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High-aspect ratio fillers: Fiber-reinforced composites and their anisotropic properties

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Objectives. To present an overview of fiber-reinforced composites (FRCs) that are a group of non-metallic dental biomaterials used in several fields of dentistry.
Methods. A range of relevant publications from the past half century are surveyed, with emphasis upon recent publications.
Results. FRCs vary according to the type of fiber fillers and orientation of fibers, the latter being responsible for several properties which can vary from isotropic to anisotropic. The length of the fibers, i.e. the aspect ratio of the filler, is another factor or variable that contributes to the properties and the development of new types of composite resins for restorative and prosthetic dentistry, as well as to reconstructive medicine.
Significance. Understanding the anisotropic nature of FRCs from the perspective of dental applications has increased in recent years. This review describes some fiber orientation related anisotropic properties of FRCs which contribute to the increased use of FRCs in clinical dentistry.

1. Introduction

Using high aspect ratio fillers in composite resins can significantly change the resin's physical properties in comparison to using particulate fillers which provide isotropic properties for the material. High aspect ratio fillers have a high ratio of the length of the filler to its cross-sectional diameter. In composites, high aspect ratio fillers are fibers but shorter filament like fillers of whiskers can be also considered high aspect ratio fillers [1]. Different types of fibers with various orientations and lengths have been utilized for decades in engineering applications to construct devices with high strength and fracture toughness. The first glass fiber-reinforced boat was produced in 1937 in Russia and since then the anisotropicity of fiber-reinforced materials has been utilized in everyday life and recently in dentistry and medicine.

In natural constructs, reinforcing fibers of cellulose can be found, e.g. in wood, where the length of the oriented polysaccharide based cellulose fibers and shorter branched hemicellulose fibers is between 0.8 and 2.3 mm [2]. Chiral and crystalline cellulose fibers in wood are embedded in the lignin matrix, which is a natural biopolymer of aromatic alcohols. Other examples of natural systems that contain high aspect ratio components include bone and dentin [3]. Osseous tissue of bone and dentin is composed of a hard, lightweight composite, where mineral calcium phosphate in the chemical arrangement of hydroxyapatite forms the inorganic matrix for

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the protein origin collagen fibers, which are formed from thinner type I fibrillar collagen. The collagen fibers with a diameter of 20–400 nm consist of collagen molecules, which are stabilized by four cross-linking covalent bonds per molecule [4]. The length of collagen fiber is around 23 μm [5]. High aspect ratio fibers in collagen provide high tensile strength and fracture toughness for bone and dentin, whereas hydroxyapatite is responsible for the compressive properties. Both collagen fibers and crystals of hydroxyapatite are oriented best to withstand physiological loading conditions. Mineralized collagen fibers provide toughness through crack-tip shielding through osteons, especially with lower strain rates [6].

Man-made high aspect ratio fillers have been used since ancient times to reinforce bricks and buildings [1]. Modern fiber-reinforced composites (FRCs) are used in applications where high static and dynamic strength and fracture toughness, especially in relation to weight, are desired properties. For example, dental and medical devices are typically subjected to hundreds of thousands of loading cycles by the masticatory system or the weight of the body during physical exercise [7]. FRCs are typically designed to have the highest possible reinforcing efficiency against the direction of stress, and thus, they often represent anisotropic material in terms of mechanical properties. However, some other properties, such as optical properties, surface physical properties, thermal properties and polymerization contraction properties are related to the orientation of the fibers in the FRC. From the point of view of high fatigue resistance and toughness, FRC is part of a group of choice materials for dental and medical needs. FRCs in dentistry were first developed in the early 1960s but an increase in the number of published scientific papers occurred in the early 1990s [8–15]. Currently, FRCs are used in fixed prosthodontics, restorative dentistry, periodontology, orthodontics and in repairs of prosthetic devices [16–26]. There are also cranial implants made of glass FRCs and attempts to develop oral and orthopedic implants are ongoing [27,26,28,29]. This is a review of the current status of knowledge of some anisotropic properties of FRCs used in dentistry.

2. Reinforcing efficiency of fibers

The majority of dental FRCs are presently produced from glass fibers due to their surface chemistry, which allows for their adhesion to the resin matrix via silane coupling agents, and to the transparency of their fibers [30–32]. Glass fibers do not cause severe problems related to the appearance of the restoration. Out of the several different types of fibers (carbon/graphite, aramid, polyethylene), glass fibers have been adopted for use in dentistry and medicine. The most common glasses, namely E-glass and S-glass, and their behavior as components of dental FRCs were recently reviewed in more detail in another publication [33].

FRC is a material which contains at least two phases, one of which is characterized by its high aspect ratio, i.e. ratio between the length and diameter (l/d). Among many parameters (interfacial adhesion, elongation of fibers, fiber volume fraction) which contribute to the reinforcing efficiency of fibers, length and orientation of fibers are important in terms of the isotropicity–anisotropicity of the material [1]. FRCs are

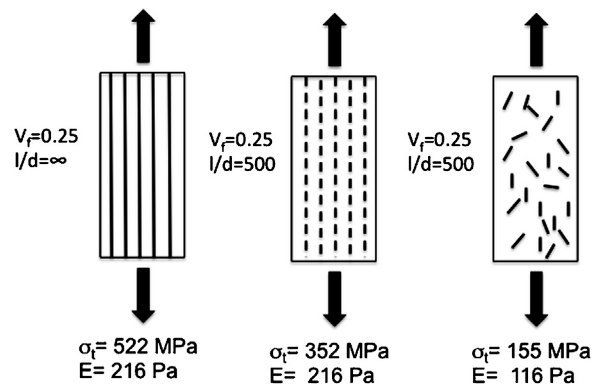

Fig. 1 – Influence of the aspect ratio (l/d) of fibers and their orientation to the tensile stress (σ_t) and modulus of elasticity (E) with the same volume fraction of fibers (V_f) [34].

classified as short discontinuous and long continuous FRCs; which have different mechanical properties although the fiber volume fraction could remain the same [34]. By changing continuous unidirectional fibers to longitudinally oriented discontinuous short fibers of lower aspect ratio, ultimate tensile strength of the composite is reduced (Fig. 1). In this case both continuous and discontinuous FRCs are anisotropic. Changing the orientation of short fibers so they lay randomly causes the tensile strength to reduce even more, and the FRC material becomes isotropic. Consequently, strength, unlike stiffness of continuous FRCs, cannot be attained by discontinuous short fiber systems even with high aspect ratios [34]. Failure types of discontinuous short FRCs including cracking of the polymer matrix, debonding of the fiber and fracture of the fiber (Fig. 2). Depending on the length of the fiber, aspect ratio of the fiber, interfacial fracture energy (adhesion of fibers to the matrix) and fiber volume fraction, some of the failure types are more common. Dependence between the orientation and length of the fibers is also described by Krenchel's factor, in which the reinforcing efficiency factor for fiber reinforcement goes against the known direction of stress [35]. Reinforcing fibers in the direction of the stress provides the highest reinforcing efficiency and finally axial failure of the fibers and polymer

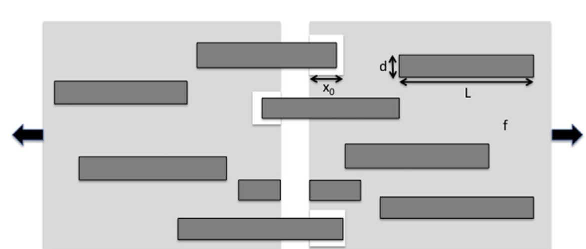

Fig. 2 – Schematic presentation of the types of failures (crack of the matrix, debonding of the fiber, fracture of the fiber) of discontinuous short fiber-reinforced composite (X_0 = embedded fiber length which as debonded, d = diameter of fiber, L on fiber length, f = volume fraction of fibers). Arrows show the direction of load.