

ORIGINAL ARTICLE

Evaluation of some properties of two fiber-reinforced composite materials

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Abstract

Objective. Water sorption, flexural properties, bonding properties, and elemental composition of photopolymerizable resin-impregnated fiber-reinforced composite (FRC) materials (everStick C&B and BR-100) (FPD) were evaluated in this study. **Material and methods.** Bar-shaped specimens (2 × 2 × 25 mm) were prepared for water sorption and flexural strength testing. The specimens ($n = 6$) were polymerized either with a hand light-curing unit for 40 s or, additionally, in a light-curing oven for 20 min and stored in water for 30 days. Water sorption was measured during this time, followed by measurements of flexural strength and modulus. A shear bond strength test was performed to determine the bonding characteristics of polymerized FRC to composite resin luting cement (Panavia-F), ($n = 15$). The cement was bonded to the FRC substrate and the specimens were thermocycled 5000 times (5–55°C) in water. SEM/EDS were analyzed to evaluate the elemental composition of the glass fibers and the fiber distribution in cross section. **Results.** ANOVA showed significant differences in water sorption according to brand ($p < 0.05$). Water sorption of everStick C&B was 1.86 wt% (hand-unit polymerized) and 1.94 wt% (oven polymerized), whereas BR-100 was 1.07 wt% and 1.17 wt%, respectively. The flexural strength of everStick C&B after 30 days' water storage was 559 MPa (hand-unit polymerized) and 796 MPa (oven-polymerized); for BR-100, the values were 547 MPa and 689 MPa, respectively. Mean shear bond strength of composite resin cement to the FRC varied between 20.1 and 23.7 MPa, showing no statistical difference between the materials. SEM/EDS analysis revealed that fibers of both FRC materials consist of the same oxides (SiO₂, CaO, and Al₂O₃) in ratios. The distribution of fibers in the cross section of specimens was more evenly distributed in everStick C&B than in BR-100. **Conclusion.** The results of this study suggest that there are some differences in the tested properties of the FRC materials.

Key Words: Fiber-reinforced composite, FRC, flexural strength, shear bond strength, water sorption

Introduction

In recent decades, fiber-reinforced composites (FRC) have been introduced into dentistry to improve the mechanical properties of denture bases or composite resin restorative materials. Previous research has shown that, among different types of fiber, E-glass and S-glass have been the most suitable owing to their translucent color and the possibility to obtain good adhesion with the resin matrix by means of silane coupling agents [1]. Development of the resin preimpregnated FRC systems has led to the increased application of FRCs in the fabrication of laboratory made single crowns and partial or full coverage fixed

partial dentures [2], as well as chair-side periodontal splinting [3], adhesive fixed partial dentures [4], post-core systems [5], and in orthodontic applications [6].

Resin-preimpregnated FRC has been shown to possess adequate flexural modulus and flexural strength to function successfully in the oral cavity [7–9]. The performance of the FRC system depends on the polymer matrix as well as fiber type, volume fraction, and the quality of the fiber-polymer matrix interface [8–11]. In addition to mechanical performance, the composition of the polymer matrix and fibers also has a major role in the bonding ability of FRCs to the luting resin cements and to the veneering composite resin. Therefore, various fiber and polymer

Table I. Materials used in this study

Brand	Manufacturer	Lot no.	Chemical composition
BR-100	Kuraray Medical Inc., Tokyo, Japan	030528	Glass-fibers impregnated with UTMA-based resin with ultra fine silica filler
Experimental everStick C&B	Stick Tech Ltd, Turku, Finland	2021008-EL-002	Dimethacrylate resin impregnated glass-fibers
Panavia F	Kuraray Medical Inc., Tokyo, Japan	Paste A: 00002A Paste B: 00001A	Silica, MDP, hydrophobic and hydrophilic dimethacrylates, BPO Fillers, silica, hydrophobic and hydrophilic dimethacrylate, NDT
Clearfil SE Bond	Kuraray Medical Inc., Tokyo, Japan	A: 309 B: 390 C: 00133B D: 299	A: HEMA, hydrophilic dimethacrylate, MDP, water B: Silica, BisGMA, HEMA, hydrophobic dimethacrylate, MDP, NDT C: Hydrophobic dimethacrylate, MPTS, Bis-PMA D: Phosphoric acid

UTMA=Urethane tetramethacrylate, MDP=10-Methacryloyloxydecyl dihydrogen phosphate, BPO=Benzoil peroxide, NDT=N,N'-Diethanol-p-toluidine, HEMA=2-hydroxyethyl methacrylate, bisGMA=Bisphenol A-glycidyl dimethacrylate, Bis-PMA=Bis-Phenol-A-polyethoxy dimethacrylate, MPTS=3-methacryloxypropyl trimethoxy silane, A=Clearfil SE Bond primer, B=Clearfil SE Bond bond, C=Clearfil Porcelain Bond activator, D=K-etchant, etching agent gel.

matrix compositions have been developed [12]. Preimpregnation is based on the use of either photopolymerizable dimethacrylate monomer resin only or on a combination of dimethacrylate monomer resin and linear polymer, which forms a semi-interpenetrating polymer network (semi-IPN) after being polymerized [12–13].

The former system based on photopolymerizable dimethacrylate monomer, usually consists of Bisphenol-A-diglycidyl dimethacrylate (bisGMA)-triethyleneglycol dimethacrylate (TEGDMA) resin combinations as matrix for FRC, e.g. the Vectris[®] system (Ivoclar-Vivident) [7], FibreKor[®] system (Jeneric/Pentron) [14]. The latter system is based on the impregnation of E-glass fibers with photopolymerizable semi-IPN resin of polymethylmethacrylate (PMMA)-bisGMA resin combination [9,12,13].

Previous studies have shown that water is absorbed into the methacrylate resin systems by diffusion. Absorbed water can act as a plasticizer and, furthermore, causes a well-documented reduction in the strength of the material [7,15,16]. Obviously, from the clinical point of view, the chemical composition of resin matrix is of major importance for the water sorption behavior of FRC, which affects the long-term mechanical stability of the restorations, as well as the bonding properties in the oral cavity. Today's clinician enjoys a wider selection of materials; so independent studies of basic comparative data are necessary to characterize the materials in relation to mechanical and physical properties.

The most recent product, BR-100 (Kuraray), introduced onto the market is based on urethane tetramethacrylate (UTMA) monomers in the resin matrix of FRC. However, only little information is available in the literature about the properties of this product. The aim of the present study was therefore to investigate water sorption, flexural properties, and

bonding properties of the highly cross-linked FRC system of BR-100 in two different polymerization conditions, and to compare them to those of a semi-IPN FRC system. Additionally, the elemental composition of fibers was determined and compared.

Material and methods

The materials used in this study are listed in Table I. The everStick C&B FRC contained resin-impregnated continuous unidirectional FRC (experimental version containing 9,000 single E-glass fibers). The resin matrix of everStick C&B consisted of bisGMA and PMMA, which formed the semi-IPN structure. The second FRC material, BR-100, also contained continuous unidirectional fiber reinforcement (20,000 single E-glass fibers) preimpregnated with UTMA-based resin matrix.

Specimen preparation for water sorption and flexural tests

Fiber-reinforced composites were placed in the mold with fiber orientation along the long axis of the test specimen (2 × 2 × 25 mm). The FRCs were covered by Mylar film from both sides and compressed by glass plates. Polymerization of the specimens at two points from both sides of the mold was initially done using a hand light-curing unit (Optilux-501; Kerr, Ct., USA) for 40 s (hand-unit polymerized). Wavelength range of the unit was 400–500 nm and measured light intensity 720 mW/cm², according to the light-curing unit's internal radiometer. After hand light-curing polymerization, half of the specimens were further polymerized in a light-curing oven (Licu Lite; Dentsply DeTrey, Dreieich, Germany) for an additional 20 min (oven polymerized). Six specimens (n = 6) were fabricated for each group (Table II). After polymerization, the edges of each specimen were finished with a silicon carbide grinding paper (FEPA grit no. 1200). The

Table II. Test groups used in this study

Test	Material	Polymerization condition	Storing conditions
Water sorption and flexural strength test (n = 6/group)	everStick C&B	Hand-unit polymerization	30 days water
	everStick C&B	Oven polymerization	30 days water
	BR-100	Hand-unit polymerization	30 days water
	BR-100	Oven polymerization	30 days water
Shear bond test (n = 15/group)	everStick C&B	Hand-unit polymerization	Thermocycled
	everStick C&B	Oven polymerization	Thermocycled
	BR-100	Hand-unit polymerization	Thermocycled
	BR-100	Oven polymerization	Thermocycled

specimens were conditioned in a desiccator at room temperature for 2 days before being immersed in a water bath for 30 days (37°C).

Water sorption test

Bar-shaped specimens were stored in 120 ml water (Grade III) for 30 days at 37°C. The dry weight (W_d) of the specimens was measured with a balance (Mettler A30; Mettler Instrument Co., Highstone, N.J., USA) to an accuracy of 0.1 mg. During storage in water, the specimens were weighed at 1, 3, 7, 14, 21, and 30 days, and the weight of specimens that had absorbed water (W_w) was measured following the procedure specified in ISO 10477 standard [17]:

$$\text{Water sorption} = (W_{wx} - W_d) / W_d,$$

where x is days of water immersion.

Mechanical testing

The same specimens as used in the water sorption test were used to measure the ultimate flexural strength and flexural modulus of the FRCs according to the ISO 10477:92 standard [17] (span 20 mm, crosshead speed 1.0 mm/min). The three-point bending test was used with a universal testing machine (Lloyd LRX; Lloyd Instruments Ltd., Fareham, UK) and the load-deflection curves were recorded with computer software (Nexygen; Lloyd Instruments).

Ultimate flexural strength (σ) and flexural modulus (E_f) were calculated from the formulae below:

$$\sigma = \frac{3F_{\max} l}{2bh^2} \quad E_f = \frac{Sl^3}{4bh^3}$$

where F_{\max} is the applied load (N) at the highest point of the load-deflection curve, l is the span length (20 mm), b (2 mm) is the width of the test specimen, and h (2 mm) is the thickness of the test specimens. S is the stiffness (N/m) $S = F/d$ and d is the deflection corresponding to load F at a point in the straight line portion of the trace.

Shear bond test

For shear bond test specimens, the FRC material (everStick C&B and BR-100) was used as a bonding

substrate for composite resin luting cement (Panavia F). FRC was placed within a cavity that was prepared in an acrylic resin block. The fiber direction of the substrate was along the bonding surface and longitudinally to the load. There were 15 specimens in each shear bond strength measurement group (Table II). Polymerization of the substrates of the shear bond strength measurement groups was identical to that used in the water sorption and flexural strength test specimens. Before the adhesive procedure, the substrates were stored at room temperature for 1 week.

The surface of the FRC substrates was wet-ground flat with 1200-grit (FEPA) silicon carbide grinding paper. The dry substrates were then etched with K-Etchant etching agent gel for 10 s and water-sprayed for 10 s. Clearfil SE Bond primer and Porcelain Bond activator were mixed, applied to surface, and gently air-blown. After that, the Clearfil SE Bond adhesive resin was applied to the surface and left there to diffuse into the substrate for 5 min in a dark container to prevent polymerization of the adhesive resin. SE Bond adhesive resin was light-cured for 20 s (Optilux). Panavia F A & B pastes were mixed and applied to the substrate at a height of 3 mm using a translucent polyethylene tube with a diameter of 3.6 mm. The cement was polymerized with the hand light-curing unit (Optilux) for 40 s.

The specimens were stored at room temperature for 24 h and then thermocycled for 5000 cycles between 5°C (± 2) and 55°C (± 2), with a dwell time of 30 s and a transfer time of 5 s. Twenty-four hours after thermocycling, a shear bond strength test was performed using a universal testing machine (Lloyd LRX). The specimens were secured in a mounting jig (Bencor Multi-T Shear Assembly; Danville Engineering Inc., San Ramon, Calif., USA) and loaded at a crosshead speed of 1.0 mm/min with a shear-tip of circular shape [18].

SEM/EDS analysis

The FRC materials were examined with a scanning electron microscope (SEM) (JSM-5500; Jeol Ltd., Tokyo, Japan) to determine surface morphology, impregnation of the fiber by the resin, diameter of the

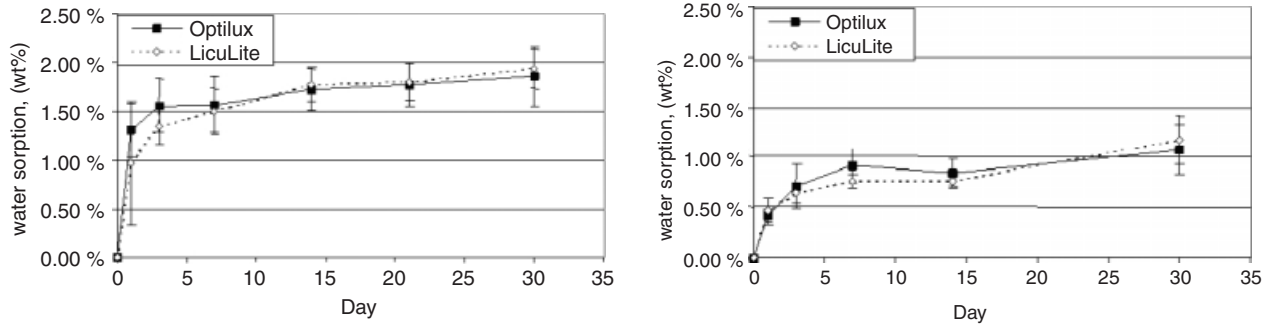


Figure 1. (a) Water sorption (wt%) of everStick C&B during 30 days' water immersion. (b) Water sorption (wt%) of BR-100 during 30 days' water immersion. (Optilux=hand-unit polymerized, Licu Lite=oven polymerized).

single fibers, area percentage of the fibers, and the cross-sectional fiber distribution of the FRC test specimen. Evaluation was made at the cross section of specimens which were wet-ground with 4000-grit (FEPA) and carbon sputtered (SCD 050; Bal-Tec, Balzers, Liechtenstein). Additionally, the surface was analyzed using the EDS (energy dispersive X-ray spectroscopy) system (Spirit; Princeton-Gamma Tech, Princeton, N.J., USA) to measure the elemental composition of the inorganic phase (glass fibers and possible particulate fillers in the polymer matrix) of the FRCs.

Statistical methods

Data were analyzed statistically with analysis of variance (ANOVA) with SPSS software (SPSS Inc., Chicago, Ill., USA) using as independent factors of polymerization method and the brand of the material. To determine the statistically significant results, the Tukey post hoc test was used. Weibull analysis was carried out from shear bond results using Weibull++6.0 software (ReliaSoft Corporation, Tucson, Ariz., USA).

The basic form of the Weibull distribution is shown as:

$$P_f = 1 - \exp \left[- \left(\frac{\sigma - \sigma_u}{\sigma_o} \right)^m \right]$$

where m is Weibull modulus (also known as a shape factor), a constant, which determines the slope of the distribution function and characterizes the spread of the failure data with respect to axis. σ_o is characteristic strength (i.e. the stress level at which 63% of the specimens have failed) and σ_u is theoretical failure stress ($=0$). Correlation coefficient r was calculated with linear regression from logarithmic transformations and r -values above 0.95 were considered statistically acceptable [19,20].

Results

Water sorption

Water saturation of everStick C&B was more rapid compared to BR-100 FRC (Figure 1a, b). ANOVA

revealed that the type of FRC material had a significant effect on water sorption ($p < 0.01$), whereas the polymerization method did not show any significant effect on water sorption values ($p > 0.05$). Water sorption of everStick C&B was higher in both the hand-unit polymerized and oven polymerized groups compared with BR-100 (Table III).

Flexural properties

Mean flexural strength and flexural modulus for each group are given in Table IV. Two-way ANOVA revealed that the polymerization method had a statistically significant effect ($p < 0.001$) on the flexural strength values, whereas the brand of the materials showed no significant effect ($p = 0.221$). However, in general, the mean flexural strengths of everStick C&B in both polymerization conditions tended to be higher compared to BR-100 (Table IV).

The mean flexural modulus of everStick C&B was 26.1 GPa (hand-unit polymerized) and 26.7 GPa (oven polymerized) (Table IV). For BR-100 FRC, the modulus was 24.2 GPa and 25.5 GPa, respectively. The flexural modulus did not show a significant difference between the materials ($p = 0.494$) (Table IV).

Shear bond strength

Comparison of groups (the brand of FRC and polymerization method) did not reveal any difference in the shear bond strength values, with the characteristic shear bond strength varying between 20.1 and 23.7 MPa (Table V). The correlation between the Weibull model and the experimental data was between 0.964 and 0.996, and it was at a statistically acceptable

Table III. Water sorption (wt%) of the test materials after 30 days water storage at 37°C

Materials	Polymerization conditions	Water sorption % (SD)
everStick C&B	Hand-unit polymerization	1.86 (0.30)
everStick C&B	Oven polymerization	1.94 (0.19)
BR-100	Hand-unit polymerization	1.07 (0.25)
BR-100	Oven polymerization	1.17 (0.25)

Table IV. Flexural strength and flexural modulus of FRC materials polymerized with hand light-curing unit or with hand light-curing unit and in light-curing oven after 30 days water immersion

Material	Polymerization condition	Strength MPa (SD)	Modulus (SD)
everStick C&B	Hand-unit polymerization	559 ^a (81)	26.1 ^c (5.1)
everStick C&B	Oven polymerization	796 ^b (105)	26.7 ^c (3.5)
BR-100	Hand-unit polymerization	547 ^a (72)	24.2 ^c (1.1)
BR-100	Oven polymerization	689 ^b (19)	25.5 ^c (1.0)

Superscript letters indicate that values marked with the same letter do not differ significantly ($p < 0.05$), determined by the ANOVA post hoc Tukey test.

level [20,21] (Table V). Weibull graphs of the distribution of shear bond strength values are given in Figure 2(a, b).

SEM/EDS analysis, quantity of fibers, and area percentage of fibers

SEM micrographs showed that both FRC materials have good impregnation with the resin; no voids in the polymer matrix could be found (Figure 3a, b). However, BR-100 revealed a fiber-rich and polymer matrix-rich area, whereas everStick showed a more even fiber distribution. Single glass fiber diameter of everStick C&B FRC was 20.2 μm (SD 1.9), and in BR-100 FRC it was 9.8 μm (SD 1.1).

Elemental SEM/EDS analysis of the inorganic phase of FRCs showed similar main compounds: SiO_2 , CaO , and Al_2O_3 (Table VI). SEM/EDS analysis from the region of the polymer matrix of everStick C&B revealed only signs of carbon and oxygen, whereas BR-100 FRC showed signals of SiO_2 from polymer matrix, although no inorganic fillers were detected by SEM.

The combustion analysis showed that the weight fraction of the inorganic phase (consisting only of fibers) in everStick C&B was 66.0 wt%, while for BR-100 the weight fraction of the inorganic phase (consisting of both inorganic fillers or/and fibers) was 65.5 wt%. Evaluation of the surface area percentage of glass fibers in the FRC test specimens, based on image analysis from SEM micrographs, identified that the fiber area fraction of BR-100 was 46.3%, while everStick C&B was 59.2%.

Discussion

This study was designed to compare basic physical and mechanical properties of two preimpregnated FRC materials.

Water sorption

Water sorption is an important property determining the long-term strength and stability of the restoration. Previous studies have shown that the number of fibers in the composite matrix influences the water sorption [15,21]. In optimally impregnated systems, increased inorganic fiber and filler volume fraction decreases water sorption. It should be noted that in this study a method of measuring water uptake (or weight gain) was used instead of the precisely determined water sorption. As the flexural strength of the test specimens after the water storage period was also of major interest, the test specimens were not dehydrated during measurement of water sorption at each time-point. In the highly cross-linked matrix systems, the solubility of the material into water is quite low ($< 0.1\%$), which was expected to be the case in the present study, so the water sorption and water uptake values can be considered practically equal. Water saturation by diffusion into the bar-shaped test specimen occurred during the first week in both materials. A somewhat higher velocity was observed for everStick C&B compared with BR-100. However, complete water saturation requires at least 1 month for a bar-shaped specimen of this size. The diffusion rate of the water sorption is related to the shape of the specimen. The ISO 10477 standard [17] uses a thin round disk-shaped specimen for testing water sorption ($\varnothing 20$ mm, 1.0 mm thick), which leads to faster water saturation than the bar-shaped specimens. However, when water sorption of unidirectional FRC is determined, the round-shaped specimens are hard to use because of difficulties in the fabrication process.

This study showed significant differences between the tested materials, possibly due to differences in the matrix compositions of the materials. EverStick C&B is based to a large extent on bisGMA monomer, which

Table V. Results of the Weibull analysis for the shear bond strength

Material	Polymerization condition	Characteristic strength = S_0	Weibull Modulus = m	Correlation r-coefficient
everStick C&B	Hand-unit polymerization	21.870	2.272	0.970
everStick C&B	Oven polymerization	20.117	3.043	0.982
BR-100	Hand-unit polymerization	23.057	2.657	0.964
BR-100	Oven polymerization	23.699	2.163	0.994

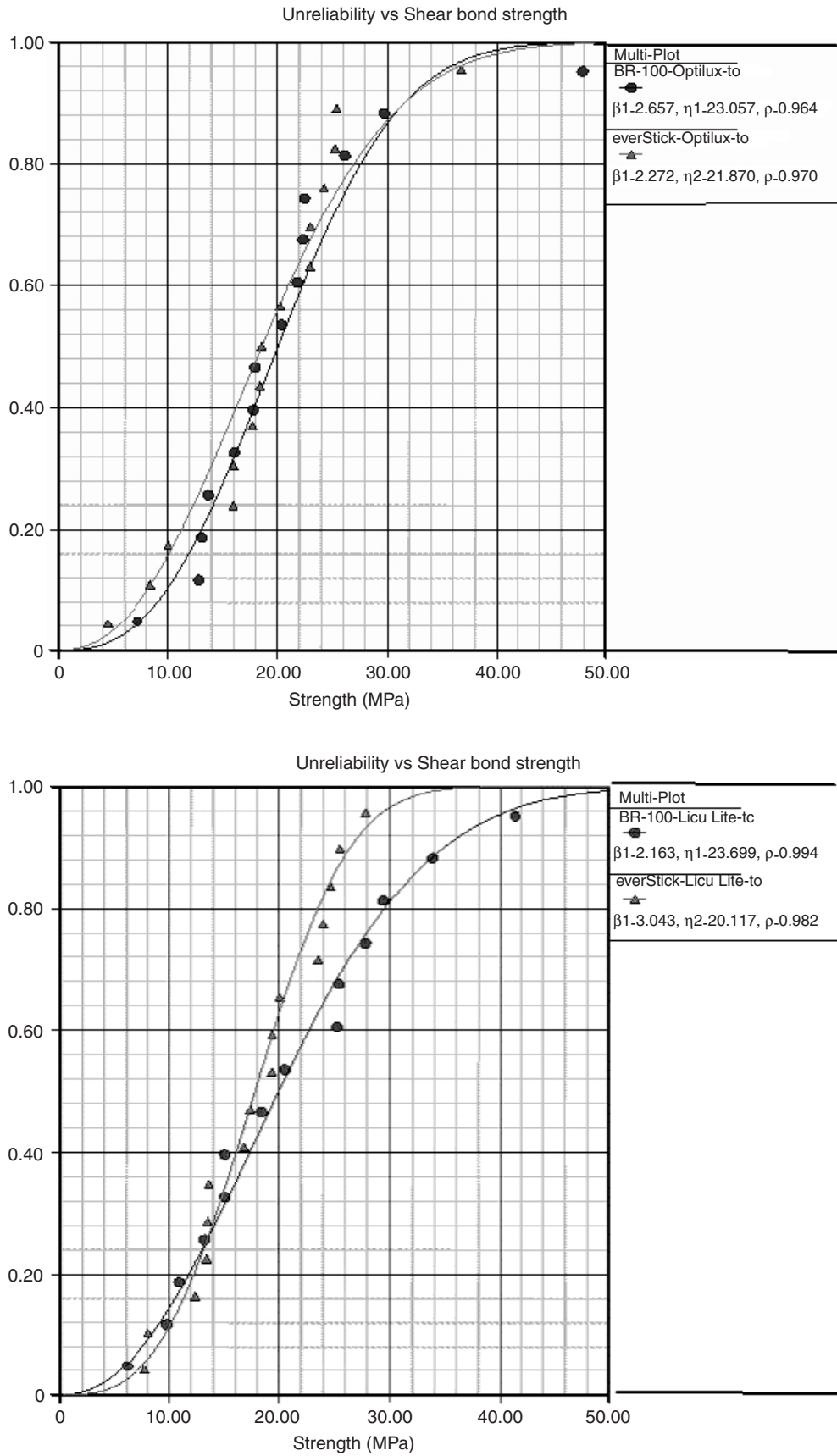


Figure 2. (a) Weibull cumulative failure probability for oven polymerized FRCs. (b) Weibull cumulative failure probability for hand-unit polymerized FRCs. (Optilux = hand-unit polymerized, Liculite = oven polymerized, TC = Thermocycled).

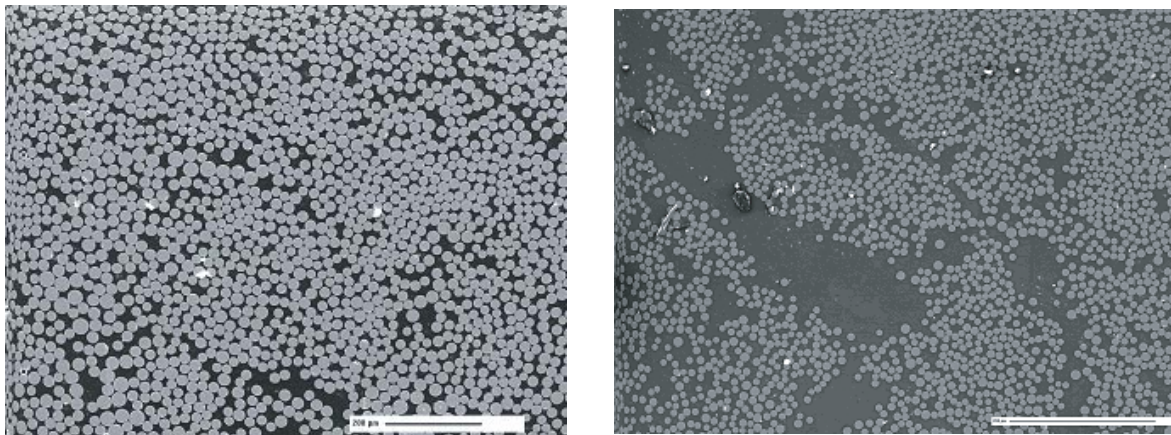


Figure 3. (a) SEM micrographs of everStick C&B FRC (original magnification $\times 150$). (b) SEM micrographs of BR-100 FRC (original magnification $\times 150$).

consists of two —OH groups in the monomer molecule. On the other hand, BR-100 consists of UTMA monomers, which also have polar side groups of urethane (—CN). These, however, are less polar than the hydroxyl groups [22]. A study by Lassila et al. [15] showed that water sorption of UDMA-based FRC was 1.2 wt%, which is close to the water sorption of BR-100 found in the present study. Water sorption of typical particle filler composites is similar to these FRC materials, which is obvious if total filler volume content is about equal [23].

Flexural properties

In this study, flexural strength values obtained after 30 days water immersion were higher than in a previous study carried out by Behr et al. [7], who reported that after 30 days of water immersion the flexural strength value of Vectris FRC was 545 MPa and FibreKor FRC 499 MPa, i.e. lower than the values obtained in this study for everStick C&B and BR-100 [7]. However, direct comparison with previous studies is not always possible, as factors such as fiber volume fraction, location of the fiber-rich phase in the test specimen, bending test span-length-height of the specimen ratio, and degree of water saturation of the test specimens [24] may have an effect on the resultant flexural strength values. The slightly higher flexural strength values obtained for everStick C&B compared to BR-100 in the present study may have been caused by

the semi-IPN polymer matrix of the everStick C&B FRC. The partially non-cross-linked polymer matrix is not as brittle as the cross-linked UTMA-based polymer matrix, which may result in higher flexural strength values. It should also be noted that in the present study the flexural strength test was performed on specimens which had already reached water saturation. Previously, it has been shown that there is a relationship between flexural strength and water uptake of the polymer matrix of FRCs [15]. This was explained by the hydrophilic property of the polymer and the plasticization of the polymer matrix by the absorbed water. Despite the high water sorption, the high flexural strength of Everstick suggests that the difference between the flexural strengths of the materials might be even higher for the dry specimens, but this was not tested in the current study.

In this study, half of the FRC test specimens were additionally polymerized in a light-curing oven, indicating that the degree of monomer conversion was higher in those groups compared to the groups polymerized with a hand light-curing unit only. Previously, post-polymerization in the oven has been shown to provide a higher degree of conversion of the polymer matrix of FRC compared to the hand light-curing polymerization method [25,26], which explains the differences in the strength of FRCs obtained in the present study according to the polymerization method.

Bonding properties

In this study, it was hypothesized that the bonding properties of everStick C&B should be better than those to BR-100. However, this could not be confirmed within the limitations of this study. The hypothesis was based on the semi-IPN polymer resin matrix composition of everStick C&B, which has previously been shown to have a pronounced benefit for the bonding of the materials. This was explained by

Table VI. SEM/EDS analysis of oxides in inorganic phase of FRC

Oxide	BR-100 wt%	everStick C&B wt%
SiO_2	58.4	55.6
CaO	24.8	26.5
Al_2O_3	14.7	15.8
MgO	1.3	1.0
Na_2O	0.3	0.9
K_2O	0.3	0.5
Fe_2O_3	0.2	0.2

the ability of the adhesive monomers to diffuse into non-cross-linked phases of FRC structure when applied to the surface for a sufficient time (5 min) [13,18,27]. This process was called interdiffusion bonding. Interdiffusion bonding requires dissolving parameter of the adhesive resin to be equal or close to that of PMMA, which forms the non-cross-linked phase of the everStick C&B [13,18,28,29]. On the other hand, theoretically it is not possible to obtain interdiffusion bonding if the polymer matrix is highly cross-linked in structure, which was hypothesized to be the case in the BR-100, containing dimethacrylates in the matrix structure. However, interestingly, BR-100 did show comparable or somehow higher bond strength values.

There are two aspects which may contribute to the comparable bond strength obtained with the studied materials. One is the possibility that the adhesive resins of Panavia cement did not have the capability to form interdiffusion bonding to everStick C&B, i.e. the dissolving parameter of the resin system differs from that of the PMMA phase of the polymer matrix of everStick C&B. On the other hand, owing to the high area percentage of glass on the bonding surface of high strength FRCs (everStick C&B, BR-100), the bonding was obviously also influenced by factors other than the existence of the semi-IPN polymer matrix. In this context, Tezvergil et al. [29] showed better bond strength by primers including HEMA and acidic phosphate monomers to FRC substrate than that obtained with HEMA containing primers only. This was explained by the possible benefit of acidic phosphate monomers on bonding to the high glass-containing FRC structures, which was also included in the primer composition of the Panavia cement used in this study. Furthermore, earlier literature has shown that this composition is also beneficial for the adherence of resin-based materials to oxide-containing surfaces like ceramics and glass. The results obtained using SEM-EDS analysis showed a high area percentage of glass in both materials. Thus, the results of the present study suggest that the amount of glass on the bonding surface as substrates were ground also has a significant role in the bonding of new composites to FRCs.

The shear bond strength data were analyzed using Weibull analysis, in which the failure probability could be predicted at any stress level [19]. A high Weibull modulus is desirable, as this indicates more predictable failure behavior and a homogenous interface between the substrate and the adhered material. The Weibull modulus of the tested specimens showed a similar result. The polymerization device did not affect the bond strength values and the modulus of the groups was similar. It could have been expected that the FRC substrate, which is only hand-polymerized and has a lower degree of conversion and cross-linking density, would provide a better bonding facility for the free radical bonding of the possible unreacted groups

[30,31]. Again, this finding suggests that in composites containing a high percentage of fiber the polymer matrix, which is the relatively minor part of the bonding surface, has a limited role in bonding. However, the situation might be different for different clinical applications. At the load-bearing areas, where high density FRC is used, the effect of high-glass content should be considered, whereas in the direct clinical applications, where the unidirectional FRC is spread on the tooth surface to form a large bonding wing for surface-retained adhesive FPD, the matrix area will increase and the matrix composition might again become a predominant factor influencing the bonding properties.

SEM/EDS analysis and fiber quantity

Combustion of everStick C&B and BR-100 gave approximately equals amount of polymer matrix in the FRC. However, based on SEM/EDS analysis, the polymer matrix of BR-100 also consisted of inorganic fillers meaning that the actual fiber fraction was higher in everStick C&B than in BR-100. This was also confirmed by the image analysis. The elemental EDS analysis showed that both FRCs consisted of oxides which resembled each other, and the oxides have been reported to be typical for E-glass [31]. Boron oxide (B_2O_3) was not included in this quantitative analysis because of having too low an atomic weight for a reliable analysis. However, signals of the existence of boron oxide were found.

Conclusions

Within the limitations of the study, the following conclusions were drawn. FRC with semi-IPN polymer structure (EverStick C&B) showed slightly higher flexural strength than BR-100, but the difference was not statistically significant. Water sorption of highly cross-linked FRC (BR-100) was lower than that of everStick C&B. Fiber thickness was higher in the everStick C&B than in BR-100, while the fiber distribution in the cross section of specimens was more even in the everStick C&B. Despite the differences in the polymer matrix of tested FRCs, bonding properties of the composite resin cement were comparable in both materials.

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