

Laboratory and clinical evaluation of polymer materials reinforced by fibers used in dentistry

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Abstract. – **OBJECTIVE:** Fiber-reinforced composites (FRC) because of high strength and a low mass can be widely applied in many fields of dentistry.

MATERIALS AND METHODS: The types of fibers commonly used in dentistry with the description of physicochemical properties of the reinforcing phase and polymer resin, are specified. The influence of the method of fiber positioning in the sample, their diameter, length and shape of fibers visible in cross-section on the strength of the FRC material, are underlined. The work also paid attention to the volume of the material that occurs as a result of the absorption of water from the oral environment and changes in bonding between matrix and fiber.

RESULTS: The clinical procedures and a description of failures that may possibly happen in the oral cavity presented in the work, confirm that they allow fabrication of minimally invasive, lightweight, durable and biocompatible materials. At the moment, the only material group that can be used by direct technique to reach high load-bearing capacity restorations is FRC.

CONCLUSIONS: Long-term treatment effectiveness makes FRCs an alternative to prosthetic restorations whose retention is obtained only as a result of mechanically interlocking to the abutment tooth. The use of FRCs in clinical dentistry is part of value-based medicine.

Key Words

Fiber-reinforced composite (FRC), Composite restoration, Esthetic dentistry.

ment teeth through the restoration. Therefore, FRCs have found wide application, as a method of choice, in many fields of dentistry such as prosthodontics, conservative dentistry, implantology, periodontics, orthodontics and paediatric dentistry. FRC is a material made of fibers (reinforcing phase) and a resin polymer matrix (organic phase). The polymer matrix is a structural support for the reinforcing fibers, protecting them against occlusal trauma and transferring external tension. Moreover, the polymer resin combines with the luting cement and gives the material the desired shape. Introducing fibers of a high elastic modulus into a soft and malleable matrix improves the strength and stiffness of the material, ensuring great mechanical properties of the composite in selective directions. Long-term loading thereof has become possible in situations in which so far application of conventional fixed dentures has not been recommended¹.

Materials and Methods

The technological progress in material engineering has caused FRC materials to be rationally used in many aspects of every-day life, also in the oral cavity environment. With comparatively low density and mass, in relation to metal alloys, very high values of the strength have been obtained. Composite materials on polymer frameworks reinforced with fibers have become irreplaceable in many industrial branches, such as production of bulletproof vests, construction of Formula 1 cars, tennis racquets, bicycle frames, airplane and space structures. In dentistry, they are mainly applied in the production of adhesively cemented restorations of hard tissue defects of a single tooth or extensive losses separating the dental arches. Fibers found in nature, produced from raw materials of plant (cotton, flax, hemp,istle) and animal

Introduction

Fiber-reinforced composites (FRCs) are a group of lightweight and synthetic materials of a wide range of clinical indications allowing permanent reconstruction of missing teeth. High strength and a low mass of these materials make it possible to effectively move the tension generated in the stomatognathic system on the abut-

(wool, silk) origin, have not been clinically applied in medicine so far, mainly because of weak mechanical resistance and great water absorption resulting in deterioration of the performance parameters of such fibers during exploitation thereof in an environment of increased humidity².

Properties of Individual Phases (Framework and Reinforcement)

Among the fibers reinforcing dental materials the following types can be distinguished: fiberglass, polyethylene and aramid fibers. Carbon/graphite fibers are not commonly used due to the grey color undesirable in dental treatment. They are characterized by a linear tension-deformation relationship, but have varying tensile strength. Density is a significant physical property of fibers as it determines the composite mass, which translates into a reduction of the weight. The lowest value thereof, it means 1.45 g/cm³ is found for polyethylene fibers, a higher one – equal to 1.8 g/cm³ – is demonstrated by aramid fibers, whereas fiberglass is characterized by the highest value of this parameter, amounting to 2.5 g/cm³. The selected mechanical properties that may differ depending on the producer have been presented in table 1 (Table I)³⁻⁵. Fiberglass is willingly used for production of dental materials due to its transparency and chemical structure. Thanks to the process of silanization, permanent fusion of the reinforcement and the organic matrix is ensured^{6,7}. The fibers are characterized by great durability and little elongation upon fracture. The strength of the fibers may decrease in an aquatic environment, particularly if they contain strongly alkaline metal oxides⁸.

Ultra high molecular weight polyethylene fibers (UHMWPE) are characterized by low water absorption. They do not undergo hydrolysis, so their properties are stable in an environment of increased humidity⁹. Obtaining a fiber with an unusually ordered chain, as a result of forcing and elongating polyethylene, has been great

technological progress. The polymer building the structure of the polyethylene fiber makes parallel chains of the orientation degree > 95% and crystallinity > 85%, which distinguishes it from aramid fibers whose strength results mainly from a large number of intermolecular hydrogen bonds¹⁰. Fiber reinforcement is very effective. Improvement of the mechanical and thermal properties may be achieved when the fiber content in relation to that of the organic polymer framework is increased by as little as 10%. The factors increasing adhesion between the matrix and the reinforcement as well as polymerization initiators are equally important, although they are present in significantly smaller quantities. The organic matrix of most commercially available FRCs consists of a mixture of methacrylate monomers. Two main monomers are used – Bis-GMA (bisphenol A-glycidyl methacrylate) and UDMA (urethane dimethacrylate), as well as monomers of lower viscosity such as TEGDMA (triethylene glycol dimethacrylate) or HEMA (2-hydroxyethyl methacrylate). Application of the latter is caused by the necessity to dilute the extremely viscous Bis-GMA or UDMA in order to put the greatest possible amount of the filler in the matrix. Dimethacrylates are responsible for cross-linking formation, while PMMA (polymethyl methacrylate) creates linear structures. Composite material hardening is conducted via a polymerization reaction initiated chemically, thermally or with the use of light¹¹⁻¹³ on glass reinforced-reinforced composite root canal posts showing an interpenetrating polymer network (IPN).

Geometry

Fiber orientation

Fibers may be found in a continuous arrangement or a discontinuous one, it means in the form of sections cut into smaller fragments. In the

Table I. Types of fibers used in dentistry

	Glass		Aramide	Polyethylene
	E	S		
Density	2460 kg/m ³	2490 kg/m ³	1,40 – 1,47 g/cm ³	970 - 980 kg/m ³
Mohs hardness	6,0°	-	-	-
Tensile strength at 25°C	3500 MPa	4500 MPa	700 – 3450 MPa	3000 GPa
Modulus of elasticity at 25°C	73,5 GPa	86,5 GPa	17 – 179 GPa	116 GPa

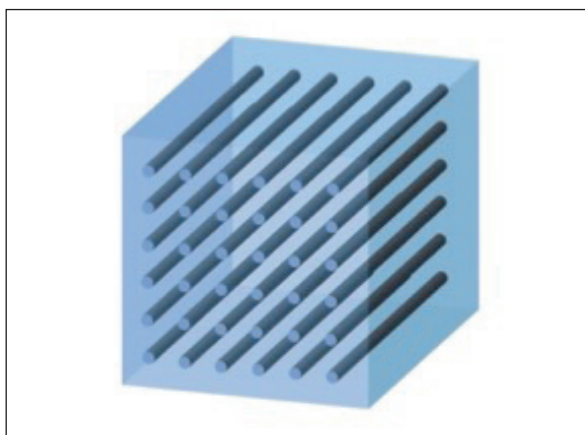


Figure 1. Unidirectional fibers orientation.

composite material, fibers may be arranged as a unidirectional bundle, bidirectional bands or a three-dimensional network of random oriented multidirectional fibers (Figures 1-3). Bundles of continuous unidirectional fibers are anisotropic, which means that they show different properties depending on the force direction; bidirectional fibers ensure orthotropic properties, it means they are identical in two directions and different in the third (orthogonal) one, perpendicular to the other two. Randomly oriented fibers provide the material with isotropic properties, so varying, depending on the force direction. The different arrangement of fibers of the same type in the composite framework affects the mechanical properties of the material. A fiber bundle arrangement perpendicular to the occlusal forces ensures appropriate and desired values of bending, flexural strength, and the risk of a matrix fracture is greatest in this direction¹⁴. When the forces are directed perpendicularly to



Figure 3. Multidirectional orientation, fibers arranged in random order.

the long axis of the unidirectional fibers, the resin participation in transferring the loads increases. At the same time, fibers in such an arrangement will change the properties of the organic matrix to a minimal extent¹⁵. Such architecture provides optimal conditions for transferring the forces between the polymer framework and the fiber. Stiffness, so resistance to bending, is greatest then¹⁶. This type of a solution, it means a longitudinal and unidirectional fiber arrangement, is recommended in the case of fixed dentures made of FRC¹⁷. The anisotropy is quite high in the case of the unidirectional composites. The modulus of elasticity in the direction perpendicular to the fiber length is similar to the modulus of the framework, so many times lower than that of the fibers. Hence the necessity to build layer constructions (laminates) in which the fibers are arranged at various angles, yielding quasi-isotropy of the material in its plane, or the need to use short fibers arranged randomly in the material¹⁸.

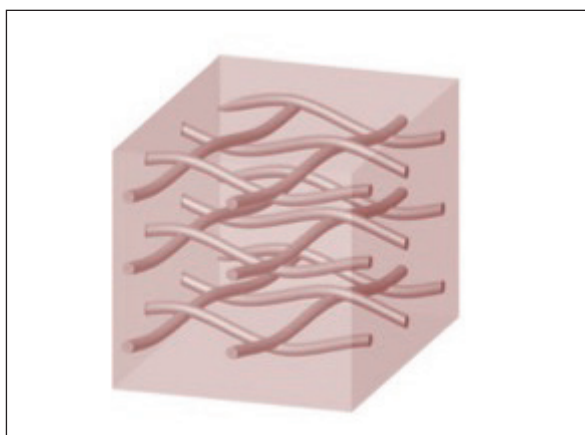


Figure 2. Bidirectional fibers orientation.

Fiber Dimensions (Diameter and Length)

The strength properties of a fiber depend on its diameter. Statistical studies show that the strength of small diameter fibers is greater than that of fibers whose diameter exceeds a certain limit value. A noticeable increase in the strength usually corresponds to a fiber diameter smaller than 15 μm . Above this value, surface flaws such as fractures and faults are more likely to appear. The use of fibers whose diameter is 10^{-9} m or smaller, so at the level of single atoms and molecules, ensures greater strength than that of fibers whose diame-

ter is measured in the micrometric scale (10^{-6} m). The fibers currently used in dentistry are characterized by a diameter of 6-16 μm ¹⁹. Fiber length also significantly affects the composite mechanical properties. If the length of discontinuous fibers is sufficient, the product obtained may be characterized by similar stiffness and strength to that of continuous fibers. There is only one condition: namely, the fiber length must be greater than the so-called critical length. Fiber critical length is defined as the minimum length (for a given diameter) at which composite destruction happens as a result of a fracture of the strained fiber, not via shearing at the boundary between the fiber and the framework. It is the minimum fiber length that ensures reinforcing properties to the material. It is assumed that the fiber length should be 50 times greater than its diameter. The diameter of fiberglass used in dentistry is 15-18 μm , therefore the critical length of such a fiber should be 0.75 – 0.9 mm²⁰. Together with the fiber elongation, its effectiveness rises linearly in the initial phase of the experiment, whereas the course of the function is exponential in the further part. More elongation of the bundle does not result in an improvement in the strength properties then (Figure 4). The strength and the elastic modulus of a FRC material depend on the number of the fibers used in relation to the amount of the organic matrix, so on the relative content of the individual phases – the framework and the reinforcement. An improvement in the strength parameters may be achieved through application of a larger number of fibers in the volume unit yet of a smaller diameter. On the basis of the results ob-

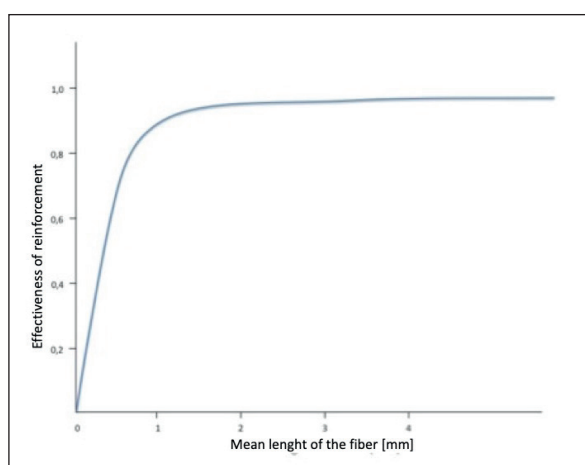


Figure 4. The influence of fiber length on the effectiveness of reinforcement of FRC materials.

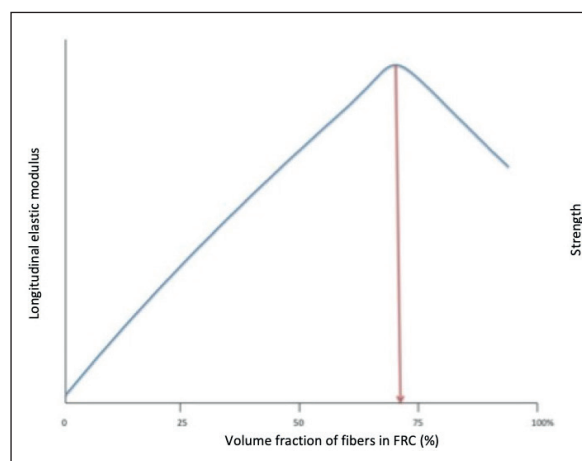


Figure 5. The influence of the volume percentage of fibers on the elastic modulus and strength of the material FRC.

tained from the mechanical studies conducted by Lassila et al²⁰, a correlation between the fiber volume input and the selected mechanical properties which means strength and longitudinal modulus of elasticity, has been found. It has been observed that the abovementioned strength parameters increase with a rise in the fiber volume, reaching their maximum at a fiber volume equal to 68%. At the fiber volume input of more than 68%, the strength and Young's modulus begin to decrease, until the fibers are broken (Figure 5)²¹.

Fiber Cross-Sectional Shape

Monofilaments do not only differ in chemical composition, but also in their cross-section. Those of a circular cross-section are most popular, but fibers of a triangular, rectangular and cross-section are also produced. Fibers in the form of microspheres and micro balloons are also used as fillers. Fibers that have sharp contours are characterized by higher strength parameters, greater stiffness and larger values of the longitudinal modulus of elasticity, in comparison to oval fibers. A bigger surface area of these fibers also results in improved adhesion of the polymer matrix to the inorganic phase reinforcing it¹⁵.

Water Absorption

The FRC organic matrix absorbs water by diffusion. The water molecules penetrate into the free spaces created between the chains of the polymer macromolecules, which results in loosening the spatial grid of the materials. The change in the volume and dimensions of the organic matrix is usually slight and can be reversible. Never-

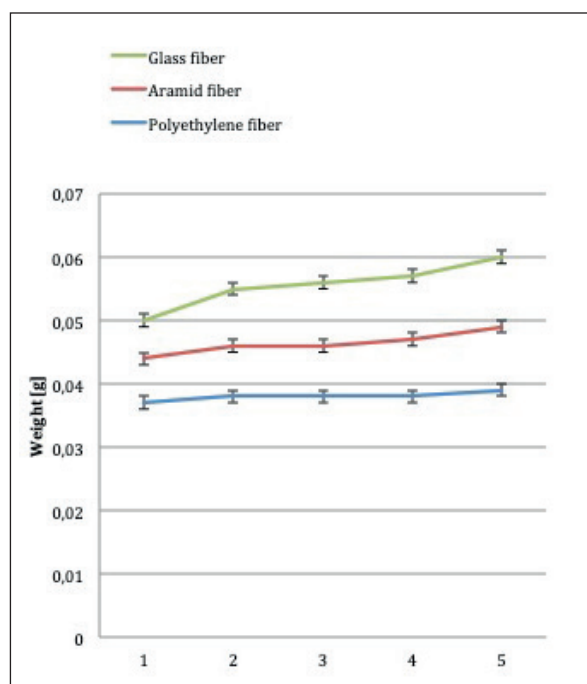


Figure 6. The weight of the tested materials presented in subsequent measurements (after 1 day, 7 days, 14 days and 28 days of the experiment).

theless, the material exploitation in the humid and changeable environment of the oral cavity may cause irreversible changes of the physical and chemical parameters of the composite material²¹. On the basis of the authors' own studies, it has been concluded that there is a diverse impact of the aqueous environment on the absorption of the FRC polymer materials²². The water absorption of all the materials did not exceed $40 \mu\text{g}/\text{mm}^3$ during the experiment, so the requirements of the norm of International Organization for Standardization (ISO) 10477: Dentistry. Polymer-based crown and bridge materials were satisfied. Nonetheless, the weakest absorption properties were characteristic of the polyethylene material (Figure 6).

Types of Bonds Between Framework and Fiber

The strength of the bond between the fiber and the matrix depends on the fiber chemical structure, the matrix chemical composition and the chemical and physical conditioning of the fibers. The process of resin saturation and penetration into the space between the fiber bundles is impregnation. This process depends on the surface wettability, the distance between the individual fibers and the mechanical properties. Close adhesion of

fibers makes them less moistened and filled with resin. The PMMA molecules are large; their size ranges between 30 and 60 μm . Therefore, the distance between the fibers is long and their number may turn out to be insufficient in the volume unit. In the process of pre-impregnation, PMMA is dissolved in a solvent that vaporizes quickly. The rapid evaporation causes porosities to appear in the resin structure, creating additional space for the fiber. $-\text{OH}$ hydroxyl groups are present at the fiberglass surface thus ensuring good adhesion to the resin materials. The fiber ability is improved via the silanization process. Silanes easily react with the $-\text{OH}$ hydroxyl groups of the fiber, as well as with unreacted $-\text{CH}=\text{CH}_2$ vinyl groups of the resins. Silane is a compound having at least one Si-C or Si-H group and different organic groups may react with a silane. Only fiberglass is able to chemically bond with the organic matrix in the silanization process.

Other fibers used in dentistry are chemically neutral. The lack of active chemical groups (ester, amide or hydroxyl) leads to their resistance to water, moisture, most chemical substances, UV radiation and microorganisms.

The UHMWPE fibers are non-polar, characterized by low surface energy values, which ensure excellent stability in the changeable and difficult oral environment. The inertness makes adhesion of UHMWPE to the polymer matrix hard to achieve²³. In order to improve the strength of the bond between the fibers and the organic matrix, their surfaces are modified in the oxidation process²⁴. The oxidation reaction causes an increase in the energy and surface affinity, as well as the strength of the connection with some hydrophilic polymer systems, in contrast to unmodified fibers. Wettability is also improved in proportion to the non-activated polymers, which prevent progressive damages of the material, consisting in a mutual loss of the cohesion of the fibers and the organic matrix, resulting from the variable straining forces affecting them²⁵.

Results

Clinical Procedure

FRC adhesive bridges may be made directly in the oral cavity or in a prosthetic laboratory and finally cemented during the next appointment (indirect method). In the semi-indirect method, a fiber-reinforced composite bridge is produced on the basis of a model made of silicone mass in the



Figure 7. Fiber-reinforced composite bridge FRC 31-41 with attachments for better stabilization placed on 32 and 42.

dental surgery, during one appointment outside the patient's oral cavity. Depending on the clinical indications, the restoration may be maintained at the surface of the pillar teeth without additional preparation thereof. The adhesion is obtained chemically and depends solely on the strength of the bond between the luting cement and the enamel surface, as well as the spatial occlusal conditions. Additional retention elements, for example wings, which improve the restoration, stabilization and maintenance on the foundation and render the clinical procedure more efficient and easier, may be formed in the bridge structure (Figure 7)²⁶. FRCs may also be anchored in the crown, inlay and onlay structure, if it is necessary, to first remove caries or modify the previ-

ously placed composite fillings. Various retention types can also be combined within one prosthetic restoration in the hybrid method (Figures 8-10). Van Heumen et al²⁷ did not notice a statistically significant difference between the FRC anchoring manner and success in the treatment with the use of FRC. Some authors claim that the survival rate is lower in the case of adhesive bridges anchored in the mandible. However, Ayna et al²⁸ and Monaco et al²⁹ obtained similar values of the survival rate for bridges made both in the maxilla and the mandible.

In fixed prosthetic restorations made of FRC, the pontic should be placed at the gingival side away from the occlusal forces operating in the oral cavity, particularly if composite onlays/inlays, not full-size crowns embracing all the walls of the pillar tooth, are used for anchoring¹⁸. It is also recommended that the preparation bed should be oval so that the walls of the cavity do not join each other with the sharp contours, in order to improve the biomechanical properties, especially fracture resistance. When planning to strengthen the removable denture base, one should remember that the FRC bundles must be placed transversally and on the rims, as peripherally as possible, in relation to the fracture/crack line³⁰. A desired feature of the FRC materials is their ability to adhere to the surface to which they bond closely. FRCs may be arbitrarily shaped and adjusted to the pillar tooth surface. The fiber elasticity and shape memory make the procedure of putting the FRC in the desired place, uncomplicated. Unlike the materials reinforced with the polyethylene or aramid fibers, fiberglass-reinforced composites are stiff, in particular those reinforced with bundles



Figure 8. Secondary caries 17, extensive carious cavity 16 and missing tooth 15.



Figure 9. Composite inlay 16 and composite full crown 15 made indirectly in dental laboratory.

arranged longitudinally in the form of a single bunch, which may additionally prolong the clinical procedure time³¹. The strength of the bond between the luting cements and FRC fixed dentures is greater than that of those made of conventional dental alloys³². The application of restorations of the lost teeth cemented by means of mechanical retention only carries a risk that the luting cement will be rinsed out or chipped. This may create a potential risk that places facilitating adhesion of

pathogenic microorganisms and the development of secondary caries will appear. In the case of FRCs, chemical integration of the composite material and the tooth hard tissues ensures permanent connection of the prosthetic restoration with the pillar tooth in the multiannual perspective. Basic information including a synthetic description of the properties of the fiber-reinforced composite materials, indications, contra-indications and detailed hints about the clinical procedure should be provided by the producer together with the material³³.

Treatment Failures

Long-term studies have shown the durability of FRC restorations³⁴ non-randomised, controlled, prospective and retrospective clinical studies were included. The Preferred Reporting Items for Systematic Reviews and Meta-Analyses were applied. The Overall Strength of Clinical Recommendation (OSCR. The number of failures is not large and may differ depending on the author, ranging from 5% to 16% during the first 4 years of use^{32,35,36}. In composite materials, a phenomenon of gradual, slow changes of the values of the elastic modulus, durability rates, characteristics of vibration damping and other properties are found. The gradual and slow accumulation of the fatigue changes, connected with the long-term load of the dentures in use, may frequently result in a necessity to make a new one. This is caused by the process of gradual development of fractures and other damages to the material. The gradual deterioration of the properties over time is a characteristic feature of many plastic materials and polymer composites. Unidirectional com-



Figure 10. Cemented restorations in the oral cavity. The fiber extends between the teeth 17, 16, 15 and 14.

posites loaded parallel to the direction of the fiber arrangement are more resistant to the property changes. Greater susceptibility to such changes is demonstrated by composites containing layers of various structure and orientation, for example the reinforcement from mats and textiles. In clinical trials, the composite bond and the fiber-reinforced composite bond are similar. The reason for the failures of the FRC materials may be the degradation of the bond between the fiber-framework phases over time³⁷.

Conclusions

Thanks to the desired mechanical properties, fiber-reinforced composite materials are helpful in effective settlement of the issues and problems emerging during dental treatment. They are an equivalent alternative to fixed dentures cemented conventionally, whose maintenance on the foundation is achieved by means of mechanical retention. It becomes a justified necessity, then, to deepen the extensive knowledge in this area persistently.

Conflict of Interest

The Authors declare that they have no conflict of interests.

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