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Effect of fiber volume fraction and length on the wear characteristics of glass fiber-reinforced dental composites

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Summary *Objective.* The main objective of this study was to evaluate the wear characteristics of fiber-reinforced dental composites. Variables under investigation include the fiber weight percent added to the matrix as well as fiber length.

Methods. Dental specimens with glass fiber content of 2, 5.1, 5.7, and 7.6 wt% with fiber length of either 1.5 or 3 mm, were prepared by mixing an activated dental resin with commercial glass fibers. The specimens were then tested on a pin on disc setup, where the antagonist disc was manufactured of a similar fiber-reinforced composite with 5.1 wt% fiber and fiber length of 3 mm. The volume loss and coefficient of friction of the specimens was monitored periodically throughout testing. In addition, the wear surfaces of all specimens were evaluated using a scanning electron microscope.

Results. The specimens with 5.7 wt% fibers and fiber length of 3 mm performed better in this study compared to all other fiber-reinforced specimens under all load conditions. In fact, this specimen had a comparable wear rate to a particle-filled dental composite. For the fiber lengths considered, increasing the length of the fibers increased the wear resistance of the specimen. The coefficient of friction showed a good correlation with the wear resistance of specimens.

Significance. Fiber-reinforced composites demonstrated a high resistance to wear and may therefore be advantageous for dental applications, where high wear resistance is essential to functionality.

Introduction

The wear resistance of dental composites is of great consideration in the case of dental restorations, as significant loss of tooth surface due to wear can leave the voids susceptible to bacterial infiltration

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and result in the degradation of the tooth [1-5]. This loss of substance in the dental context can be due to abrasive, erosive, corrosive, impact and other minor types of wear as they are subjected to multiaxial cyclic loads during their service life. Therefore, the wear behavior of dental composite is a continuing major research area and must be thoroughly investigated when developing novel materials for dental applications.

Generally, clinical evaluations of composite performance are the most widely accepted measure of wear resistance [6]. However, the time involvement and costs associated with clinical studies have driven manufacturers to predict restorative performance using prototype materials in a wear simulator [7,8]. The development of an effective, efficient, and repeatable in vitro wear test therefore has the potential to make a significant impact in dental materials research [9, 10]. Unfortunately, the complex and variable conditions in a human mouth are difficult, if not impossible, to reproduce experimentally.

There are several variables that affect the extent and rate at which dental composites wear during the in vitro wear test, including composition of material, degree of cure, wear antagonist material, load applied to opposing surfaces, the quality and quantity of lubricant, duration of contact between surfaces, and the relative speed and direction of movement between surfaces [7,11,12]. For the case of particle-filled composites (PFC), it was shown that resistance to wear could be significantly improved with decreased average filler particle size and with increased filler volume fraction [13-19]. Xu et al. [20] studied the wear resistance of 20 composites using a three-body wear-testing machine. They observed that no linearity exists between wear resistance and filler volume fraction for the cases of filler-reinforced bio-composites.

The results of these investigations have shown that the wear resistance of most PFCs is not adequate for posterior applications, especially when compared to the corresponding property of amalgam [6]. Another means of effectively improving the mechanical performance of a composite is to incorporate fibers into the matrix for reinforcement. While this type of composite is commonly used in various industries, the technology has not been thoroughly investigated for the purpose of dental restorations. These fiber-reinforced composites (FRC) have been produced by incorporating various fibers into the resin matrix [11]. Based on a literature survey, there is minimal data available on the mechanical behavior and wear characteristics of the dental FRCs. While many PFCs may contain a very high percentage of filler particles (some up to 90% by weight), FRCs are limited to a much smaller filler ratio, for proper homogenous mixing.

From the available compatible fibers, glass fibers have drawn the most attention due to their esthetic qualities and easy manipulation [21]. While some investigators have studied the effect of the fibers on mechanical properties such as ultimate strength and fracture resistance of these composites [22], the literature survey reflects that there are very few studies on the wear properties of such FRCs. Manhart et al. [12] studied the wear rate of one commercially available dental composite reinforced with glass fibers. They concluded that the increased wear rate of the FRC compared to the PFCs was due to the micro-filamentous glass fiber particles present in the matrix. It was suggested that the ‘plucking’ of the fibers left the adjacent matrix susceptible to further breakdown, therefore resulting in increased wear rates. However, the effects of neither fiber weight percent nor fiber length were investigated in this study.

In addition to interest on the friction and wear of dental FRCs, there has been significant study on the effect of reinforcement on its various mechanical properties and the role of reinforcement on the adhesion of *Streptococcus mutans* [23-28]. Lassila et al. [23] showed that fiber volume fraction and the water sorption of the polymer matrix had a significant effect on the flexural properties of FRCs. Dehydration of specimens recovered the mechanical properties. A decrease of flexural properties after water immersion was considered to be mainly caused by plasticizing effect of water and the amount depended on the amount of water sorption. Well-impregnated FRC have theoretically lower water sorption than poorly impregnated FRC. Voids in the polymerized matrix could increase the water sorption. Lastumaki et al. [24] examined the shear bond strength of visible light-curing composite resin (VCR) to aged glass fiber-reinforced composite substrate with multi-phase polymer matrix. It was found that the use of intermediate monomer resin greatly influences the mean shear bond strength values when the test specimens are thermocycled.

Tezvergil et al. [25] studied the effects of the fiber orientation on the thermal expansion and dimensional changes of various FRCs. It was suggested that the anisotropic nature of the linear thermal expansion coefficient might influence the interfacial adhesion of FRC appliances. Tannr et al. [26-29] studied the adherence of *S. mutans* to an E-glass FRCs and conventional restorative materials used in prosthetic dentistry. The results of these studies suggest that the restoratives are rather similar with respect to *S. mutans* adhesion and that a saliva pellicle may promote adhesion of *S. mutans* to glass fibers. Furthermore, the results of this in vitro study suggest that in order to avoid the possible increase in *S. mutans* adhesion, the reinforcing glass fibers should be covered with the matrix polymer of the composite. This study clearly indicates that FRCs can have a potential application in dental restoration.

The main objective of this study is to investigate the in vitro wear characteristics of the dental FRCs when abraded against an antagonist of similar composition. The relationship between fiber weight fraction and fiber length of glass fibers incorporated into a dental resin and the wear resistance of these composites is studied for various applied loads. Furthermore, the effect of these parameters on the coefficient of friction is investigated. In addition, the results are compared with the result of the wear test for a PFCs with the same polymer matrix material currently available on the market.

Materials and methods

Composite materials

FRCs were manufactured by mixing an activated dental resin ($\sim$75% Bis-GMA monomer and $\sim$24.5% triethyleneglycol dimethacrylate monomer) with commercial glass fibers (average diameter $\sim$10 μm) of different lengths, assuring the consistency of the mix. For the proper weight percentage, the weight of the matrix and fiber were measured prior to their mixing. No coupling agent was added to the mixture. The mix was placed into a machined aluminum half-spherical (diameter = 6.8 mm) mold and cured under a 500 W halogen light at a distance of 0.5 m for 30 min. The flat surface of the specimen was then bonded to an aluminum SEM mount using an epoxy. These specimens were used as the pins on the pin on disk wear apparatus. The tray antagonist specimens with a diameter of 75 mm and thickness of 5 mm were produced with the same dental resin and glass fibers for reinforcement. Due to the increased mass and thickness, the tray specimens were cured under the same halogen light for 1 h to ensure complete cross-linking. The tray was used as the disc on the wear apparatus. The manufacturer of the resin recommended curing of the resin using either curing light or halogen light for polymerization of the composite. For safety considerations, we used mostly halogen light for curing the composites in this study except for the particle-reinforced dental composite, which was cured using a Dentsply curing light with 120 V at 2 A. Although the curing regimens were not consistent between materials, the manufacturer instructions were followed to ensure complete polymerization.

For studying the effect of fiber length and volume fraction on the wear characteristics of the composites, the following specimens were produced:

- 3-2.0 wt% 1.5 mm fiber
- 315.1 wt% 1.5 mm fiber
- 3-5.7 wt% 3 mm fiber
- 3-7.6 wt% 1.5 mm fiber

The tray antagonist specimens were manufactured with 5.1 wt% 3 mm fibers. The tray specimens were sanded and polished using 120 grit sandpaper followed by 600-grit sandpaper with a grinding/polishing machine. All specimens were stored in desiccators prior to wear experiments. Experiments were performed in the absence of any liquid.

Furthermore, in order to compare the wear characteristics of the FRCs with the PFCs, six specimens were produced with a commercially available dental PFC (SureFil dental restorative—Denstply) These specimens were produced following the same methods except that they were cured using a dental curing light for 30 s. All specimens were stored in a vacuumed desiccator chamber until the testing was conducted.

Wear test

The wear apparatus used was similar to a pin on disc setup commonly utilized for wear-testing [46]; except that the FRC tray specimen was used as the disc portion of the setup. Fig. 1 shows the schematic diagram of the wear apparatus. Most researchers who have investigated the wear resistance of dental composite specimens used either stainless steel or tooth enamel acting as the wear antagonist [7-10]. In order to accurately assess the most suitable specimen for our experiments both cylindrical and spherical specimens were produced and tested prior to testing the actual materials. The cylindrical abraders did in fact exhibit inconsistent wear mechanisms and fluctuating friction coefficients. This variation was possibly due to the angle and area of contact between the cylindrical specimen and the antagonist disc, possibly causing phenomena other than abrasion or attrition. Wassell et al. [29] commented on the edge loading effect of cylindrical specimens which can affect the wear rate of the specimen and also alter the wear mechanisms. Due to these factors all of the specimens in this study were created with a half-spherical shape. Despite the changes in contact area and pressure associated with the spherical

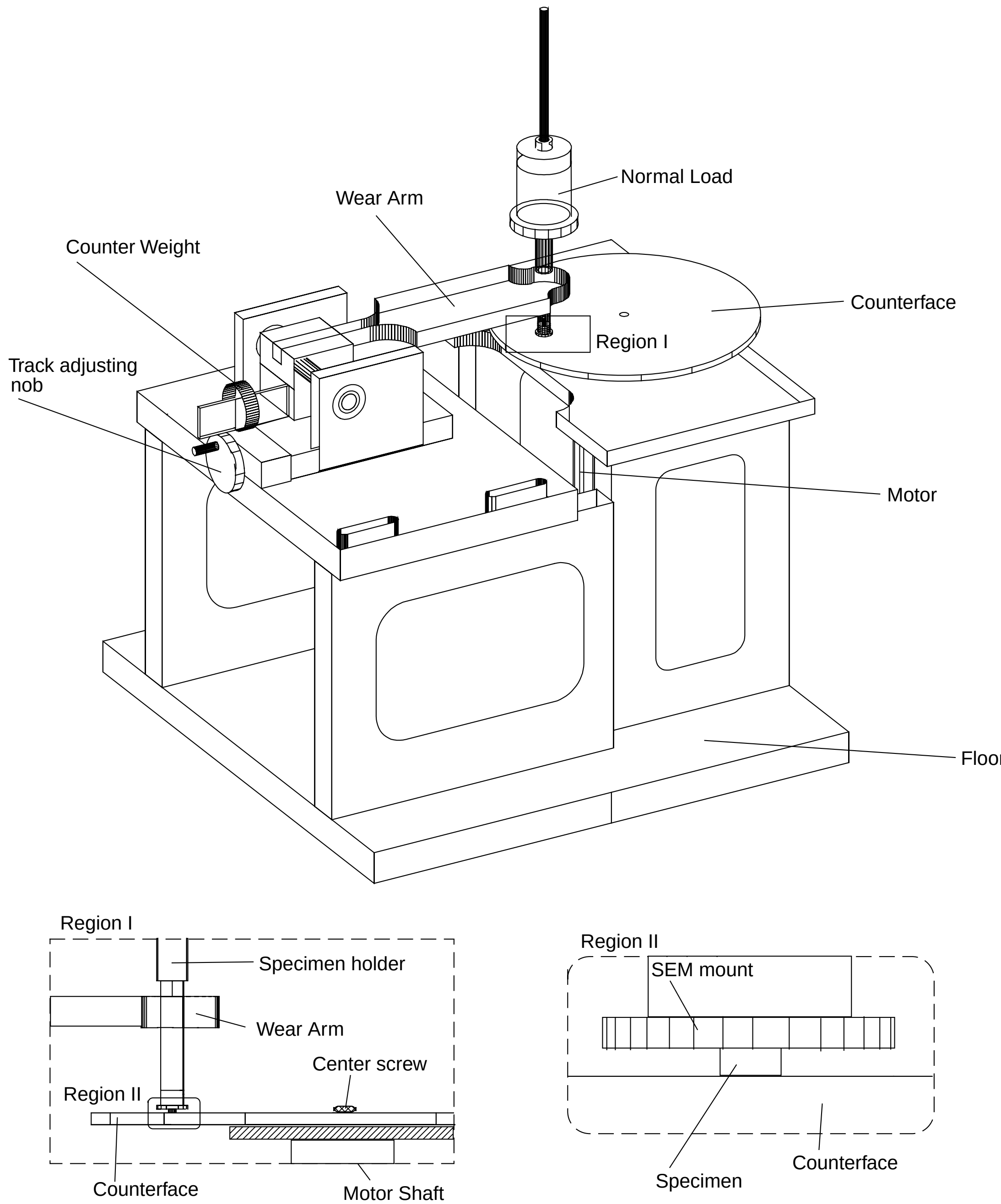

Figure 1 Experimental pin on disc set-up.

specimen, Archard [30] reported that for the homogenous materials the wear rate is independent of the apparent area of contact. The wear rate was reported to be proportional to the applied load and sliding distance and inversely related to the materials hardness. Wassell et al. [29] found that the wear volume in a dental composite increased linearly with the number of cycles, which was proportional to the sliding distance.

All tests were conducted at 60 rpm. This rotational frequency was chosen to mimic other researchers, which commonly test at a rate between 1 and 2 Hz [8,9]. Since the three tracks were tested at the same disk rotational frequency, the relative velocity between the specimen and the composite disc was different, depending on the wear track distance from the center of rotation. However, Kaidonis et al. [7] tested composite specimens and concluded that the velocity does not affect the wear rate of the specimen at moderate velocities. Therefore, the effect of a small difference in the relative velocities of the different wear tracks on the wear rate was not considered in this investigation. The test was controlled by the wear distance of each specimen. As the spherical specimens began to wear, there was a circular area created by the removal of wear debris. Periodically, the circular section of the worn material was measured under the microscope and the associated volume loss was calculated. In between each test both the specimen and the antagonist disc were cleaned of all wear debris. Since the wear weight loss was very small in our experiments, there was negligible change in the contact area; therefore, we can assume that the small variation in the developed stress in the contact region has a negligible effect on the wear rate [30-32].

The normal load was applied on top of the arm and was varied in the range of 4.45-22.24 N. This load range was within that in oral environment and was used by Hu et al. [10] in their wear experiments. One specimen of each composition was tested under each load condition. The horizontal load due to friction was monitored continuously using a lever arm equipped with strain gages. The strain gage signals were continuously monitored and recorded using the MGC Plus data acquisition system (HBM Inc., Marlborough, MA, USA).

The frictional force was observed to display a trend of variation between two well-defined extreme positions. The possible explanations for this friction variation phenomenon were discussed in Nayeb-Hashemi et al. [31,32]. In this study, the coefficient of kinetic friction was evaluated for each test.

Results and discussion

Figs. 2-4 show the wear volume versus the sliding distance for all specimens subjected to three

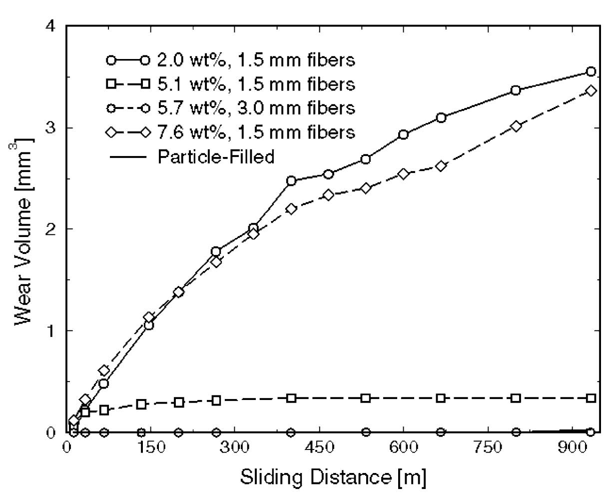

Figure 2 Specimen volume loss versus sliding distance for an applied load of 4.45 N for all specimens.

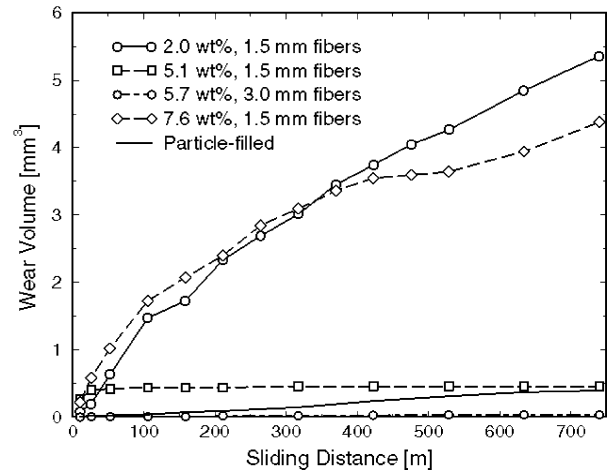

Figure 3 Specimen volume loss versus sliding distance for an applied load of 11.12 N for all specimens.

normal loads of 4.45, 11.12, and 22.45 N, respectively. Since only one specimen from each sample was tested under each load condition, no statistical analyses were performed. The results indicate that both the 2.0 wt% fiber specimens and the 7.6 wt% fiber specimens exhibit much higher wear rates than the 5.1, 5.7 wt% fibers, and particle-reinforced specimens for all the applied loads. Apparently, the specimen with 2.0 wt% fibers does not provide enough support to the matrix material, causing specimen wear due to adhesion and abrasion. This conclusion is in agreement with the micro-mechanism of wear observed in the SEM pictures of the wear surface of the specimen (Fig. 5).

The 7.6 wt% fiber specimen is possibly loaded with too many fibers resulting in a cluster of fibers with little matrix between the fibers. In this case there are significant interactions between fibers resulting, in a poor bonding between fibers and

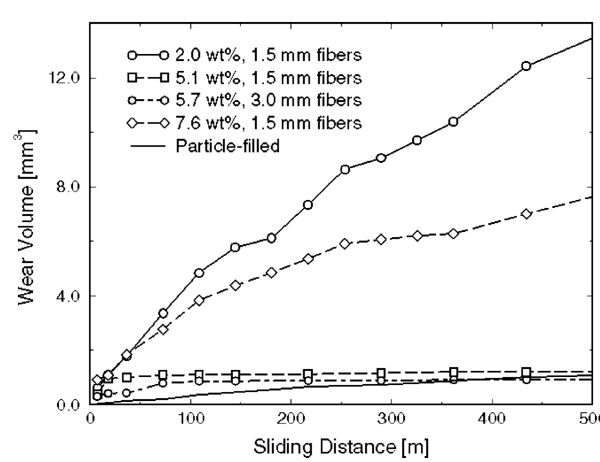

Figure 4 Specimen volume loss versus sliding distance for an applied load of 22.24 N for all specimens.

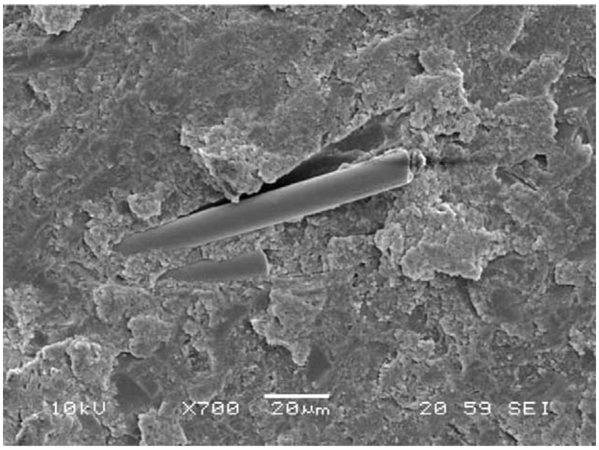

Figure 5 This SEM of the wear surface of a 2 wt% specimen shows the detachment of the fiber from the surrounding matrix which leads to fiber plucking.

matrix. This result is in agreement with the SEM pictures (Fig. 6), where fibers apparently are not well bonded to the matrix material due to the presence of excessive fibers. This results in fibers being pulled out of matrix as well as matrix being removed from around the fibers, leading to a high wear rate (Fig. 6). In addition, SEM observation of the wear surface of these specimens showed that for these specimens the distribution of the fibers was not uniform (Fig. 6(a)). The high concentration of fibers could lead to the premature fiber fracture during wear experiments, in addition to a significant amount of fiber plucking (Fig. 6(b)). The effect of the fibers on the matrix polymerization was not considered, since the primary interest in this research was to understand the role of fibers weight percent on the wear behavior of FRCs. However, the degree of polymerization as well as fiber content may effect overall, the wear behavior of composites.

The ideal amount of fiber for superior wear resistance is therefore between 2.0 and 7.6 wt% for the matrix and fiber type/length used in this investigation. It was concluded that the relationship between the wear resistance and the fibers weight percent was not linear. Xu et al. [22] found that the ultimate strength and fracture resistance of fiber-reinforced dental composites was not linear with the number of fibers. Furthermore, it was concluded that the wear volume was changing linearly with the sliding distance after the transition period. The transition period distance of FRCs depends on the fiber volume fraction and the applied normal load and initial surface roughness. However, the transition period distance of PFC is very small for all the applied normal loads. The initial wear rate (transition period) of each FRC (5.1 and 5.7 wt%) is much higher than the initial wear rate of the PFC. Despite the high initial rate, the wear rate of these FRCs quickly approaches zero within the first 100 m of sliding distance. Thus, the wear volume of these FRCs mainly depends on the wear volume within the first 100 m and increases slightly afterwards. The initial high wear rate could be related to the initial surface roughness of the specimens. There was no attempt to polish these specimens before the wear test. In a possible dental application it is recommended to polish the surface of the restorative composite. Furthermore, since the presence of the fibers may promote adhesion of *S. mutans*, it is desirable to cover the surface of the composite with the polymer matrix or PFC [26–28]. SEM evaluation of both the 5.1 and 5.7 wt% specimens revealed minimal fiber plucking as compared to the 7.6 wt% fiber specimens. Furthermore, it was found that the wear surface was significantly

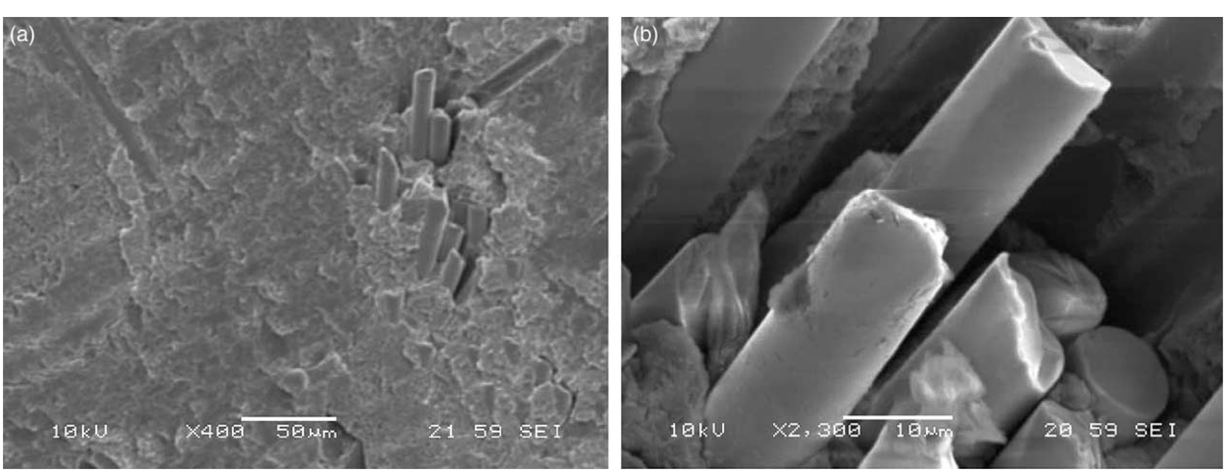

Figure 6 The SEM photographs of the 7.6 wt% wear surface display (a) a clump of fibers which was not consistently mixed with the matrix and (b) the occurrence of fiber fracture.

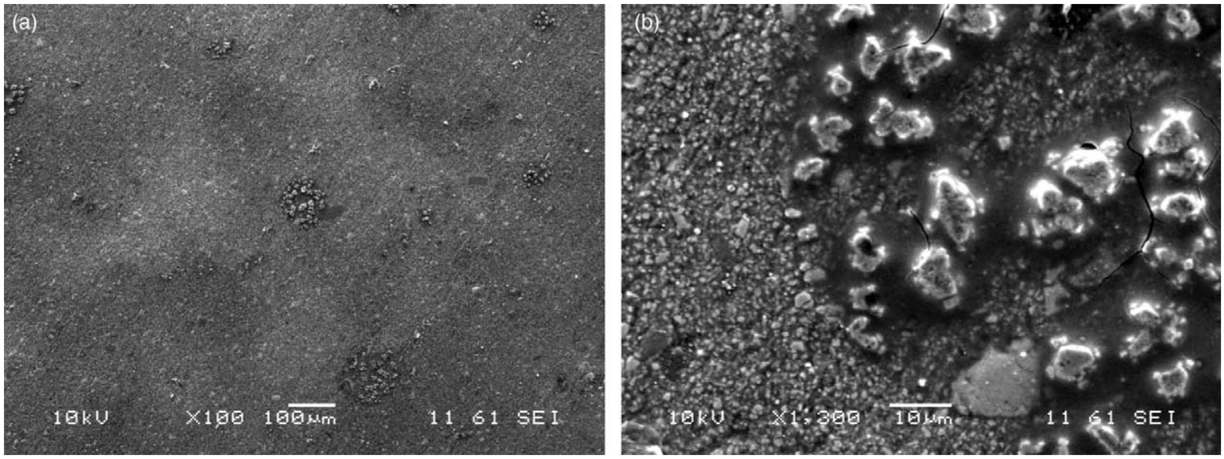

Figure 7 (a) SEM evaluation of the particle-reinforced wear surface reveals several silica particle 'clusters' distributed throughout the material. (b) Examination of the 'cluster' at an increased magnification reveals the incidence of micro-cracking around the edges of the particles.

smoother than that of corresponding specimens with the 2.0 and 7.6 wt% fibers.

The PFCs showed superior wear resistance in comparison to all fiber-reinforced composites with an applied load of 4.45 N throughout the entire test. In contrast, the 5.7 wt% fiber specimen resulted in a better wear resistance in comparison to the PFC after a critical sliding distance for the applied loads of 11.12 and 22.24 N. This can be justified considering the result of SEM observation. SEM evaluation of the wear surface of the PFC (Fig. 7(a)) shows several 'clusters' of silica particles randomly distributed. For the specimens that were subjected to normal loads of 11.12 and 22.24 N, micro-cracks were present around the silica particle clusters (Fig. 7(b)). These micro-cracks could have been developed around the cluster of silica particle due to a high stress field. These micro-cracks could accelerate wear rate in the PFC due to crack growth and delamination of the matrix materials. This phenomenon is apparently less prominent for the specimen subjected to the normal load of 4.45 N.

The effect of glass fiber length on the wear resistance of FRC is shown in Fig. 8 for all the applied normal loads. Apparently, the transition period distance of FRC does not depend on the fiber length. The results show that the composite with the longer fibers exhibited lower wear volumes and wear rates for all load conditions. This could be justified considering that the full strength of the FRC may not have been utilized with fibers of length less than the critical length. The critical length of a fiber depends on the fiber strength and interfacial shear strength. In addition, short fibers may be easily clustered and result in a weak region in the composite. These results are in agreement with those reported by other investigators [12,22]. Manhart et al. [12] studied the wear resistance of several commercial dental composites, including one manufactured with very short (average length = 60-80 μm) fibers incorporated into the material. It was concluded that short fibers could be easily removed from the matrix resulting in increased wear. Xu et al. [22] showed that increasing the fiber length generally increased the FRC ultimate strength and fracture resistance. Furthermore, the results show that the wear volume of the FRC does not change linearly with the applied load. This can be justified considering the different wear mechanisms of the composites.

Fig. 9 presents the average wear rate over the first 500 m of sliding distance for all specimens and all the applied normal loads. The results clearly

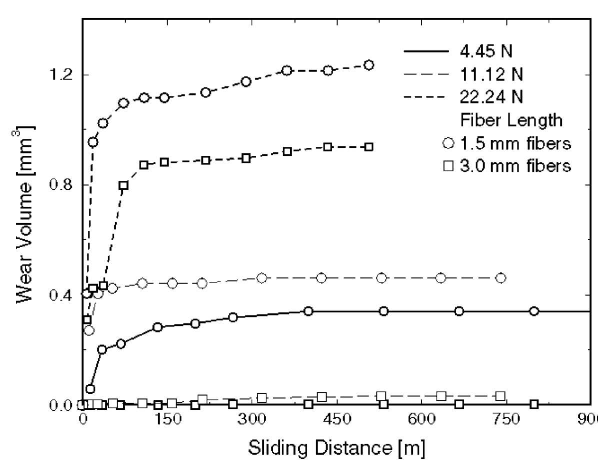

Figure 8 The effect of the fiber length on the wear volume of the fiber-reinforced bio-composite for all load conditions.

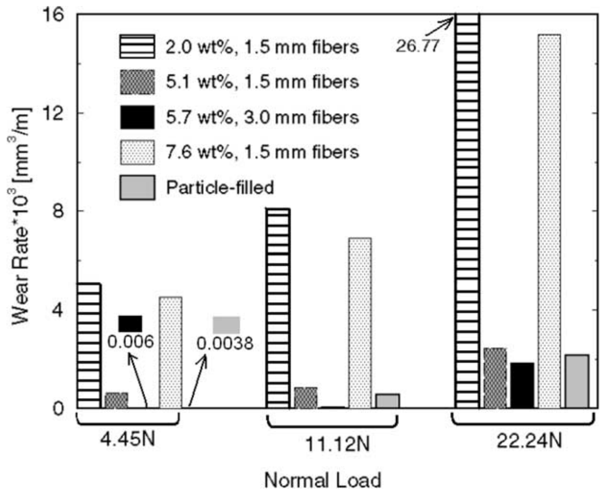

Figure 9 Average wear rate over the first 500 m of sliding distance for all specimens and all load conditions.

show that the specimen with 5.7 wt% fibers has superior wear resistance compared to all other materials tested while the specimen with 2.0 wt% fibers has the highest wear rate for all applied loads.

Fig. 10 presents coefficient of friction of all specimens after the transition period under the normal load of 22.24 N. The result showed that the coefficient of friction for 2.0 and 7.6 wt% specimens were significantly higher than for other specimens. This is in agreement with the SEM pictures where the wear surface for these specimens was significantly rougher in comparison with other specimens. The coefficient of friction for 5.1 and 5.7 wt% specimens were approximately equal. The results provided here are in a good agreement with the results provided in Fig. 4 for the wear volume of the specimens.

Fig. 11 shows the effects of fiber length and normal load on the coefficient of friction of 5.1

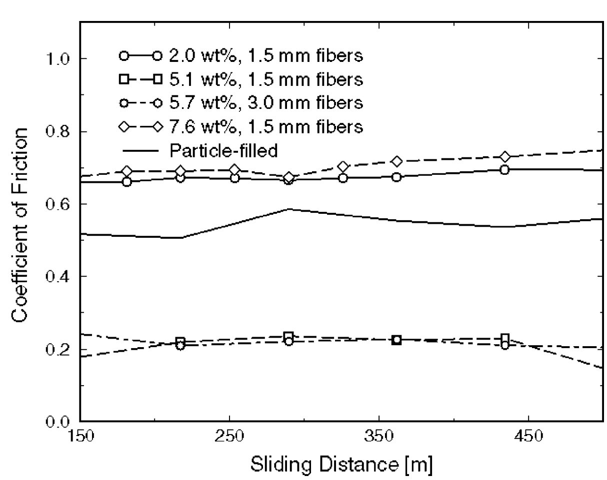

Figure 10 Coefficient of friction versus sliding distance for an applied load of 22.24 N for all specimens.

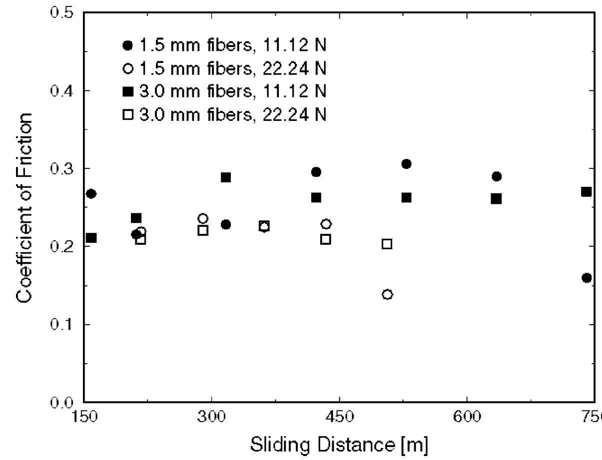

Figure 11 Coefficient of friction versus sliding distance for different fiber lengths for applied loads of 11.12 and 22.24 N.

and 5.7% fiber specimen after the transition period. The results show that the coefficient of friction decreased slightly by increasing the normal load. In addition, it was observed that the fiber length has very little effect on the coefficient of friction.

The results provided in this paper simply compare the effect of fiber weight percent on the friction and wear of the dental composites. Furthermore the same wear test was conducted using a PFC as a basis for comparison. The actual wear process in the in vivo condition is extremely complex. Further research should be conducted to substantiate application of FRCs as a restorative material.

Future research should consider the effects of water sorption on the friction and wear resistance of these FRCs.

Conclusions

The friction and wear behavior of glass fiber-reinforced 75% Bis-GMA monomer and ~24.5% triethyleneglycol dimethacrylate monomer were studied using a pin on disc setup for various fiber weight fractions and fiber lengths. It was found that:

- The wear volume of dental FRC specimens was proportional to the sliding distance after an initial transitional period.
- The wear mechanism and wear rate of the FRC specimens after the transition period depends mainly on the fiber volume fraction.
- For the range of fiber length studied, the fiber length apparently affects the initial wear rate of the specimen, which was at slightly higher

contact pressure. However, it does not significantly influence the steady-state wear rate.

- 2% and 7.6 FRC specimens exhibited highest wear rates. This was attributed to insufficient reinforcement and clustering of fibers, resulting in fiber plucking of the matrix material. FRC specimens with 5.1 and 5.7 wt% exhibited the lowest steady-state wear rate for all applied load.
- The wear rate of the PFC posterior dental restorative remained relatively constant throughout the entire test.
- 5.7 wt% specimens performed best under wear conditions compared to the particle-reinforced composite depending on the applied load and the sliding distance.
- The coefficient of friction depends mainly on the fiber volume fraction after the transition period.
- The wear rate in composites with longer fibers was lower compared to that of shorter fiber and same weight percent. Longer fibers in general provide better strengthening mechanisms compared to that of short fibers and thus more wear resistance.
- The wear rate of the specimens closely correlates with the friction coefficient.

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