: Magnesium oxide; Li: Lithium; Na: Sodium; K: Potassium; B_2O_3: Boron oxide; Pre-preg: Pre-impregnation; GFRCs: Glass fiber-reinforced composites; FRC: Fiber-reinforced composite; SiO_2: Silicon oxide; CaO: Calcium oxide; FPDs: Fixed partial dentures; nHA: Nanohydroxyapatite; TMSPMA: 3-(Trimethoxysilyl) propyl methacrylate.

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