



Effect of water storage, thermocycling, the incorporation and site of placement of glass-fibers on the flexural strength of veneering composite

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Water storage

Summary Objectives. To evaluate the effects of water storage, thermocycling, and the incorporation of glass-fibers, on the flexural strength of veneering composites.

Methods. Veneering composites with different fillers, matrices and polymerization methods (Belleglass Kerr Inc., Orange, CA, USA; Sculpture, Pentron Inc. Wallingford CT, USA; Sinfony, 3M Espe, Seefeld, Germany; SR Adoro LC and HP, Targis, Ivoclar Vivadent, Schaan, Liechtenstein), a glass-fiber framework material (Vectris Pontic VP, Ivoclar Vivadent) and a direct restorative composite control (Tetric Ceram, Ivoclar Vivadent) were selected. For the first part of the study, 30 bar specimens ($25 \times 2 \times 2 \text{ mm}^3$) per material were fabricated. Ten were stored for 24 h and 10 for 14 days in water at 37 °C. Ten were thermocycled ($3000 \times$; 5-50-5 °C). Three-point bending tests (crosshead speed: 0.5 mm/min) were performed. For the second part of the study, all veneering materials were combined with a glass-fiber framework (VP). Sixty specimens were produced for each material ($25 \times 4 \times 2 \text{ mm}^3$) and treated as in the first part. Three-point bend tests were performed with the reinforcing glass-fiber framework either on the tension or the compression side. Data was evaluated by ANOVA and Weibull analysis.

Results. A decrease in flexural strength was observed after water storage or thermocycling for all veneering materials tested. None of the tested materials exhibited significant advantages compared to the control. The flexural strength of glass-fiber reinforced frameworks was ten times higher and not influenced by water storage or thermocycling. A significant reinforcing effect from glass fibers was

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observed when they were placed on the tension but not when placed on the compression side.

Significance. A glass-fiber framework on the tension side significantly improved the flexural strength of veneering composites. There was less deterioration due to water storage and thermocycling with the glass-fiber reinforced veneering composite compared to the non-reinforced materials.

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Introduction

In recent years, indirect, laboratory-made composite restorations have become an alternative to all-ceramic restorations for the esthetic treatment of posterior teeth.

In combination with glass-fiber frameworks, the indication has been extended from intracoronal restorations to fixed partial dentures [1-4].

However, the composition of the veneering composites is not very different from those of current hybrid and microfilled composites for direct restorations. They are still composed of a resin matrix, fillers, and a coupling agent [5]. In dental composites γ -metacryloxypropyltrimethoxysilane, a bipolar organic molecule, is most commonly used as a coupling agent. Since its introduction in the 1960s, bisphenol glycidyl methacrylate (Bis-GMA) has been the monomer of choice as the principal matrix monomer of practically all dental resins. Because of its high viscosity, additional monomer—for example triethyleneglycol dimethacrylate (TEGDMA) or ethyleneglycol dimethacrylate (EGDMA)—are often used as diluents. Later, more complex monomers were introduced. Urethane dimethacrylate (UDMA) was found to have increased tensile properties, faster and more complete conversion, and its lower viscosity allows its use without low viscosity diluents [6]. To improve the inadequate properties of resins, fillers were added to the material [7]. The main types of filler materials used in dental composites are glass, glass-ceramics, silicates and silicon dioxides. In spite of their similar composition, indirect composite restorations are thought to have superior mechanical properties compared to in situ-cured composite restorations. These enhanced properties are due to a higher degree of conversion obtained by the use of different post-polymerization procedures [8] that involve photoactivation, heat between 90 °C and 140 °C, and/or vacuum or a nitrogen atmosphere. Diametral tensile strength, hardness, coefficient of thermal expansion and polymerization conversion are some of the properties that seem to be positively influenced by post-heat curing. A high degree of conversion is

also believed to make a polymer more resistant to chemical attack and softening [9]. A nitrogen atmosphere is thought to avoid oxygen inhibition and consequent reduction in the degree of polymerization—during polymerization on the composite's outer surface as well as in fabrication incorporated air bubbles [10,11].

In the oral cavity, restorative materials are subjected to cyclic mechanical and thermal loading (fatigue). Evidence exists indicating fatigue as responsible for the wear, chipping, and generalized failure of dental restorative materials [12,13]. Because of the cyclic nature of clinical loading, there is an inclination to perform cyclic fatigue testing in vitro and evaluate the material's resistance to fatigue in that manner. In pontic areas of fixed partial dentures, materials are especially subjected to tensile stresses. For brittle materials such as dental composites, the usual method tests bar specimens in flexure.

The aim of the first part of the present study was to compare the flexural strength of different veneering materials for fiber-reinforced composite restorations following water storage and thermocycling. A high filler content is expected to increase the physical properties of a composite material [7]. On the other hand, different thermal expansion coefficients of fillers and resin matrices may lead to high interfacial stresses during cyclic temperature changes. Five commercially available fine-hybrid composites with different fillers, different filler content, different matrix compositions and different post-curing methods were compared to an unveneered glass-fiber element and two inhomogeneous microfilled composite materials with either light and heat or heat and nitrogen atmosphere post-curing. The null hypotheses were: (1) a high filler content leads to high and stable flexural strength; and (2) heat and nitrogen atmosphere treated materials will exhibit less negative effects from water storage and thermocycling.

In the second part, the veneering composites were polymerized with uniaxially directed glass-fiber framework elements and loaded on either the veneering material or the reinforcing framework material to determine the reinforcing effect.

The null hypotheses were: (1) a reinforcing effect was expected only when the veneering composite was loaded with compressive forces—a veneering composite with a high modulus of elasticity was expected to show brittle fracture mechanism when placed on the tensile side—and (2) copolymerization between the matrices of veneering and reinforcing composites plays an important role when combining both materials. It seems inadvisable to remove the superficial oxygen inhibition layer, rich in unreacted double bonds, from the framework material before covering the latter with veneering composite.

Materials and methods

The materials tested in this study are listed in Table 1 in order of their type and filler content. Three were commercially available indirect fine-hybrid veneering composites with high filler content (Belleglass: BEL, Sculpture: SCU, Targis: TAR). One was a low-filled fine-hybrid veneering composite (Sinfony: SIN). Two inhomogeneous microfilled materials (SR Adoro LC: ALC and SR Adoro HP: AHP) associated with different polymerization methods were selected. A commercially available glass fiber element (Vectris Pontic: VP) was also tested. As a control, a fine-hybrid composite resin for direct restorations (Tetric Ceram: TCE) was selected for this study (Table 1).

Two of the highly filled composites (BEL, TAR), the glass-fiber reinforced composite (VP) and the control (TCE) used a Bis-GMA matrix diluted with TEGDMA (BEL, TCE, VP) or DECDMA (decandiol dimethacrylate) and UDMA (TAR), whereas the third one used a PCDMA (polycarbonate dimethacrylate) containing matrix (SCU). The low-filled composite (SIN) used a Bis-GMA-free matrix with a high content of the hydrophilic monomer HEMA (2-hydroxyethyl methacrylate). The microfilled composites (ALC, AHP) used the hydrophobic cross-linking monomer UDMA only, which is known for its improvement of tensile properties [6] (Table 1).

For the first part of the study, 30 bar specimens $25 \times 2 \times 2$ mm were fabricated per material, according to the respective manufacturer's instructions, using a stainless steel split mold. The mold was placed over a glass plate, and the composite or the cut-to-fit glass-fiber element was inserted with a spatula in one single movement to avoid air entrapment. The resin was covered with another glass plate, and gently pressed against the mold to extrude excess material. Polymerization schedules for the various resins are described in Table 1.

For the second part of the study, 60 bar specimens $25 \times 4 \times 2$ mm³ were fabricated per material using a Teflon split mold. The 4 mm high form was used instead of the 2 mm high mold because the Vectris pontic element had a height of 2 mm leaving no extra space in the mold for the placement of the veneering composite. It was too difficult to separate exactly the matrix-embedded fibers without excessive air entrapment. The mold was placed over a glass plate, and a fiber bundle (Vectris pontic) was cut to fit and placed at a height of 2 mm in the 4 mm high mold. For six veneering materials, the matrix of the fibers was light cured (Optilux 500, Kerr Demetron). Composite was inserted with a spatula in one single movement to avoid air entrapment. To extrude excess material, the resin was covered with another glass plate and gently pressed against the mold. The specimens were light cured through the glass plate. After removal, the specimens were covered with glycerin gel and post-cured in the respective devices. For one combination of veneering and reinforcing material (TAR + VPV), the fibers (VP) were placed in a $25 \times 2 \times 2$ mm³ mold, condensed and light cured in a vacuum and pressure device (Vectris VS-1, Ivoclar Vivadent). The polymerized bars were taken out of the mold and surplus pressed-out polymerized matrix was carefully deburred with silicon carbide paper (400 grit, Struers, Copenhagen, Denmark). The surface was then air abraded (aluminum oxide 50 μm, Deltablast, Kaladent Zürich, Switzerland), at 2 bar pressure. A coupling agent (Monobond S, Ivoclar Vivadent) was applied and dried after 60s. A thin layer of Vectris Glue was applied and the specimens were again placed in the mold. A woven glass-fiber cloth (Vectris Frame) was placed over the mold, and the samples were again condensed with vacuum and pressure and light cured (Vectris VS-1). The specimens were taken out of the mold, surplus pressed-out matrix was deburred and the surface was air-particle abraded. The coupling agent was applied and air dried after 60 s. The glass-fiber bars were placed in a $25 \times 4 \times 2$ mm³ mold, and composite (TAR) was applied and cured as described above. All specimens were polished to 1000 grit (Planapol 2, Struers).

For the first part of the study, 10 specimens per material, and for the second part 20 specimens per material, were stored in tap water at 37 °C for 24 h. For 10 and 20 specimens per material respectively, storage was prolonged to 14 days. Ten and 20 specimens per material, respectively, were thermocycled for 3000 cycles of 5 °C-50 °C-5 °C in a computer-controlled device (CoCoM, PPK, Zurich, Switzerland). In this device, mixing of cold and warm water was avoided by emptying the chamber

Table 1 Material data^a, curing, and post-curing modes.

Composite type	Product name	Manufacturer	LOT	Curing	Post-curing	Filler and size ^a	Filler content ^a	Shade	Matrix ^a	E-Modulus ^a , G-PA ^b
Fine hybrid	TCE (tetric ceram [control])	Ivoclar vivadent schaan, liechtenstein	A20635	Light ^c 60 s	-	Glass 79 wt% (BaO, YbF, BaALFSi, SiO ₂ , mixed oxides) 0.2 to 2.7 μm	60 vol%	Dentin 140	Bis-GMA (8 wt%) UDMA (8 wt%) TEGDMA (4 wt%)	9.4
	BEL (belleglass HP)	Kerr Inc. orange, CA, USA	008029	Light ^c 10 s	20 min, 140 °C, 80 psi nitrogen pressure, belleglass HP	Glass 79 wt%, (SiO ₂ , BaO, Al ₂ O ₃ , Na ₂ O) 0.3-2 μm	57vol% ^d	Trans dentin A2	Bis-GMA, TEGDMA	9.9
	SCU (SculptureVLC-HV)	Pentron Inc. Wallingford, CT, USA	35051	Light ^c 10 s	15 min, 107 °C, vacuum, conquestomat	Glass 78 wt% (SiO ₂ , BaO, others) 0.01-3 μm	N.A.	Body A2	EDMA 15 wt%, PCDMA 7 wt%	14.4
	TAR (Targis Upgrade 99)	Ivoclar vivadent schaan, liechtenstein	B26145	Light ^c 10 s	25 min, 130 °C, ambient, targis power	Glass 75 wt%(SiO ₂ , BaO, Al ₂ O ₃ , mixed oxides) 0.2-2.7 μm	54 vol% ^d	D 120	Bis-GMA (9 wt%) UDMA (9 wt%) DECDMA (5%)	11.0
	SIN (Sinfony)	3M ESPE, Seefeld, Germany	011	Light ^c 10 s	15 minHeat vacuum, visio Beta vario	Glass and Glasionomer 45 wt%, (SiO ₂ , Al ₂ O ₃ , K ₂ O, CaO, F, Na ₂ O, P ₂ O ₅ , SrO) 0.5-0.7 μm	26 vol% ^d	Dentin A2	HEMA 30-40 wt% Octahydro-4,7-methano-1H-indenediyl bis(methylene-diacrylate) 10-30 wt%	3.1
Microfilled	ALC (SR Adoro LC)	Ivoclar Viva-dent Schaan, Liechtenstein	E15066	Light ^c 10 s	25 min104 °C Ambient, Lumamat 100	Prepolymerized Splinters, 63 wt% (SiO ₂)	40 vol% ^d	Dentin 210	UDMA 17 wt%	8.3
	AHP (SR Adoro HP)	Ivoclar Viva-dent, Schaan, Liechtenstein	ZZ2386	-	20 min, 140 °C, 80 psi nitrogen pressure, Belle-glass HP	Prepolymerized Splinters, 63 wt% (SiO ₂)	40 vol% ^d	Dentin 230	UDMA 17 wt%	8.3
Glass-fiber reinforced	VPV (Vectris Pontic VLC)	Ivoclar, Viva-dent, Schaan, Liechtenstein	E94015	Vacuum, Light&heat	25 min, 110 °C, Ambient, Targis Power	Uniaxially orientated glass-fibers 65 wt%	50 vol%		Bis-GMA 25 wt%, TEGDMA 6 wt%	36.0
	VPL (Vectris Pontic LC)	Ivoclar Viva-dent, Schaan, Liechtenstein	E94015	Light ^c 60 s	25 min, 110 °C, Ambient, Targis Power	Uniaxially orientated glass-fibers 65 wt%	40 vol%		Bis-GMA 25 wt%, TEGDMA 6 wt%	36.0

^a Manufacturer's information.^b ISO 10477.^c Optlux 500, 700 mW/cm².^d Chaabane and Wigren (2003) [14].

automatically with compressed air after each cycle of 2 min. To estimate the temperature inside the specimen, a bar specimen was created with a temperature sensor (TES 1303, TES Electrical Electronic Corp., Taipei, Taiwan) in the center, covered with a layer of 1 mm of composite (TAR). During thermocycling, two sensors measured the temperature, one in the water, and the other inside the specimen. The temperature pattern was recorded (YEW 3022, Yokogawa Hokushin Electric, Tokyo, Japan) and is displayed in the Fig. 1.

A three-point bending test was used in this investigation to assess the flexural strength of dental composites. Three-point flexural bending was performed in a universal testing machine (Schenk Trebel, Darmstadt, Germany) at a cross-head speed of 0.5 mm/min. The distance between the supports was 20 mm, and the radius of the supporting rods and the loading steel sphere was 5 mm. Before testing, specimen dimensions were determined with a digital caliper (CAPA 150, Tesa SA, Renens, Switzerland) with 0.01 mm accuracy.

Half of the glass-fiber reinforced specimens were loaded on the veneering material (glass-fiber

framework on the tension side, veneering material on the compression side), and the other half was loaded on the glass fibers (glass-fiber framework on the compression side, veneering material on the tension side). Specimens were loaded in a noise-protected room until the investigator's ears detected the first sound of a crack, and the load (N) was recorded.

Flexural strength was calculated with the following formula [15]:

$$\sigma = \frac{3Fl}{2bh^2}$$

where σ is the flexural strength (in MPa), F is the failure load (in Newton), l is the distance between the supports, and b and h are the width and height of the specimen, respectively (all expressed in mm).

Mean flexural strength, SD, maximum and minimum values were determined (StatView 4.5, Abacus Concepts, Berkeley, CA, USA). After testing for normal distribution using the Kolmogorov-Smirnov test, the groups were compared statistically using one-way analysis of variance (ANOVA). Bonferroni-

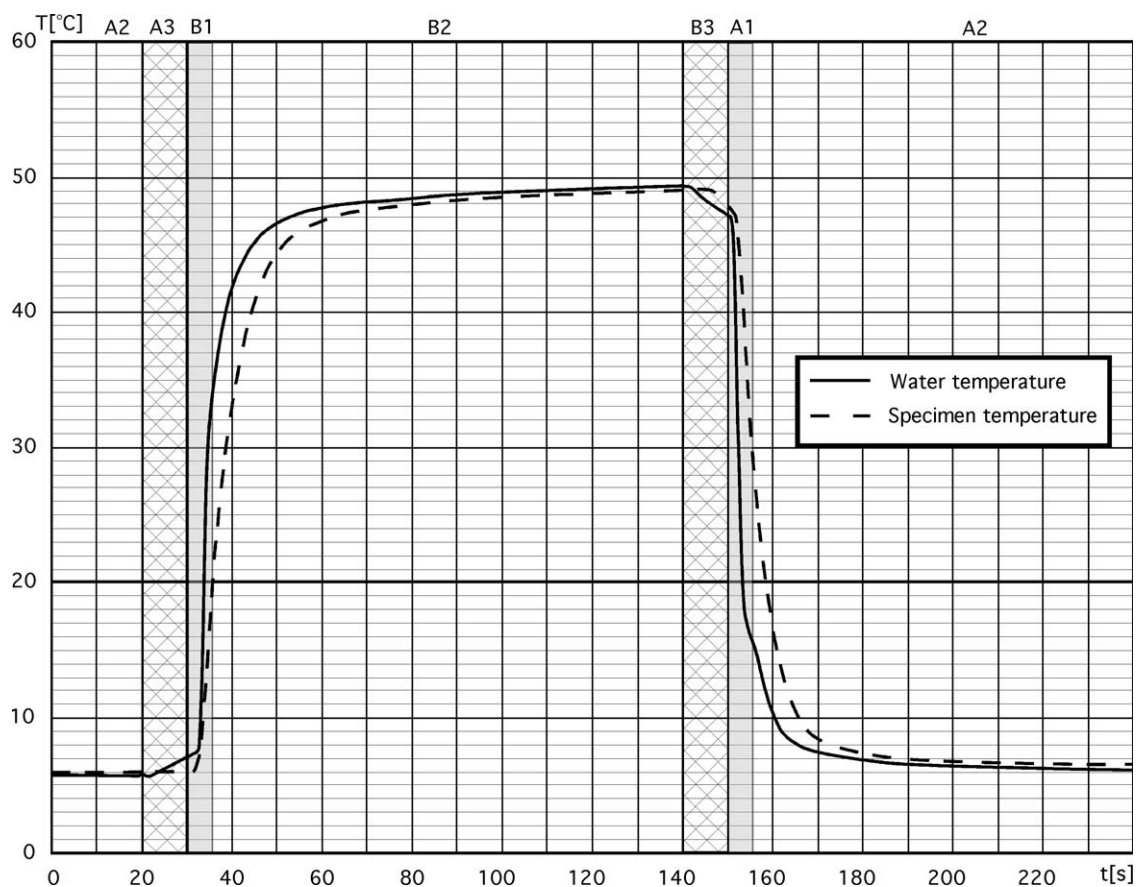


Figure 1 Changes in temperatures of the water bath and of the sample as a function of time for one complete cycle of thermocycling: cold water circulation (A2), cold water emptying (A3), warm water entrance (B1), warm water circulation (B2), warm water emptying (B3), cold water entrance (A1).

Dunn correction was applied for multiple testing. The levels of significance were set at 95%. To determine the clinical significance of this analysis, the characteristic strength and the Weibull modulus of the tested materials were calculated using the Weibull distribution [16] (SyStat 10.2, Systat Software Inc., Richmond, CA, USA). The 95% confidence intervals (95% CI) were calculated. Experimental groups were considered to be statistically similar in characteristic strength when their confidence intervals overlapped.

Results

The results of the flexural strength test and the statistical analysis of the first part of the study are listed in Tables 2.1 and 2.2. The results for the second part of the study are displayed in Tables 3 and 4.

The results of the first part of the study indicate that the low-filled (SIN) and microfilled composite materials (ALC, AHP) had lower flexural strength than the highly filled hybrid composite materials (BEL, SCU, TAR, TCE). Conversely, the materials with a lower E-modulus, especially SIN and, to a lesser degree the microfilled materials (ALC, AHP), exhibited an elastic deformation before fracturing, whereas highly filled fine-hybrid composites fractured with no visible deformation.

For all materials except SCU and ALC, a significant decrease in mean flexural strength was observed after water storage for 2 weeks. Although most materials exhibited a further decrease in mean flexural strength after thermocycling, this was only significant for TAR.

After water aging, significant changes of characteristic strength were found for TAR, SIN, ALC and AHP. Here, TAR had a significant decrease after water storage and again a significant decrease after thermocycling. SIN and AHP had a significant decrease after water storage and ALC after thermocycling (Table 2.1).

Neither water storage nor thermocycling influenced flexural strength of the tested glass-fiber framework material (Table 2.2). The glass-fiber bar did not break during the test: the fibers held the fractured matrix together and the bar could be bent further.

The results of the second part of the study indicate that placement of the glass fibers on the tensile side significantly improved the flexural properties of all tested composites (Table 3). The use of the vacuum and pressure device (Vectris VS-1) for glass-fiber framework

preparation (VPV) did not have any positive effect on flexural strength compared to the light-cured-only framework material (VPL). The mean flexural strength of TAR+VPV was significantly lower for fresh, water-stored and thermocycled specimens than TAR+VPL. Characteristic strength was significantly lower only for fresh TAR+VPV (Table 3).

After the test, the veneering composite showed fracture lines but was not separated from the glass-fiber framework. Only with TAR+VPV were parts of the veneering composite chipped from the glass fibers.

When the veneering material was placed on the tensile side, no reinforcing effect was observed for all highly filled fine-hybrid composites compared with unreinforced specimens. A significant improvement was observed only for the relatively elastic, low-filled SIN, which exhibited significantly higher mean and characteristic flexural strength. A tendency towards improvement was also observed with both microfilled composites (ALC, AHP; Table 4) when compared to unreinforced material. In this test, fracture lines were observed in the veneering composites, but in most cases, the veneering material was still connected to the glass-fiber framework.

Discussion

Flexural strength data show some variability because the testing configuration is sensitive to surface flaws and defects that initiate the cracks that lead to fracture of the tensile-loaded side. However, a dental technician has to work with the materials provided—with very different characteristics—and with mostly far-from-ideal handling; therefore, this variability is also present in clinical situations. Because of this variability, in addition to mean values, the calculated characteristic strength and Weibull modulus were considered to be appropriate analyses, although reliable Weibull analysis requires high numbers of specimens. A high value of Weibull modulus indicates a close grouping of fracture stress values and means that a material is more dependable. A low value indicates a wide distribution with a long tail at low stress levels [16].

It is likely that the stress pattern distribution in the three-point bend test is the most common pattern of stress distribution in three-unit fixed partial dentures. Because masticatory forces are normally concentrated on a single point, the three-point bend test is clinically relevant [17]. The evaluation of the temperature

Table 2.1 Flexural strength test, ANOVA and Weibull analysis of fresh, water stored and thermocycled composite veneering materials.

Material		Mean (SD) [MPa]		ANOVA ^a	Minimum [MPa]	Maximum [MPa]	Characteristic strength (95% CI) [MPa] ^b	Significance ^c	Weibull modulus	
TCE	24 h water at 37 °C	156.8	(22.7)	A	115.6	182.3	151.3	(138.2-165.7)	AB	10.0
	14 d water at 37 °C	138.2	(9.9)	B	123.1	155.0	134.6	(127.1-142.5)	BC	15.6
	Thermocycled	132.5	(11.3)	B	111.9	145.9	129.2	(121.6-137.3)	BC	14.9
BEL	24 h water at 37°C	158.6	(24.0)	A	134.8	214.5	144.4	(119.9-173.8)	ABC	17.9
	14 d water at 37 °C	123.4	(17.9)	BC	102.5	150.5	116.9	(104.3-131.0)	CD	17.9
	Thermocycled	123.3	(19.2)	BC	199.2	148.0	116.6	(103.6-131.5)	CD	17.6
SCU	24 h water at 37 °C	145.9	(19.4)	AB	123.8	172.2	139.3	(125.8-154.2)	ABC	18.9
	14 d water at 37 °C	132.1	(12.6)	B	111.4	148.7	128.5	(120.2-137.4)	BC	13.6
	Thermocycled	128.9	(8.7)	B	110.1	140.1	126.7	(121.2-132.5)	C	20.2
TAR	24 h water at 37 °C	167.1	(14.8)	A	147.9	191.0	161.7	(150.6-173.5)	A	12.6
	14 d water at 37 °C	135.8	(12.1)	B	118.4	152.3	132.3	(124.2-141.0)	BC	14.3
	Thermocycled	106.3	(18.7)	CD	183.6	138.1	99.1	(86.3-113.9)	DE	16.5
SIN	24 h water at 37 °C	126.0	(10.2)	BC	106.1	141.0	123.2	(116.3-130.4)	C	15.7
	14 d water at 37 °C	87.1	(6.6)	D	179.9	97.3	84.9	(80.1-90.0)	E	15.3
	Thermocycled	83.0	(9.7)	D	164.0	94.6	80.4	(74.3-86.9)	E	11.6
ALC	24 h water at 37 °C	122.8	(6.9)	BC	111.5	134.9	120.2	(114.8-125.9)	C	19.3
	14 d water at 37 °C	106.1	(7.9)	CD	197.4	121.7	102.9	(96.6-109.6)	CD	14.0
	Thermocycled	91.3	(12.8)	D	173.5	115.6	86.3	(77.1-96.5)	E	17.9
AHP	24 h water at 37 °C	115.6	(12.9)	BC	198.2	133.2	111.3	(102.4-121.1)	CD	10.7
	14 d water at 37 °C	90.7	(5.6)	D	182.4	97.6	89.1	(85.1-93.3)	E	19.7
	Thermocycled	91.0	(6.4)	D	181.8	105.3	88.0	(82.6-93.8)	E	13.7

^a Values followed by the same letters are statistically similar (ANOVA with post-hoc testing and Bonferroni/Dunn correction; $p < 0.0002$).

^b Characteristic strength: stress level at which 67% of the specimens will fail.

^c Values followed by the same letters are statistically similar (Weibull analysis, $p < 0.05$).

Table 2.2 Flexural strength test, ANOVA and Weibull analysis of fresh, water stored and thermocycled glass-fiber framework material.

Material	Mean (SD) [MPa]	ANOVA ^a	Minimum [MPa]	Maximum [MPa]	Characteristic strength (95% CI) [MPa] ^b	Significance ^c	Weibull modulus
VPL	1014.0	A	760.6	1206.4	1054.0	A	12.8
24 h water at 37 °C	(128.6)				(982.4-1130.9)		
14 d water at 37 °C	1033.4	A	908.3	1135.3	1011.7	A	17.8
Thermocycled	1074.3	A	963.2	1205.0	1047.5	A	15.3
	(84.2)				(961.8-064.1)		
					(987.7-1111.0)		

^a Values followed by the same letters are statistically similar (ANOVA with post-hoc testing and Bonferroni/Dunn correction; $p < 0.0002$).

^b Characteristic strength: stress level at which 67% of the specimens will fail.

^c Values followed by the same letters are statistically similar (Weibull analysis, $p < 0.05$).

development inside the specimens during thermocycling showed that the temperature changes could be expected to have more than a superficial effect. After approximately 1 min, the temperature of the surrounding water was reached and maintained for the remaining minute of the respective cycle. When shorter cycle times or larger specimens are used, the specimen's internal temperatures should be evaluated.

Two observations were obvious: (1) a decrease in the flexural strength of veneering materials through water storage, and (2) no reinforcement in terms of improving the flexural strength was realized when the glass-fiber framework was placed on the compression side of the specimens.

The majority of the tested materials in this study were mostly influenced by water storage and the decrease in flexural strength was not significant between water-stored and thermocycled specimens. Therefore, in agreement with Lassila et al. the use of polymers with low water absorption seems to be beneficial [18].

In another study, an influence of thermocycling was observed with higher temperatures, shorter dwell times, and more thermocycles. A significant decrease was observed from fresh specimens to thermocycled specimens, but beyond 5000 cycles, flexural strength hardly changed in this study [19]. The influence of water storage alone was not tested [19]. In another test, specimens were thermocycled and water stored, but the influence of either aging method was not discriminated [20].

Unfortunately, restorations such as fixed partial dentures cannot be made from uniaxially orientated glass-fiber elements alone. Those exhibited extremely high flexural strength, and flexural strength and Weibull modulus were not influenced by short-term water storage or thermocycling. For esthetic reasons and because the rough surface of these elements would be immediately colonized with bacterial plaque, glass fibers must be completely veneered with composite.

In agreement with others [21], all tested veneering materials exhibited a decrease in flexural and characteristic strength with water storage and/or thermocycling. Compared to the light-cured-only direct restorative composite, none of the tested post-cured laboratory composite materials had significant advantages.

The hypothesis that a high content of inorganic fillers would lead to higher flexural strength compared to a low filler content was supported by the results. However, after thermocycling, one of the tested fine-hybrid composites (TAR) was not superior to the low (SIN) and microfilled materials.

Table 3 Flexural strength test, ANOVA and Weibull analysis of fresh, water stored and thermocycled combinations of veneering and framework composite materials. Three-point bend test performed with the reinforcing glass-fiber framework on the tension side.

Material		Mean (SD) [MPa]		ANOVA ^a	Minimum [MPa]	Maximum [MPa]	Characteristic strength (95% CI) [MPa] ^b	Significance ^c	Weibull modulus
BEL + VPL	24 h water at 37 °C	647.1	(43.5)	A	579.1	702.1	635.9 (607.1-665.9)	A	19.6
	14 d water at 37 °C	608.2	(25.0)	A	569.7	641.3	601.6 (584.2-619.5)	A	30.9
	thermocycled	611.8	(11.9)	A	599.8	629.9	607.8 (598.3-617.5)	A	56.9
SCU + VPL	24 h water at 37 °C	553.0	(24.3)	B	516.2	588.0	544.9 (526.3-564.1)	B	25.9
	14 d water at 37 °C	512.3	(31.9)	BC	449.3	556.2	502.3 (479.7-526.1)	C	19.4
	thermocycled	494.9	(32.6)	BC	438.2	541.1	485.4 (463.2-508.8)	CD	19.1
TAR + VPV	24 h water at 37 °C	483.3	(19.4)	CD	277.7	614.5	452.8 (485.8-515.9)	CD	6.9
	14 d water at 37 °C	482.9	(86.5)	CD	258.4	549.4	444.2 (437.7-469.6)	BCD	5.3
	thermocycled	447.8	(85.3)	D	303.3	616.9	422.7 (452.3-486.4)	CD	7.1
TAR + VPL	24 h water at 37 °C	581.4	(47.5)	AB	487.7	633.5	569.1 (485.0-511.8)	AB	16.4
	14 d water at 37 °C	609.0	(41.9)	AB	541.8	669.1	596.9 (428.8-461.7)	AB	18.2
	thermocycled	524.1	(33.5)	C	493.0	607.7	506.0 (411.6-458.2)	BC	13.7
SIN + VPL	24 h water at 37 °C	504.6	(15.7)	CD	486.9	535.3	498.2 (512.9-580.6)	C	32.8
	14 d water at 37 °C	456.9	(18.5)	D	434.9	487.0	445.0 (497.4-548.8)	D	27.6
	thermocycled	443.5	(36.2)	D	367.6	491.8	434.3 (475.9-528.5)	D	16.8
ALC + VPL	24 h water at 37 °C	558.6	(53.1)	B	466.1	624.2	545.7 (538.4-601.6)	BC	14.7
	14 d water at 37 °C	533.8	(33.4)	B	484.9	587.7	522.5 (568.1-627.2)	BC	18.2
	thermocycled	514.4	(33.5)	BC	449.1	578.2	501.5 (474.9-539.2)	BC	16.7
AHP + VPL	24 h water at 37 °C	506.9	(20.4)	BC	469.2	538.3	500.6 (398.1-515.0)	C	29.7
	14 d water at 37 °C	460.6	(19.3)	D	437.6	491.6	453.4 (374.0-527.7)	D	25.4
	thermocycled	475.1	(26.4)	BCD	426.7	505.6	469.1 (372.5-479.6)	CD	25.0

^a Values followed by the same letters are statistically similar (ANOVA with post-hoc testing and Bonferroni/Dunn correction; $p < 0.0002$).

^b Characteristic strength: stress level in which 67% of the specimen will fail.

^c Values followed by the same letters are statistically similar (Weibull analysis, $p < 0.05$).

Table 4 Flexural strength test, ANOVA and Weibull analysis of fresh, water stored and thermocycled combinations of veneering and framework composite materials. Three-point bend test performed with the reinforcing glass-fiber framework on the compression side.

Material		Mean (SD) [MPa]		ANOVA ^a	Minimum [MPa]	Maximum [MPa]	Characteristic strength (95% CI)[MPa] ^b	Significance ^c	Weibull modulus
BEL + VPL	24 h water at 37 °C	163.2	(30.0)	CD	118.8	218.8	151.2 (130.7-174.9)	BC	16.1
	14 d water at 37 °C	132.1	(19.3)	CD	198.9	158.0	125.8 (113.0-140.0)	CD	8.4
	Thermocycled	137.6	(14.5)	CD	118.4	159.1	132.1 (121.3-143.9)	CD	10.5
SCU + VPL	24 h water at 37 °C	142.1	(27.7)	CD	197.7	167.8	135.3 (120.7-151.6)	BCD	8.0
	14 d water at 37 °C	125.4	(20.8)	CD	199.5	156.0	117.7 (103.3-134.0)	CDE	6.9
	Thermocycled	120.1	(14.1)	DE	101.4	147.7	114.4 (103.9-126.0)	DE	9.2
TAR + VPV	24 h water at 37 °C	170.7	(24.3)	C	136.4	211.4	165.0 (148.6-183.2)	BC	8.6
	14 d water at 37 °C	172.3	(33.9)	C	116.7	215.2	149.1 (125.0-177.8)	BCD	5.1
	Thermocycled	105.1	(12.7)	E	169.3	116.6	103.1 (97.0-109.5)	E	4.6
TAR + VPL	24 h water at 37 °C	167.3	(18.0)	C	145.2	208.8	156.7 (138.3-177.5)	BC	11.3
	14 d water at 37 °C	166.0	(20.0)	C	145.3	209.2	156.9 (141.2-174.4)	BC	8.3
	Thermocycled	117.0	(33.9)	DE	190.0	148.1	110.1 (97.4-124.5)	DE	7.3
SIN + VPL	24 h water at 37 °C	271.6	(33.4)	A	222.8	327.2	259.8 (236.4-285.6)	A	9.5
	14 d water at 37 °C	244.3	(27.3)	A	197.6	296.7	233.1 (212.4-255.8)	A	9.5
	Thermocycled	223.9	(30.1)	B	196.6	280.3	210.2 (186.5-236.7)	A	7.4
ALC + VLC	24 h water at 37 °C	145.6	(31.0)	CD	193.7	200.8	133.5 (113.2-157.3)	BCD	5.4
	14 d water at 37 °C	123.5	(27.7)	CDE	188.1	165.3	113.2 (95.4-134.2)	CDE	5.3
	Thermocycled	114.6	(25.2)	DE	195.4	181.1	109.3 (81.6-146.2)	CDE	5.5
AHP + VLC	24 h water at 37 °C	151.2	(16.8)	CD	126.7	189.1	143.3 (119.6-171.6)	BCD	8.8
	14 d water at 37 °C	131.7	(19.8)	CDE	103.3	170.9	123.3 (108.9-139.7)	CDE	7.1
	Thermocycled	131.7	(18.59)	CDE	106.2	157.9	124.7 (111.8-139.2)	CD	8.2

^a Values followed by the same letters are statistically similar (ANOVA with post-hoc testing and Bonferroni/Dunn correction; $p < 0.0002$).

^b Characteristic strength: stress level at which 67% of the specimen will fail.

^c Values followed by the same letters are statistically similar (Weibull analysis, $p < 0.05$).

Although flexural strength of the low and micro-filled materials was at least initially lower than that of the fine-hybrid materials, the combination of those materials with glass fibers may be interesting. The combination of glass fibers and the low-modulus of elasticity veneering composite SIN led to the highest flexural strength when the veneering material was placed on the tensile side. This may make laboratory fabrication of FPDs more forgiving. The brittleness of the other tested fine-hybrid composites led to a critical sensitivity to tension and may affect the strength of fiber reinforced FPDs owing to laboratory fabrication variables [17]. Unfortunately, SIN exhibited the strongest decrease in mean flexural strength: a more than 30% decrease after water storage and 35% after thermocycling. This decrease may be attributed to the high content of hydrophilic monomer (HEMA).

Attempts were made to determine the factors responsible for composite degradation, and it was related predominately to the uptake of water by the polymer matrix [22]. Others have shown that radio-opaque fillers (barium glass) are responsible for an increased water uptake followed by composite degradation [23].

There is also evidence for degradation of the filler [24] and the filler-matrix interface [25] owing to solvent exposure. Two materials used the same kinds of fillers but whereas BEL had a decrease in mean flexural strength of 22% after water storage and no further decrease after thermocycling, TAR exhibited a decrease of 29% after water storage and 37% after thermocycling. At least two factors could be responsible for this phenomenon: the smaller (by up to 30%) particle size of TAR, followed by increased water absorption [23] or a higher degree of conversion of BEL due to higher polymerization temperatures and a nitrogen pressure atmosphere during post-polymerization. This might support our second working hypothesis. On the other hand, no improving influence was observed for flexural strength values from the use of nitrogen pressure in the microfilled materials. However, the higher values of Weibull modulus of the latter after water storage, and especially after thermocycling, may indicate a better reliability.

Flexural strength was generally observed to increase with the degree of conversion [22] and therefore it should increase following heat treatment. However, none of the tested heat-treated materials was superior to the in situ-cured control (TCE).

Confirming the first working hypothesis for the second part of the study, the combination of glass-fiber framework and veneering composite

resulted in an increase in flexural strength when the veneering material was loaded on the compressive side. In agreement with Behr et al. [26], the use of the vacuum and pressure device (Vectris VS-1) for glass-fiber framework preparation did not have any positive effect on flexural strength compared to light-cured-only framework material. The complex and technique-sensitive manufacturing process offers many possibilities for entrapment of flaws, and the low value of Weibull modulus indicates a low reliability of these specimens. Additionally, in this process, the oxygen-inhibition layer, which allows copolymerization of the matrices of glass-fiber element and veneering material, was removed. The highest flexural strength and the highest reliability especially after water storage and thermocycling were recorded for the combination of BEL and VPL. Both materials used an identical monomer matrix, which may have led to very good copolymerization. These observations confirmed the working hypothesis, that copolymerization plays an important role in the successful combinations of veneering and reinforcing composites.

Conclusions

Within the limitations of this in vitro study, it was concluded that water storage with and without thermocycling caused deterioration in flexural strength of the tested veneering composites regardless of filler content and resin matrix composition. There was no deterioration in flexural strength of the reinforced structure as a result of water storage or thermocycling. Placement of reinforcing structure (i.e. glass-fiber framework) on the tension side significantly enhanced the flexural strength of the veneering composites. When building up frameworks for dental restorations, care should be taken to support the veneering material completely with a framework to limit its exposure to tensile stresses.

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