PARAMETERS THAT INFLUENCE THE PROPERTIES OF FIBER-REINFORCED COMPOSITES. REVIEW

Vieriu Raluca-Maria[1], Țănculescu Oana[2*], Savin Carmen[1*], Solomon Sorina[2], Sălceanu Mihaela[2], Săveanu Iulia Cătălina[1]

[1]Department of Surgery, Faculty of Dentistry, "Gr. T. Popa" U.M.Ph. - Iași, Romania
[2]Department of Odontology – Periodontology, Fixed Prosthodontics, Faculty of Dentistry, "Gr. T. Popa" U.M.Ph. - Iași, Romania

Corresponding author: **Țănculescu Oana**, PhD, Associate Professor
"Grigore T. Popa" University of Medicine and Pharmacy, Iasi, Romania
e-mail: ot@umfiasi.ro
Savin Carmen, PhD, Associate Professor
"Grigore T. Popa" University of Medicine and Pharmacy, Iasi, Romania
e-mail: savin.carmen@gmail.com

ABSTRACT

FRC is a material combination of polymer matrix and reinforcing fibers with multiple dental applications. Fibers are the reinforcing component of the system that confers resistance against the applied load on the restoration. Comparing with other restorative materials, FRC present an adequate toughness, high stiffness and strength per weight. These properties are tributary to the characteristics of each component separately but also to the ratio and interaction between them. The performances of FRC restorations depend on the correct clinical decision, appropriate selection and handling of the materials.

Key words: fiber reinforced composite, FRC, fiber orientation, fixed prosthetic restorations, minimally invasive restorations

The major interest in dentistry for fiber-reinforcing materials is due to the need of replacing the metal for prophylactic, biological and aesthetic reasons [1], making them an option for minimally invasive restorations. Their versatility and potential recommend them for different clinical uses that can be divided into three categories: for *direct placement splints and fixed partial dentures*, *direct-placement single-restoration reinforcement* (endodontic post and composite filling material), and *indirect restorations* (single-crown restorations, dentures, and orthodontic and occlusal appliances) [2]. The main clinical applications of fiber reinforced composites in dentistry are presented in Table 1 [3].

Fiber-reinforced composites (FRCs) are composite materials with three different components: the matrix (continuous phase), the fibers (dispersed phase), and the zone in between, or interface (interphase) [4]. This last zone corresponds to the adhesive interface ideally created between the fibres within the composite matrix and the resin to which they are bonded. The matrix (polymerised monomers) holds the fibers together, transfers stresses between fibers and protects the fibers from outside environment [5]. The fibers can be glass, polyethylene, polyester, carbon, aramid, quartz and ceramic [6].

These materials combine the mechanical properties of the fiber with those of the matrix. The fibers exhibit increased tensile strength and elasticity, and low shear strength; the polymeric matrix is characterized by increased hardness [7]. When compared with other structural materials, FRC materials present high stiffness and strength per weight along with adequate toughness [4]. Reinforcing technology is used when low-weight structures that can take up high stresses are needed, as it is the case with dental restorations.

Table 1. Main clinical applications of fiber reinforced composites in dentistry [3]

Dentistry field	Clinical use
Prosthodontics	Provisional or definitive fixed dental prostheses, veneers, direct or indirect pontics, and repair of removable devices
Endodontics	Prefabricated or customized root canal anchoring systems
Conservative dentistry	Direct and indirect fillings, inlays, and overlays
Orthodontics	Retention splints, space maintainers, active "en-masse" units, metal-free brackets, and orthodontic wires
Periodontology	Periodontal splints and posttraumatic splints
Paediatric dentistry	Crowns in primary molars, splints, space maintainers, and direct fillings

Microscopically, the chemical adhesion with covalent bonds between reinforcing fibres and polymeric matrix allow the prevention of cracks propagation by the fibres [8]. The reinforcing component can also act as a stress concentrator due to the interface between the fiber and the composite [9]. The properties of fiber-reinforced composites are strongly influenced by the characteristics of the components, their distribution and the interaction between them. In the literature, various factors with impact on the characteristics of fiber-reinforced composites have been systematized and evaluated [10-13]. The main factors influencing the mechanical properties of fiber-reinforced composites are schematized in Table 2 [14-19].

Table 2. Factors influencing the properties of fiber reinforced composites

▪	Fiber orientation
▪	Fiber quantity
▪	Fiber surface treatment
▪	Fiber impregnation with polymeric matrix
▪	Adhesion of fibers to polymer matrix
▪	Fiber and matrix intrinsec properties
▪	Fiber distribution
▪	Water absorption by the matrix

Orientation of fibers

Dental restorations use unidirectional, bidirectional or multidirectional fibers with various architectures (Fig. 1). Fiber-reinforced composites are anisotropic or orthotropic, the properties being variable depending on the direction. Unidirectional orientation fibers provide anisotropic mechanical properties to the final composite material and are indicated when the direction of the highest stresses is known (Fig. 2). Otherwise, when the direction of the highest stress is not predictable, as for splints, the use of bidirectional or multidirectional fibers is indicated. This confers to the composite orthotropic mechanical properties [5, 20-22].

Fiber quantity

The quantity of fibers should be defined as the volume unit relative to the polymer matrix, not as a mass unit [25, 38] (Fig. 3).

The strength of the reinforced composites depends on the fiber volume. The higher the fiber density is, the better the mechanical properties are [22, 26, 27]. Because the fibers have to be completely covered by the non-filler polymeric resin, too much fiber can have a negative impact on the long-term behaviour, resulting in increased wear and fracture of the reinforced composite. The appropriate amount of fiber relative to the polymer matrix should be between 2-7.6 wt.%, in order to provide the strength of the reinforced composite [25, 28].

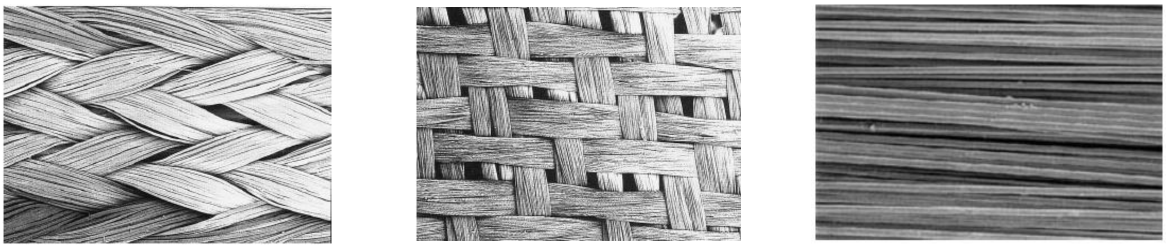

Fig. 1. Types of reinforcing fiber orientation: bidirectional (braided and woven) and unidirectional [23]

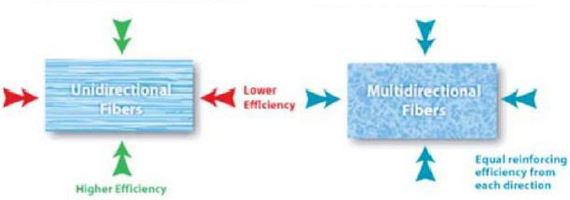

Fig. 2. FRC reinforcement efficiency according to fiber orientation [24]

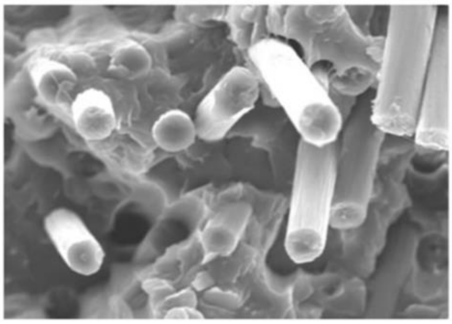

Fig. 3. SEM Image - Amount of fibers in the polymer matrix [38]

Surface treatment of the fiber and its impregnation with the polymeric matrix

Fiber preimpregnation means that fibers are impregnated with the resin matrix prior to fabrication stages of dental restoration. [1]. Preimpregnation of fibers is accomplished with fluid resins (monomer, polymer), part of matrix composition [21, 22]. Insufficient fiber impregnation creates voids between the fiber and the matrix, leading to the reduction of mechanical properties [29]. Another issue correlated with poor impregnation is water absorption. Cracks and defects in the laminate structure allow water to diffuse, which results in a reduction in adhesion and may generate hydrolytic degradation of the polysiloxane mesh of glass fiber reinforced composites. Also, colour defects and microbial infiltration may occur at these defects [18, 30, 31].

Adhesion of the fiber to the polymer matrix

The adhesion between glass fibers and matrix is achieved by a layer of silanes. This is by definition a hybrid chemical compound based on a direct Si-C bond [32]. Another method to ensure fiber adhesion to the matrix is cold gas plasma treatment of polyethylene fibers [33]. In this technique, the fibers are exposed to partially ionized oxygen, which acts through an ablation and activation process. The results of the ablation result from an etching and an increase in the chemically active groups on the surface of the fiber. These groups provide chemical adhesion to the resin, while the etched surface of the fiber facilitates a micromechanical bond [34].

It is necessary to specify that a durable adhesion between fibers and matrices provides an adequate transfer of loads between the two components. Thus, the fiber will take up the stress and strengthen the reinforced structure, which is the principle of the composite materials. If adhesion is not durable and if voids occur between the fiber and the matrix, they can act as initial fracture sites in the composite mass and will facilitate the failure of the material. In view of these aspects, adequate adhesion between fiber and matrix is necessary to ensure mechanical performance and longevity of dental restoration [35].

Water absorption

Local conditions in the oral cavity may induce the occurrence of a "corrosion" phenomena caused by the diffusion of water in the polymer matrix. This may reduce the mechanical properties and may cause changes in the composite structure since the surface of the glass fibers is affected by the hydrolysis of the alkali oxides in its structure. The hydrolytic stability of the reinforced composite is determined by the fiber composition and its silanization [22, 30, 36].

The analysis of a reinforced composite material cannot be done without knowing the phenomena that occur at the fiber-composite interface, which is a transition region with a gradual evolution of properties. In this area, complex physical and chemical processes take place, which influence each other and which can change the conditions for making contact between the two components in a favourable or unfavourable sense. Effort transfer to the interface is only possible if intimate molecular contact is made between the components. Interface failure is often critical for the restoration and the bonding is provided when done chemically [26].

Saygili et al analysed the effect of glass and aramid fibers position on the flexural strength of temporary restorative materials. Composite materials reinforced with glass fibers have shown a high transverse strength and a bending strength of 20-50% higher than those reinforced with aramid fibers [37]. The mechanical properties of polymer-based materials present both macroscopic behavioural and molecular behavioural aspects, including chemical composition and physical structure. The main mechanical test methods used provide information on compressive strength, flexural strength, modulus of elasticity and fatigue strength. The results obtained from these tests can provide information on patterns of destruction and ways of improve [38].

Compared to traditional dental materials, reinforced composites have complex properties. If the metallic alloys are uniform, homogeneous and isotropic (they have the same properties regardless of the direction in which they are loaded), the reinforced composites are heterogeneous and anisotropic, which means that their properties are dependent on the direction in which they are loaded in relation to the orientation of the fibers. Mechanical, optical, thermal properties and curing shrinkage of the FRC are dependent on the fiber quantity and orientation [39, 40].

For composites reinforced with unidirectional (long, continuous and parallel) fibers, the best properties are recorded when the direction of the force is parallel to the direction of the fibers, and the weakest are in the direction perpendicular to that of the fibers [23, 41].

The resistance of fiber-reinforced composites is correlated with the fiber reinforcement efficiency (Krenchel factor), which is significantly influenced by the orientation in plane of the fibers (Fig. 4) [42, 43].

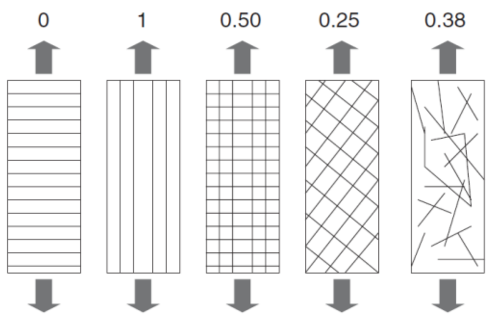

Fig. 4. FRC reinforcement efficiency according to fiber orientation [42]

For composites reinforced with unidirectional fibers, the factor has the highest theoretical value when the direction of force is parallel to the direction of the fibers and the value is null when the stress of the material occurs in the direction perpendicular to the direction of the fibers. The perpendicular orientation of the bi-directional fiber reinforcement is expressed by a factor of 0.5, this reinforcement efficiency being twice the bi-directional fiber at an angle of 45° in the direction of force. In the case of short, discontinuous fibers, the Krenchel factor value is 0.38 [38, 44].

As a result, the restoration and design of its components must be correlated with the biggest loads direction. For example, in the case of a dental bridge, in the region of the pontic most of the fibers have a mesial-distal orientation and only a few fibers are oriented in other directions [23]. Some authors recommend placing additional fibers to prevent fracture of the composite veneer, especially when fixed prosthetic restorations are in the lateral area [45]. Studies on the viscoelastic behaviour of FRC with glass have shown that they have a value close to that of dentine (15.32GPa / 17 GPa) [46].

The clinical performances of FRC restorations are tributary to the continuous improvements of materials structure (fibers, resin matrix and fillers), adhesion protocols, new technologies (CAD/CAM) and, consequently, new design principles, opening preclinical and clinical alternative research directions [47, 48].

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