Reinforcing effect of discontinuous microglass fibers on resin-modified glass ionomer cement

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This study investigated the reinforcing effect of discontinuous-glass fiber fillers with different loading-fractions on selected mechanical properties and wear of resin-modified glass ionomer cement (RMGIC). Experimental fiber-reinforced RMGIC (Exp-RMGIC) was prepared by adding discontinuous-glass fiber of 200–500 µm in length to the powder of RMGIC (GC Fuji II LC) with different weight ratios (15, 20, 25 and 30 wt%). Mechanical properties and wear were determined for each experimental and control material. Scanning electron microscopy was used to evaluate the microstructure of the Exp-RMGICs. Wear pattern was analyzed by a three-dimensional (3D) noncontact optical profilometer. Fiber-reinforced RMGIC (30 wt%) had significantly higher mechanical performance of fracture toughness (1.9 MPa•m1/2), flexural strength (90.3 MPa), and diametral tensile strength (31 MPa) (p<0.05) compared to unreinforced material (0.8 MPa•m1/2, 51.9 and 20.7 MPa). The use of discontinuous-glass fiber fillers with RMGIC matrix is novel reinforcement and yielded superior toughening and flexural performance compared to conventional RMGIC.

Keywords: Mechanical properties, Discontinuous fiber reinforcement, Resin-modified glass ionomer cement

INTRODUCTION

Over the course of the last several decades, an increasing variability of dental restorative materials has conquered the market. The concepts in restorative dentistry are also changing, and adhesive dentistry has steadily gained in importance. Today, the modern operative dentistry focus is on minimal removal of tooth tissue and on application of adhesive restorative materials that possibly perform mineralizing action on dentin. Those requirements are matched by glass ionomer cements (GICs).

GICs are clinically attractive materials due to several unique advantages among restorative dental materials1). Their benefits include fluoride ion hydrodynamics, biocompatibility, favorable thermal expansion and contraction, and chemical bonding to tooth structure1). However, despite having these significant advantages, GICs suffer from poor surface polish, a high porosity and weak mechanical properties such as fracture toughness (FT), brittleness and surface wear compared to modern composite restorative materials2-5). Different approaches have been suggested and tested to overcome GIC’s weaknesses. Incorporation of a resin system into the GIC cement was introduced, to provide a material that incorporates the advantages of a resin (e.g. improved strength) with the improved properties of GICs6,7). This was first introduced as a new GIC development in 19897). Since then these cements have been further developed into a range of what we now know as resin-modified glass ionomer cements (RMGICs). This type of cement incorporates two setting mechanisms: the conventional acid-base reaction and polymerization of the resin monomer, where polymerization can be either light or chemically activated8). These materials have the same composition as conventional GICs, with the incorporation of poly (acrylic acid), but the difference in RMGIC is the addition of a polymerizable resin monomer, commonly 2-hydroxyethyl methacrylate (HEMA)9).

All the above compositions and developments did not improve two important mechanical properties associated with RMGICs, FT and flexural strength (FS) which correlate strongly with the clinical outcomes of the material10,11). Reinforcement of RMGIC restorative materials is essential and many researchers have focused on improving the mechanical properties by adding various filler types to the GIC powder component. The fillers used included hydroxyapatite powders, bioactive glass particles, nanoclay and discontinuous glass fibers11,12). Discontinuous microfiber reinforcement, i.e. reinforcing fibers with diameter from few micrometers to twenty micrometers with high aspect ratio, are utilized in many fields of technical application as well as in dentistry and medicine13). However they have not been studied to a larger extent with RMGICs12). Although, little information about the use of discontinuous glass fibers with conventional GICs are available, hence further investigation is required in order to produce a material with improved mechanical properties11). Many of the properties of fiber composites are strongly dependent on fiber-matrix adhesion and microstructural parameters such as fiber diameter, fiber length, fiber orientation and fiber loading13). Therefore, the intent of this study was to evaluate the effect of microfibers with different loading fractions and surface treatments on select mechanical properties and wear of resin-modified GIC.
To the author's knowledge, very little research exists in this field. Thus, the hypothesis evaluated was that a resin-modified GIC may be significantly reinforced by incorporating randomly distributed microfibers.

**MATERIALS AND METHODS**

*Production of experimental discontinuous fiber reinforced RMGICs*

The discontinuous E-glass fibers having length scale of 200–500 micrometer (Ø7 µm), so-called discontinuous E-glass microfibers as-received silanized (3-[Trimethoxysilyl] propyl methacrylate, MPS) were used in this study. Experimental fiber reinforced RMGICs were prepared by adding discontinuous glass microfiber to the glass powder of commercial light cured RMGIC (GC Fuji II LC, shade A3, GC, Tokyo, Japan) with different weight ratios (15, 20, 25 and 30 wt%). The mixing was performed by using a high speed mixing machine for 3 min until a homogenous powder mixture was obtained (Hauschild Speed Mixer DAC 400.1, 3,500 rpm). Finally, the materials produced were reinforced powders with different weight ratios of silanized discontinuous glass microfibers which were compared with unmodified material. Additional experimental fiber reinforced RMGIC (20 wt%) was prepared with non silanized discontinuous glass microfibers which was compared with silanized group. The reinforced glass powder and the cement liquid were mixed and manipulated according to the manufacturers' instructions.

**Mechanical tests**

FS was determined by conducting a 3-point bending of test specimens (2×2×25 mm³) from each tested material. The recommended powder/liquid ratio was dispensed on a glass plate. Then this powder was mixed into the liquid using a plastic spatula. The mixing time did not exceed 1 min and the working time was in the range of 2–3 min. Bar-shaped specimens were made in a half-split Teflon mold between transparent Mylar sheets and a glass slide. Polymerization of resin-modified GICs specimens were made using a hand light-curing unit (Elipar S10, 3M ESPE, St. Paul, MN, USA) for 20 s in five separate overlapping portions from both sides of the Teflon mold. The wavelength of the light was between 430 and 480 nm with a light intensity of 1,600 mW/cm². The specimens from each group (n=7) were stored wet at 37°C for 24 h before testing. The three-point bending test was conducted according to the ISO 4049 (test span: 20 mm, cross-head speed: 1 mm/min, loading pin: 2 mm diameter). All specimens were loaded in a material testing machine (model LRX, Lloyd Instruments, Fareham, England) and the load-deflection curves were recorded with computer software (Nexygen 4.0, Lloyd Instruments).

FS (σ) was calculated from the following formula (ISO 1992):

\[ \sigma = \frac{3F_{\text{m}}I}{2bh^2} \]

Where \( F_{\text{m}} \) is the applied load (N) at the highest point of a load-deflection curve, \( I \) is the span length (20 mm), \( b \) is the width of test specimens and \( h \) is the thickness of test specimens.

Single-edge-notched-beam specimens (2.5×5×25 mm³) according to adapted ISO 20795-2 standard methods were prepared to determine the FT¹⁰. A custom-made Teflon split mold was used, which enabled specimen removal without force. An accurately designed slot was fabricated centrally in the mold extending until its mid-height, which enabled the central location of the notch and optimization of the crack length (x) to be 0.5. The RMGIC material was inserted into the mold placed over a Mylar-strip-covered glass slide in one increment. Before setting and polymerization, a sharp and centrally located crack was produced by inserting a straight edged steel blade into the prefabricated slot. Polymerization of the RMGIC was conducted for 20 s in five separate overlapping portions. The upper side of the mold was covered with a Mylar strip and glass slide from both sides of the blade, before being exposed to the polymerization light. Upon removal from the mold, each specimen was polymerized also on the opposite side. The specimens from each group (n=7) were stored wet at 37°C temperature for 24 h before testing. The specimens were tested in three-point bending mode, in a universal material testing machine at a crosshead speed of 1.0 mm/min.

The FT was calculated using the Equation:

\[ K_{\text{max}} = \frac{P.L}{B.W} \sqrt{a/W} \]

where: \( f(x) = 3/2 \times 1/2 \times (1.99 - x(x - x)(2.15 - 3.93x + 2.7x^2))/2(1+2x)(1-x)3/2 \) and 0<x<1 with x=a/W. Here \( P \) is the maximum load in kilonewtons (kN), \( L \) is the span length (20 cm), \( B \) is the specimen thickness in centimeters (cm), \( W \) is the specimen width (depth) in cm, \( x \) is a geometrical function dependent on \( a/W \) and \( a \) is the crack length in cm.

Work of fracture (the energy required to fracture the specimen) was calculated from the area under the load-displacement curve of single-edge-notched-beam specimens and reported in units of N cm.

Diametral tensile strength (DTS) and compressive strength (CS) were determined on cylindrical specimens (4 mm in diameter and 6 mm in height) that were prepared in the same way according to ISO 4104¹⁴. The manipulation of the RMGIC materials was the same as mentioned earlier. For the DTS, each specimen was placed with its longitudinal side between the platens of the testing machine. The specimens (n=7) were loaded in compression until failure at a crosshead speed of 1 mm/min. The length and diameter of each specimen were measured before testing with a digital caliper, and the DTS was calculated based on specimen length, diameter, and peak load. For the CS, the same testing performances were used, with the specimen (n=7) being placed with the flat end on the supporting plate. The flat ends were fixed between the platens of the testing machine. In this case, a compressive load was applied axially until failure. The CS was determined using the peak load at fracture and the diameter of the specimen.

DTS in megapascals (MPa) was calculated using
Fig. 1 Typical 3D surface profile of the wear pattern where wear depth was measured.

the Equation 1: \( T = \frac{2F}{\pi lD} \), where: \( T \) is the DTS, \( F \) is the maximum applied load in newtons (N); \( D \) is the diameter of the specimens in mm and \( l \) is the length of the specimen in mm. CS was calculated in megapascals using the Equation 2: \( P = \frac{4F\pi D^2}{l} \), where: \( P \) is the CS, \( F \) is the maximum applied load in newtons (N) and \( D \) is the diameter of the specimen in mm\(^{15}\).

Wear test
Two specimens of each experimental and commercial RMGICs were prepared in acrylic resin block for localized wear testing. Longitudinal cavities (20 mm length×10 mm width×3 mm depth) were prepared in and then RMGIC materials were placed in one increment into the prepared cavities and covered with a Mylar strips and glass slides before light irradiated for 40 s in five separate overlapping portions. The surfaces were then polished flat using a sequence of #1200- to #4000-grit silicon carbide papers. Reference material consisting of a hybrid composite resin (G-aenial Anterior, shade A3, GC) was used and handled according to the manufacturers’ instructions.

After one day of water storage (37°C), 2-body wear test was conducted using the chewing simulator CS-4.2 (SD Mechatronik, Feldkirchen-Westerham, Germany) which has two chambers simulating the vertical and horizontal movements simultaneously with water. Each of the chambers consists of an upper sample holder that can fasten the loading tip (antagonistic) with a screw and a lower plastic sample holder in which the RMGIC specimen were embedded. The manufacturer’s standard loading tips (Steatite ball, Ø 6 mm) were embedded in acrylic resins in the upper sample holders, and were then fixed with a fastening screw. A weight of 2 kg, which is comparable to 20 N of chewing force and 15,000 loading cycles with frequency of 1.5 Hz were used.

The wear patterns (n=4) on the surface of each specimen were profiled with 3D optical microscope (Bruker Nano, Berlin, Germany) using Vision64 software. The maximum wear depth values (µm), representing the average of lowest or deepest points of all profile scans were calculated from different points (Fig. 1).

Microscopic analysis
Scanning electron microscopy (SEM, JSM 5500, JEOL, Tokyo, Japan) provided the characterization of the microstructure, and fractographic examination of the experimental fiber reinforced RMGICs single-edge-notched-beam specimens. Wear surface was also examined for both experimental and commercial materials. The specimens (n=3) from each group were gold sputter coated before the SEM examination.

Statistical analysis
The data were statistically analyzed with SPSS version 23 (SPSS, IBM, Armonk, NY, USA) using analysis of variance (ANOVA) at the \( p<0.05 \) significance level followed by a Tukey HSD post hoc test to determine the differences between the groups.

RESULTS
The mean values of FS, FT, DTS, and CS for tested materials with standard deviations (SD) are summarized at Table 1. In general, the discontinuous microfiber reinforcement significantly improved most of the tested mechanical properties of RMGICs (\( p<0.05 \)). The data showed that by increasing the fiber weight ratios, the mechanical properties increased (\( p<0.05 \)). CS was the
Table 1  Mechanical properties mean values (±SD) of investigated RMGIC materials (commercial and experimental)

| Material   | FS (MPa)  | FT (MPa•m\(^{1/2}\)) | DTS (MPa) | CS (MPa)  |
|------------|-----------|-----------------------|-----------|-----------|
| Fuji II LC | 51.9±9    | 0.8±0.1               | 20.7±3    | 190.7±12  |
| Exp-15%    | 62.2\(^{ab}\)±10 | 1.4\(^b\)±0.2       | 25.2\(^{b}\)±3 | 173.1\(^{a}\)±9 |
| Exp-20%    | 78.1\(^{bc}\)±12 | 1.7\(^c\)±0.1       | 29.7\(^{c}\)±4 | 172.5\(^{a}\)±18 |
| Exp-25%    | 79.0\(^{bc}\)±6   | 1.9\(^d\)±0.1       | 31.0\(^{bc}\)±3 | 170.7\(^{a}\)±21 |
| Exp-30%    | 90.3\(^c\)±12     | 1.9\(^d\)±0.1       | 32.0\(^c\)±2   | 166.0\(^a\)±5   |

RMGIC: resin modified glass-ionomer cement; Exp: experimental glass fiber reinforced RMGIC; FS: flexural strength; DTS: diametral tensile strength; CS: compressive strength; FT: fracture toughness. Same superscript letter above the values indicates groups that were not statistically different (p>0.05).

Table 2  Mechanical properties mean values (±SD) of investigated Exp-RMGIC 20 wt% material with different fiber surface treatments

| Material   | Surface treatment | FS (MPa)  | FT (MPa•m\(^{1/2}\)) | DTS (MPa) | CS (MPa)  |
|------------|-------------------|-----------|-----------------------|-----------|-----------|
| Exp-20 wt% | MPS silane        | 78.1±12   | 1.7±0.1               | 29.7±4    | 172.5±18  |
| Exp-20 wt% | No silane         | 76.1±7    | 1.5±0.1               | 29.1±3    | 168.2±20  |

RMGIC: resin modified glass-ionomer cement; Exp: experimental glass fiber reinforced RMGIC; FS: flexural strength; DTS: diametral tensile strength; CS: compressive strength; FT: fracture toughness; MPS: 3-(Trimethoxysilyl) propyl methacrylate. Same superscript letter above the values indicates groups that were not statistically different (p>0.05).

Fig. 2  Graph illustrating typical load-strain curves of investigated RMGIC materials (commercial and experimental).

Fig. 3  Bar graph illustrating work of fracture energy (N cm) from preload to maximum load and extension of investigated RMGIC materials (commercial and experimental).

only property which did not show any improvement and unmodified commercial RMGIC had higher CS (190.7 MPa) than all other experimental RMGIC materials (p>0.05). Tukey HSD post hoc revealed that Exp-RMGIC 30 and 25 wt% had statistically significantly higher values of FT (1.9 MPa•m\(^{1/2}\)) than all other tested RMGIC materials.

No statistical (p>0.05) significant difference in tested mechanical properties was recorded between silanized (MPS) and non-silanized Exp-RMGIC 20 wt% groups (Table 2).

The total energy release (work of fracture) of experimental and unmodified commercial RMGICs was calculated from the area under the load-displacement curves, shown in Fig. 2. The contribution of microfiber plays a major role in increasing the work of fracture energy of Exp-RMGIC in comparison to unmodified commercial RMGIC. Figure 3 illustrates a pronounced increase in the energy of fracture as the percentage of discontinuous glass microfiber was increased; exhibiting stable crack propagation, while specimens without fiber reinforcement (Fuji II LC) failed in a catastrophic
Fig. 4 SEM photomicrographs of fracture surface of the experimental RMGIC single-edge-notched-beam specimen (×35 magnification; scale bar=500 µm) showing pull-out of fibers (A). Random orientation of microfibers (×1,000 magnification; scale bar=10 µm) in the matrix of the RMGIC (B).

Fig. 5 SEM photomicrographs of non-fracture surface of the experimental RMGIC (scale bar=10 µm) showing good adhesion and wettability of microfibers with the matrix.

manner (Fig. 2). SEM analysis of the tested single-edge-notched-beam specimens showed random orientation and protruded (pullout) fiber ends at fracture surfaces of discontinuous fiber reinforced RMGIC matrices (Fig. 4). In addition, it presented the good wettability of microfibers with the RMGIC matrix (Fig. 5).

Figure 6 displays the mean values for wear depth recorded for each group after 15,000 chewing simulation cycles. Reference material (hybrid composite resin) presented the lowest wear value (26 µm) which was significantly different (p>0.05) from experimental and unmodified commercial RMGICs. No differences found in wear depth between tested RMGIC materials. Representative SEM images of the wear facets for commercial and experimental RMGICs are shown in Fig. 7. Exp-RMGIC specimen showed that discontinues fibers were fractured into small pieces and polished down together with RMGIC matrix (Fig. 7B).

Fig. 6 Bar graph illustrating wear depth (µm) of investigated RMGIC materials (commercial and experimental) and hybrid composite resin (reference) after 15,000 cycles of 2-body wear test. Horizontal lines above the columns indicate groups that do not differ statistically from each other.
DISCUSSION

GICs till now are not considered as material of choice in the restoration of permanent posterior teeth especially in high stress bearing areas. Although the RMGICs achieved superior physical properties compared to conventional GICs, the reputation of GICs did not change and continued to be considered as a semi-permanent restoration material for Class I and Class II lesions in permanent teeth. Reports on the properties of currently used RMGIC are thoroughly documented by several authors. In general, the FT of all commercial RMGIC is well below 1 MPa·m$^{1/2}$, FS below 60 MPa and DTS below 23 MPa. This study confirms that the mean mechanical values reported for the commercial RMGIC without reinforcement are within the range of data previously reported.

Few previous attempts sought to improve the mechanical properties of RMGICs through substitution of reinforcing fillers to the RMGIC powder, or by modification of the RMGIC liquid. Nevertheless, major improvements through a reinforcement strategy have yet to enable clinical usage of RMGIC for the restoration of permanent posterior dentition safely. The key target of this investigation was to improve the mechanical properties of RMGIC, which is already used in dental clinics as a restorative dental material. The reinforcing was made by adding discontinuous glass microfiber as fillers in 200–500 µm length, to RMGIC powder (with different wt%) which were mixed thoroughly with RMGIC powder utilizing a high speed centrifuging mixing device, in order to achieve a homogenous mixture. Maximum fiber fraction was defined based on handling and mixing characteristics. With more than 30 wt% of discontinuous glass microfiber, the material became more fibrous and was not easy to manipulate according to the manufacturers’ instructions.

The results of this study revealed substantial improvements in FT, FS and DTS of RMGIC reinforced with micrometer short E-glass fibers filler in comparison with commercial unmodified RMGIC material. The results support the hypothesis that microfibers can still have a significant effect on mechanical properties together with the easy to mix and use properties of RMGIC material. The major goal to improve mechanical properties has been reached successfully, as the absorbed energy during the fracture process of fiber reinforced RMGICs could be dramatically improved compared with unmodified RMGIC (Figs. 2 and 3).

In the present investigation, the experimental fiber reinforced RMGIC (30 wt%) exhibited the significantly superior FT (1.9 MPa·m$^{1/2}$), FS (90.3 MPa) and DTS (32 MPa) in comparison to unmodified commercial material (Table 1). The reinforced RMGIC demonstrated enhanced resistance capability to crack propagation,
that is FT and FS, which could be explained by the fiber and matrix related properties of the material. Fibers in this RMGIC material are equal to the critical fiber length and thus, could efficiently accept the stress transferred from the matrix. This is in accordance with previous study, which showed superior mechanical properties of millimetre-scale short fiber reinforced RMGIC to conventional particulate RMGIC material\textsuperscript{12,13}.

Aspect ratio, critical fiber length, fiber loading and fiber orientation are the main factors that could improve or impair the mechanical properties of fiber reinforced RMGIC\textsuperscript{20}. Aspect ratio is the fiber length to fiber diameter ratio (l/d). It affects the tensile strength and the reinforcing efficiency of the fiber reinforced material\textsuperscript{13}. Microfibers used in this study have aspect ratio of more than 30. In order for a fiber to act as an effective reinforcement for polymers, stress transfer from the polymer matrix to the fibers is essential\textsuperscript{12,13}. This is achieved by having a fiber length equal to or greater than the critical fiber length and the given fiber aspect ratio in range of 30–94\textsuperscript{13}. It has been also concluded that for advanced fiber reinforced materials, the critical fiber length could be as much as 50 times the diameter of the fiber. The diameter of glass fibers used in this study is 7 µm and the critical fiber length should be, therefore, around 350 µm. Deteriorated or initially poor adhesion between the fibers and polymer matrix increase the critical fiber length\textsuperscript{20}. Sufficient adhesion between fiber and matrix provides good load transfer between the two ingredients, which ensures that the load is transferred to the stronger fiber and this is how the fiber actually works as reinforcement. However, if the adhesion is not strong and if any voids appear between the fiber and the RMGIC matrix, these voids may act as initial fracture sites in the matrix and facilitate the breakdown of the material. That is why adhesion between the fibers and the RMGIC matrix is significant for the mechanical performance and the longevity of restorations\textsuperscript{12}. In this experimental RMGIC, microfibers were well wetted with the matrix (Fig. 5) and this most likely explained the good reinforcing effect with no difference between silanized and non-silanized groups (Table 2). To the authors’ knowledge, comparative data between different surface treatments of glass fiber reinforcing system with RMGIC is not documented in literature. In this study, fibers were received either silanised or non-silanised from the manufacturer, the used silane is 3-(Trimethoxysililyl) propyl methacrylate (MPS), which is compatible with acrylate resins. When fiber surface silane is esterified with polyacrylic acid, a polymer with functional double bonds is established\textsuperscript{12,21,22}. Lassas et al.\textsuperscript{22} showed the formation of ion-bond polyacrylates on the silanised glass fiber surface and the amount of ions exchanged increases with increased acid concentration. On the other hand, silanol groups can react with the OH-groups and they form a siloxane bond and with metal ions can form a metal-siloxane bond but they are weak and have poor hydrolytic stability\textsuperscript{21}. Previous studies stated that the presence of aluminum and calcium ions on glass fiber surface makes it possible to obtain a reactive layer at the interface between the glass fiber surface and polyacrylic acid\textsuperscript{22,23}. Lohbauer et al.\textsuperscript{23} showed a distinct reactive layer (2–20 µm in thickness) at the interface between the GIC matrix and glass fiber formed during the setting process\textsuperscript{23}. However, the ion leaching and reactivity of the glass fiber surface might be affected by the fiber processing and silanization\textsuperscript{23}. Wilson stated in his work that the interface between the silica gel layer around the glass core tends to be weak and also that the failure’s origin was located at the interface\textsuperscript{26}. From this point of view, the great increase in both fracture load and energy of discontinuous glass microfiber reinforced RMGICs, could be explained by the chemical adhesion (differs from the siloxane bonds) between the fibers and RMGIC matrix. This seems to have enhanced the ability of the material to resist the fracture crack propagation by increasing the behavior of individual fiber as a crack stopper.

The FT of a material is a measure of how well that material hinders the progress of a crack or flaw under load. Fiber impedes the extension of a crack and develops interlocking bridges behind the progressing crack dissipating energy by fiber pullout resulting in graceful rather than catastrophic failure (Fig. 2). This might be due to the random orientation of microfibers in RMGIC matrix and forming fiber network (Fig. 4), which seemed to have enhanced the ability of the material to resist the fracture propagation, as well as to reduce the stress intensity at the crack tip from which a crack propagates in an unstable manner. As a consequence, an increase work of fracture energy and FT can be expected. Interestingly, addition of microfibers into RMGIC and forming fiber network did not effect on the handling characteristic of the material.

RMGIC is a brittle material and has a tensile strength that is markedly lower than its CS. This material fails by crack propagation that is favored by tensile rather than compressive loading. FS and FT test the material under both compressive and tensile loading\textsuperscript{20}. Dowling et al.\textsuperscript{20} demonstrated the validity of the three-point bending test for measuring GIC strengths in comparison with compression testing which they claimed it was not valid for predicting the performance of GICs. Wilson and Nicholson\textsuperscript{27} stated that FS and FT are clinically very important in evaluating the physical properties of GICs. Recent systemic review by Heintz et al.\textsuperscript{18} showed that FT being mostly correlated with clinical fracture of restorative materials and no correlations were observed between clinical outcomes and flexural modulus or CS of these materials. In general, the effect of discontinuous fiber reinforcement on the FT, flexural property, and diametral tensile tests were observable and more obvious than in the compression test. This is in agreement with literature finding where the effect of short fibers on CS of composites was not noticeable\textsuperscript{12,20,28}. This could be explained partially by the buckling instability of individual short fibers which were oriented most likely in the same load direction. It has been shown early on that fiber orientation is an important factor.
influencing the mechanical properties of fiber reinforced composite\textsuperscript{30}. In addition, the specimen's geometry and test set-up used might be another explanation\textsuperscript{13}.

The wear of RMGIC is a complex process involving fatigue, as well as erosive, adhesive, and abrasive components\textsuperscript{30}. The two-body wear test has been developed to simulate \textit{in vivo} wear and many authors have used, though a high variation in the results have been seen even with the same material and testing technique\textsuperscript{31}. The wear depth of all tested materials was in the same range. Thus, discontinuous glass microfiber loading up to 30 wt% were not improving neither worsening the wear of the RMGIC. Suzuki\textsuperscript{32} evaluated the wear resistance of commercial short fiber reinforced composite resin (Alert) in comparison to different composite resin materials after 400,000 cycles with load of 75 N using enamel as antagonist. Interestingly, the wear values of short fiber composite and enamel in his study was comparable to other tested resin materials and none of the tested materials exhibited a very coarse, worn surface after the test. Therefore, he concluded that short fiber composite fulfill the ADA criterion for wear. In another study, Wang \textit{et al.}\textsuperscript{33} evaluated the wear resistance and surface roughness of short fiber composite (Alert) after simulated tooth brushing test (100,000 cycles). They also concluded that short fiber composite has similar wear resistance and surface roughness than tested packable composite resins. In line with this, Dijken and Grönberg\textsuperscript{34} showed satisfactory clinical performance (up to 6 years) of commercial short fiber reinforced composite (Alert) in Class II cavities. They did not report high incidence of wear or loss of proximal contact with short fiber composite neither antagonist although short fiber composite has been directly exposed to oral environment without any coverage.

According to scientific studies, there is no significant correlation between the restoration hardness and the degree of wear. On the other hand, the degree of wear is more affected by the surface structure and the roughness of the restorations\textsuperscript{30,33}. The quantity of in-mixed porosities and the shapes of the filler particles, regular and round \textit{vs.} irregular and sharp, contribute to the polishability of these materials\textsuperscript{30}. The surfaces inside the wear facets of the fiber reinforced RMGICs were relatively smooth, similar to that of commercial RMGIC (Fig. 7). The protrusion of microfibers was not observed and instead of the fibers being pulled out to produce a pitted surface, the fibers were microfractured into small pieces and were polished down together with RMGIC matrix (Fig. 7). Several studies have reported poor abrasion and wear resistance with restorative RMGIC\textsuperscript{30,36}. The complexity of the two matrices, \textit{i.e.} ionic cross-linked polyalkenoate network caught with polymer chains, may not be sufficiently coherent.

In this investigation the effect of water storage on the materials was not studied. It has been previously reported that exposure of RMGIC to water can result in a decrease in mechanical properties\textsuperscript{37,38}. Since water absorption and the content of HEMA cause plasticity in the material matrix\textsuperscript{38}. Also, it has been stated that there is a potential deteriorative effect of water to the interfacial adhesion between the polymer matrix to the E-glass fibers through rehydrolysis of silane coupling agent\textsuperscript{13,39}. On the other hand, acid base reaction has been extensively documented and it reinforces and increases the rigidity of the polymeric network, but does not necessarily improve the mechanical strength\textsuperscript{6,36}.

There are still unclear issues that need to be known regarding discontinuous glass microfiber reinforced RMGIC, like the fluoride release, the type of interface between the fiber and RMGIC matrix and the bond strength to tooth structures. Therefore, further research is needed and an assessment of optimizing the formulation of this novel discontinuous glass reinforced RMGICs is now in progress.

**CONCLUSION**

Based on the results of the present study, one could conclude that the incorporation of discontinuous glass microfiber with RMGIC matrix resulted in a superior toughening and flexural performance compared to particulate RMGIC used.

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**CONFLICTS OF INTERESTS**

Author PV consults for Stick Tech —Member of GC Group in R&D and training.

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