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Repairability of CAD/CAM high-density PMMA- and composite-based polymers

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Abstract: **OBJECTIVE** The study aimed to analyse the shear bond strength of computer-aided design and computer-aided manufacturing (CAD/CAM) polymethyl methacrylate (PMMA)- and composite-based polymer materials repaired with a conventional methacrylate-based composite after different surface pretreatments. **METHODS** Each 48 specimens was prepared from six different CAD/CAM polymer materials (Ambarino high-class, artBloc Temp, CAD-Temp, Lava Ultimate, Telio CAD, Everest C-Temp) and a conventional dimethacrylate-based composite (Filtek Supreme XTE, control) and aged by thermal cycling (5000 cycles, 5-55 °C). The surfaces were left untreated or were pretreated by mechanical roughening, aluminium oxide air abrasion or silica coating/silanization (each subgroup n = 12). The surfaces were further conditioned with an etchrinse adhesive (OptiBond FL) before the repair composite (Filtek Supreme XTE) was adhered to the surface. After further thermal cycling, shear bond strength was tested, and failure modes were assessed. Shear bond strength was statistically analysed by two- and one-way ANOVAs and Weibull statistics, failure mode by chi(2) test (p < 0.05). **RESULTS** Shear bond strength was highest for silica coating/silanization > aluminium oxide air abrasion = mechanical roughening > no surface pretreatment. Independently of the repair pretreatment, highest bond strength values were observed in the control group and for the composite-based Everest C-Temp and Ambarino high-class, while PMMA-based materials (artBloc Temp, CAD-Temp and Telio CAD) presented significantly lowest values. For all materials, repair without any surface pretreatment resulted in adhesive failures only, which mostly were reduced when surface pretreatment was performed. **CONCLUSIONS** Repair of CAD/CAM high-density polymers requires surface pretreatment prior to adhesive and composite application. However, four out of six of the tested CAD/CAM materials did not achieve the repair bond strength of a conventional dimethacrylate-based composite. **CLINICAL RELEVANCE** Repair of PMMA- and composite-based polymers can be achieved by surface pretreatment followed by application of an adhesive and a conventional methacrylate-based composite.

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Repairability of CAD/CAM high-density PMMA- and composite-based polymers

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Short title

Repairability of CAD/CAM-polymers

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Abstract

Objective: The study aimed to analyse the shear bond strength of CAD/CAM PMMA- and composite-based polymer materials repaired with a conventional methacrylate-based composite after different surface pretreatments.

Methods: Each 48 specimens were prepared from six different CAD/CAM polymer materials (Ambarino high-class, artBloc-Temp, CAD-Temp, Lava Ultimate, Telio CAD, Everest C-Temp) and a conventional dimethacrylate-based composite (Filtek supreme XTL, control) and aged by thermal cycling (5000 cycles, 5-55°C). The surfaces were left untreated or were pretreated by mechanical roughening, aluminium oxide air-abrasion or silica coating/silanization (each subgroup n=12). The surfaces were further conditioned with an etch&rinse adhesive (Optibond FL) before the repair composite (Filtek supreme XTL) was adhered to the surface. After further thermal cycling, shear bond strength was tested and failure modes were assessed. Shear bond strength was statistically analysed by two- and one-way ANOVA and Weibull statistics, failure mode by Chi²-test (p≤0.05).

Results: Shear bond strength was highest for silica coating/silanization> aluminium oxide air-abrasion=mechanical roughening>no surface pretreatment. Independently of the repair pretreatment, highest bond strength values were observed in the control group and for the composite-based Everest C-Temp and Ambarino high-class, while PMMA-based materials (artBloc-temp, CAD-Temp and Telio-CAD) presented significantly lowest values. For all materials, repair without any surface pretreatment resulted in adhesive failures only, which mostly were reduced when surface pretreatment was performed.

Conclusions: Repair of CAD/CAM high-density polymers requires surface pretreatment prior to adhesive and composite application. However, four out of six of the tested CAD/CAM materials did not achieve the repair bond strength of a conventional dimethacrylate-based composite.

Clinical Relevance: Repair of PMMA- and composite-based polymers can be achieved by surface pretreatment followed by application of an adhesive and a conventional methacrylate-based composite.

Key words

CAD/CAM polymer, repair, adhesive, PMMA, composite, shear bond strength, failure

Introduction

A range of polymer-based, pre-fabricated CAD/CAM-materials is currently available on the market for the construction of temporary and even permanent dental restorations. Pre-fabricated polymeric blanks are industrially polymerized under standardized conditions at high temperature and pressure to improve material properties compared to conventional polymerisation. Recent studies showed that the load-bearing capacity of 3-unit fixed partial prostheses (FDP) milled of polymethyl methacrylate (PMMA)-based CAD/CAM-blocks was significantly higher compared to manually processed ones and glass-ceramic FDPs [1-3]. Compared to conventionally-polymerized temporary materials, high-density polymers offer a wider range of translucency [4] and a higher stability against discoloration [5]. However, PMMA-based polymer materials indicated for temporary restorations present higher wear than resin-based polymeric composites indicated for permanent CAD/CAM restorations [6].

So far, CAD/CAM polymer restorations were successfully used for the pretreatment of complex cases, e.g. as diagnostic tool to reconstruct and stabilize an adequate vertical dimension of occlusion [7,8]. Schweiger et al. [9] suggested the use of replaceable veneers made from polymer materials on modified implant abutments to allow for an easy and quick replacement in case of chipping.

However, a clinical trial comparing CAD/CAM-manufactured composite resin crowns with ceramic crowns after 3 years of clinical service found significantly lower survival rates for the composite resin crowns [10].

Thus, longevity of polymer-based restorations – even of temporary ones – might also be affected by technical complications, such as chipping, wear or secondary caries, leading to clinical failures and requiring further operative treatment. However, no information on the reparability of polymer-based materials and the preferred intraoral repair method is available so far. Therefore, the aim of the present study was to evaluate the reparability of CAD/CAM

polymer materials after different surface pretreatments and to compare the shear bond strength of repaired polymer materials with a conventional dimethacrylate based composite. For surface pretreatment the most frequently used methods to condition the substrate in order to create mechanical retention (roughening, air-abrasion with aluminium oxide and silica coating) were used, which showed best performance in in vitro studies so far [11]. To address also the aspect of chemical bonding, the use of an adhesive (alone or in combination with the mechanical pretreatment) was also investigated. The null hypotheses tested were 1) the repair bond strength of polymer-based materials is not different from a conventional dimethacrylate-based composite and 2) the type of surface pretreatment does not affect shear bond strength.

Material and methods

Specimens preparation

Six types of CAD/CAM polymer materials and a conventional dimethacrylate-based composite were used in this study. The brands, batch numbers, manufacturers and chemical compositions of the materials are listed in Table 1.

The polymeric blocks were cut under water-cooling with a low-speed cutting wheel (Struers MOD 10, Struers, Ballerup, Denmark) into specimens of 15 mm edge length and 3.5 mm thickness (each material n = 48 specimens). The specimen surfaces were polished with water-cooled silicon carbide paper (P1000-P4000, Struers, Ballerup, Denmark).

Specimens of the control group (n = 48, Filtek Supreme XTE, 3M ESPE, USA) were fabricated incrementally using a silicone mould (15 mm x 15 mm x 3.5 mm). Each increment was light-cured for 20 s (Bluephase, Ivoclar Vivadent, Liechtenstein). Light intensity was assured to be higher than 1000 mW/cm² (Bluephase meter, Ivoclar Vivadent, Liechtenstein). The specimens were removed from the moulds and polished with silicone carbide papers (P1000-P4000).

All specimens were aged by thermal cycling prior to repair (Willytec, Munich, Germany; 5000 cycles, 5 to 55° C, dwell time: 20 s, transfer time: 10 s).

Thermocycled specimens were randomly assigned to one of the subgroups (each n = 12):

- (a) no treatment
- (b) Mechanical roughening simulating diamond bur abrasion. Surfaces were ground with a diamond disk (40 μm , Intensiv, Montagnola, Switzerland) at 1.3 N for 8 s.
- (c) Air-abrasion with aluminium oxide (50 μm , Renfert, Hilzingen, Germany) for 10 s at a distance of 10 mm (90°) and 2.8 bar air pressure. Remnants of air-abrasion were air blown.
- (d) Silica coating/silanization. Surfaces were silica coated (30 μm , CoJet, 3M ESPE, Seefeld, Germany) for 10 a at a distance of 10 mm (90°) and 2.8 bar air pressure. Loose particles were air blown. Silane coupling agent (Monobond Plus, Ivoclar Vivadent, Schaan, Liechtenstein) was applied and allowed to evaporate for 60 s as recommended by the manufacturer.

Then, all surfaces were further conditioned with an etch&rinse adhesive (Optibond FL, Kerr, Orange, USA), which was applied as recommended by the manufacturer and light cured for 20 s.

The repair composite (Filtek Supreme XTE) was adhered onto the specimen surface using acrylic hollow cylinders (inner diameter: 2.9 mm, height: 3.5 mm). The composite was packed against the surface in a 2 mm thick increment and light cured for 20 s by applying the curing unit directly onto the acrylic cylinder.

All specimens were then submitted to an additional thermal cycling procedure (5000 cycles, between 5 and 55° C, dwell time: 20 s, transfer time: 10 s). The set-up is illustrated in figure 1.

Shear bond strengths and failure analysis

Bond strength was tested with an universal testing machine (Z010, Zwick, Ulm, Germany). A shear force was applied to the adhesive interface through a chisel-shaped loading device at a crosshead speed of 1 mm/min. Load at debonding was recorded and shear bond strength σ was calculated using the load at failure F (N) and the adhesive area A (mm^2): $\sigma = F/A$.

The debonded area was examined for failure mode analysis with a stereomicroscope at 25x magnification (M3Z, Leica Microsystems, Wetzlar, Germany). Failure mode was considered as adhesive if it occurred at the interface, as cohesive if the failure affected at least parts of the polymer substrate or the repair composite or as mixed.

Statistical analysis

Shear bond strength (MPa) data were submitted to Kolmogorov-Smirnov and Shapiro-Wilk tests to check normal distribution of the data. Normal distribution was found in 89% of the subgroups (25 out of 28), thus, for all statistical tests a normal distribution assumption was employed. Two-and one-way ANOVAs followed by Scheffé post-hoc tests were performed (SPSS Version 20, SPSS INC, Chicago, IL, USA). Additionally, Weibull distribution parameters (Weibull modulus m , characteristic bond strength σ_0) were calculated using the maximum likelihood estimation method at 95% confidence level (MINITAB Version 14, State College, PA, USA) [12].

Relative frequencies of failure types together with the corresponding 95% confidence intervals according to the Ciba Geigy Tables were provided. A χ^2 test was used in order to analyse differences of failure types in different groups [13].

In all tests, level of significance was set at $p \leq 0.05$.

Results

Two-way ANOVA revealed the type of substrate, the repair pretreatment and the interaction between both factors to be significant with respect to shear bond strength. Generally, significantly highest bond strength values were obtained by silica coating/silanization (mean of all subgroups: 19.9 ± 7.3 MPa), followed by aluminium oxide sandblasting (15.8 ± 5.5 MPa) and mechanical roughening (15.3 ± 7.6 MPa), which were not significantly different from each other. Lowest bond strength values were obtained when no surface pretreatment was performed (4.8 ± 4.9 MPa).

Independently of the repair pretreatment, mean shear bond strength was highest for the control group (mean of all subgroups: 18.6 ± 7.6 MPa), Ambarino high-class (18.8 ± 8.6 MPa) and Everest C-Temp (18.2 ± 7.9 MPa), while all other CAD/CAM polymers exhibited significantly lower bond strength values (LAVA Ultimate: 13.3 ± 6.9 MPa; Telio CAD: 10.1 ± 7.3 ; CAD Temp: 9.7 ± 7.2 MPa, artBloc-Temp: 9.0 ± 6.7 MPa).

Shear bond strength values of all subgroups are presented in Table 2. Within one substrate, mean shear bond strength and characteristic strength σ_0 were lowest when no additional pretreatment was performed, while silica coating/silanization mostly resulted in highest values.

In general, lowest Weibull moduli were obtained for all CAD/CAM polymeric groups ($m = 0.2 - 1.8$) and the control group ($m = 3.8$) without any pretreatment. Mechanical roughening of Everest C-Temp ($m = 11.0$) and silica coating of Ambarino high-class ($m = 9.3$) showed the highest Weibull moduli. The Weibull statistics are presented in Table 2.

Comparisons between the substrates within one repair pretreatment also showed highest shear bond strength values and characteristic strengths σ_0 for Filtek Supreme XTE, Everest C-Temp and Ambarino high-class. artBloc-temp, CAD-Temp and Telio-CAD presented significantly lowest shear bond strength values characteristic strength σ_0 , independently of the pretreatment.

Failure types were significantly different among the groups (Chi²-test: $p < 0.05$). For all materials, repair without any surface pretreatment resulted in adhesive failures only. Except for artBloc-Temp and Telio-CAD, any kind of surface pretreatment reduced the amount of adhesive failures (Table 3)

Discussion

This study showed that polymeric CAD/CAM materials require mechanical surface pretreatment - ideally in form of silica coating/silanization - prior to repair, and that Fibreglas-reinforced polymers and nanofilled composites but not PMMA-based materials achieve repair

bond strength values comparable to a conventional dimethacrylate-based composite used for direct restorations. Thus, both null hypotheses were rejected.

Shear bond strength values of Filtek Supreme XTE were in accordance to previous studies [14,15] and used as a reference value for the CAD/CAM repair. Although it is difficult to define a clinically relevant value for bond strength after repair, most in vitro studies presented repair bond strength values of dimethacrylate-based direct composites of at least 20 MPa, depending on the kind of composite material and the repair method [15]. Mean repair bond strength of Filtek Supreme XTE amounted to 18.6 MPa and was even higher, when the repair surface was pretreated mechanically instead of conditioned with an adhesive system only, thus presenting an adequate reference for the repair of CAD/CAM polymers.

As repair restorations usually become necessary after months or years of clinical service and require long-term stability, both the substrate and the repaired specimens were extensively aged by thermocycling. Shear bond strength of repaired dimethacrylate-based direct composites is significantly decreased by aging and affected by the kind of aging condition [16,17]. Adhesion between PMMA-based polymer restorations and conventional resin cements has also shown to be impaired by aging [18], indicating that thermocycling might further reduce the residual monomer content by reducing the number of carbon-carbon double bonds. Moreover, thermocycling might lead to mechanical stress on the bonding area of the repaired substrate. However, it is also discussed that thermocycling might increase the repair bond strength by intensifying the process of post-polymerisation between polymeric CAD/CAM materials and adhesive resins [19].

Adhesion was tested only on the pure polymer substrate, not taking into account that under clinical conditions the defective restoration is often surrounded by dental hard tissue, which also needs to be conditioned prior to application of the repair material. Mixed surfaces might be more difficult to repair [20], and need to be investigated in further studies.

Generally, this study showed that adhesive conditioning alone without micromechanical retention is not adequate to obtain sufficient repair bond strength, especially when PMMA-based materials are considered. As industrially polymerized materials present a high degree

of conversion, it can be assumed that the amount of residual monomer or free radicals is very low or even insufficient to allow for co-polymerisation. Moreover, monomers of the adhesive system (Bis-GMA, HEMA; GDMA) and of the composite (Bis-GMA, UDMA, TEGDMA, bis-EMA(6)) might not co-polymerise with PMMA-based materials [18].

Mechanical pretreatment prior to adhesive application increased repair bond strength of all materials. Based on the above mentioned, it is likely that the repair bond strength of PMMA-based materials is mainly depending on micromechanical retention rather than on a chemical interaction between PMMA and the adhesive. Stawarczyk et al. [21] showed that the bond strength between air-abraded PMMA-based polymer and a hybrid composite was not further increased by adhesive conditioning. In contrast, another study demonstrated that without further conditioning no adhesion between air-abraded CAD/CAM polymers and resin composite cements could be achieved [19,21].

In contrast to the PMMA-based materials, the fibreglas-reinforced polymer and the polymers based on Bis-GMA and/or UDMA resulted in repair bond strength values similar to the control. In these cases, the adhesive might penetrate into the surface irregularities improving mechanical retention and at the same time bond to silane-coated filler particles of the polymer. Compared to the PMMA-based polymers the filler content of Lava Ultimate and Ambarino high-class is significantly higher, thus explaining higher bond strength values. Silane application after silica coating might further increase bond strength as it enhances wettability of the substrate and establish bonding between unreacted monomers and inorganic fillers or silica coated surfaces, respectively [22].

Lava Ultimate (UDMA-based polymer) showed slightly lower repair bond strength values compared to Ambarino high-class (Bis-GMA, UDMA) and Everest C-Temp (fibreglas-reinforced polymer). Provided that dimethacrylate resins are polymerized under the same experimental conditions, UDMA showed a higher degree of conversion and a polymerization rate than Bis-GMA, indicating that further co-polymerisation might be more difficult for UDMA [23].

Within the limitations of this in vitro study it is concluded that CAD/CAM polymers can be repaired after adequate mechanical surface pretreatment, ideally silica coating/silanization. However, repair bond strength values of PMMA-based materials are significantly lower than of methacrylate-based direct composites.

Conflict of interest

The authors declare that they have no financial or other relationships that might lead to actual or potential conflict of interest. The major parts of this study were self-funded by the authors and their institutions. The polymer and composite materials used were provided by the manufacturers.

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Figure 1 Set-up of specimen preparation

Cutting (A) and polishing (B) of polymeric blocks followed by thermocycling (C). Specimens were pretreated by mechanical roughening, aluminium oxide air-abrasion or silica coating/silanization (D) or left untreated before the adhesive (E) was applied and light-cured. An acrylic cylinder was fixed on the specimens surface (F) and filled with the repair composite (G) followed by additional thermocycling (H) and shear bond strength testing (I).

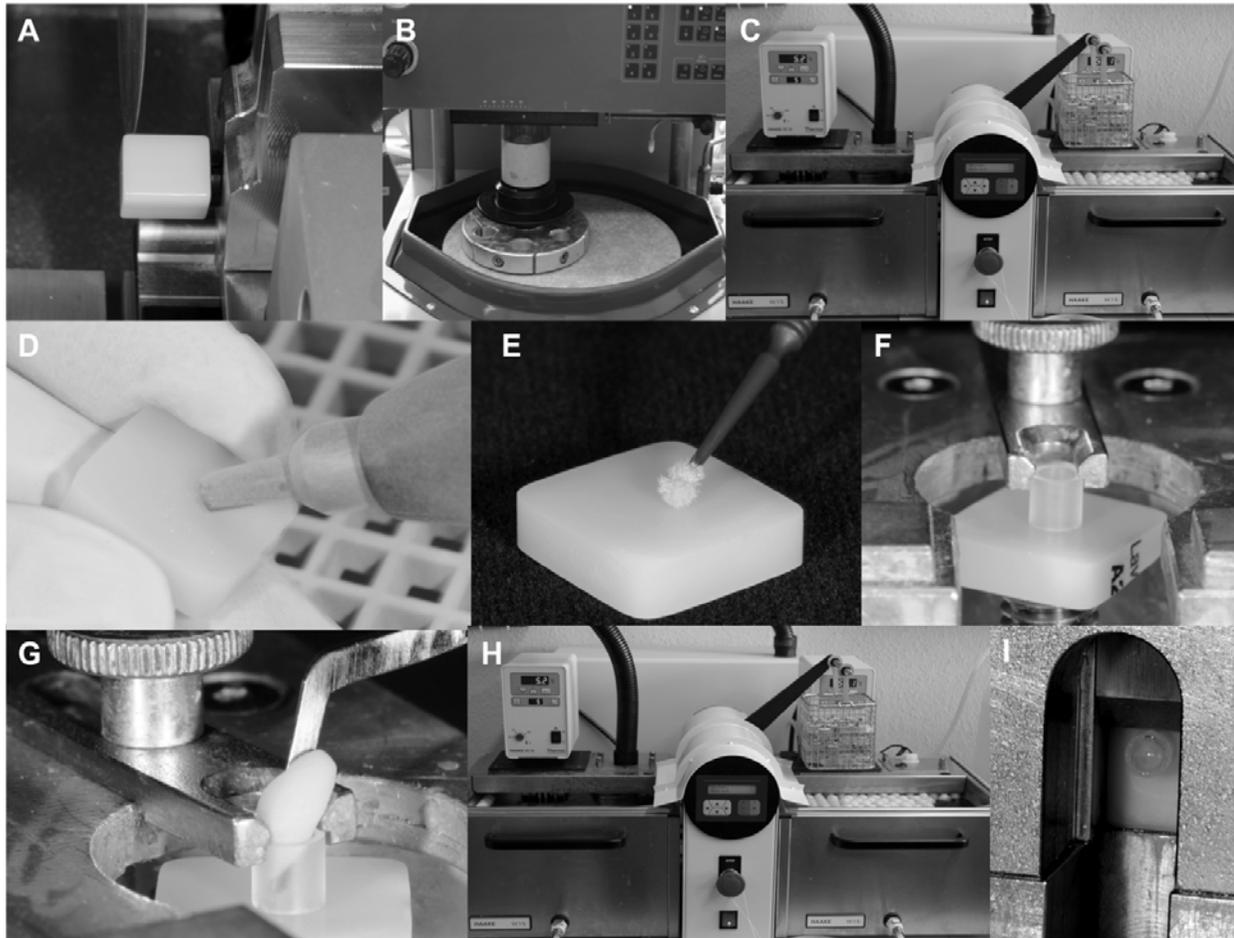


Table 1: Materials, manufacturers, composition and indication of the different materials used in this study.

Material	Manufacturer	Lot-No	Composition	Indication
Ambarino high-class	Creamed, Marburg, Germany	090313	Highly crosslinked Bis-GMA, UDMA, Butandiol dimethacrylate, 70.1 wt% anorganic silica nanofillers	Definitive inlay, onlay, veneer, partial crown and crown restorations, FDP (max. 3 unit), telescopic prostheses, tertiary structures
artBloc-Temp	Merz Dental, Lütjenburg, Germany	22813	Highly-crosslinked PMMA (OMP: organically modified polymer network), no fillers	Long-term temporization of crowns, partial crowns, bridges (3 units) and implant restoration
CAD-Temp	VITA Zahnfabrik, Bad Säckingen, Germany	-	83-86 wt% PMMA, 14 wt% micro-filler (silica), pigments (<0.1%)	Multi-unit, fully or partially anatomical long-term temporary bridges with up to 2 pontics
Telio CAD	Ivoclar Vivadent, Schaan, Liechtenstein	S20793	99.5 wt% PMMA, no fillers, pigment (<1 wt%)	Temporary crowns and bridges and implant-supported restorations
Everest C-Temp	KaVo, Biberach, Germany	5310	Fibreglas-reinforced polymer	Long-term temporary restorations, bridge frameworks for up to 6 units
Lava Ultimate	3M ESPE, Rüslikon, Switzerland	N490809	UDMA, Resin Nano Ceramic containing approximately 79 wt% nanoceramic particles	Permanent, single-unit restorations (crowns, implant-crowns, onlay, inlay, veneer)
Filtek Supreme XTE (control)	3M ESPE, Rüslikon, Switzerland	N344843	Bis-GMA, UDMA, TEGDMA, bis-EMA(6), silica fillers, zircona fillers	Direct anterior and posterior restorations (including occlusal surfaces), Core build-ups, Splinting, Indirect restorations (including inlays, onlays and veneers)

Table 2: Shear bond strength (mean \pm standard deviation) and Weibull parameters (95% confidence intervals) in the different groups.

Material	Repair pretreatment	Mean \pm SD	95% CI	Weibull Modus (95% CI)	Characteristic strength (95% CI)
Ambarino	none	7.6 \pm 4.9 ^{a/BC}	4.3;10.7	1.5 (0.8;2.5) ^{a/B}	8.3 (5.5;12.3) ^{a/BC}
	roughening	20.8 \pm 4.6 ^{b/BC}	17.7;23.8	5.5 (3.4;8.7) ^{b/BC}	22.6 (20.1;25.2) ^{b/BC}
	Al ₂ CO ₃ air-abrasion	20.0 \pm 6.3 ^{b/B}	15.9;24.1	3.8 (2.2;6.0) ^{ab/A}	22.2 (18.8;26.1) ^{b/B}
	SiO ₂ coating	26.9 \pm 3.5 ^{c/B}	24.5;29.2	9.3 (5.8;14.5) ^{b/B}	28.4 (26.4;30.3) ^{c/C}
artBloc-Temp	none	0.0 \pm 0.0 ^{a/A}	0.0;0.0	-	-
	roughening	9.0 \pm 3.3 ^{b/C}	6.8;11.1	3.3 (2.0;5.3) ^{a/B}	10.0 (8.2;12.1) ^{a/A}
	Al ₂ CO ₃ air-abrasion	11.7 \pm 4.4 ^{bc/A}	8.8;14.5	3.0 (1.8;4.5) ^{a/A}	13.1 (10.5;16.1) ^{ab/A}
	SiO ₂ coating	15.3 \pm 4.4 ^{c/A}	12.4;18.2	4.2 (2.5;6.6) ^{a/AB}	16.9 (14.5;19.5) ^{b/A}
CAD-Temp	none	2.2 \pm 3.6 ^{a/A}	-0.1;4.5	0.2 (0.1;0.4) ^{a/A}	0.2 (0.0;2.0) ^{a/A}
	roughening	8.1 \pm 4.0 ^{ab/C}	5.5;10.6	2.2 (1.2;3.7) ^{b/AB}	9.1 (6.9;11.9) ^{b/A}
	Al ₂ CO ₃ air-abrasion	13.0 \pm 3.7 ^{bc/AB}	10.6;15.4	3.5 (2.3;5.2) ^{b/A}	14.4 (12.0;17.1) ^{bc/A}
	SiO ₂ coating	15.7 \pm 8.2 ^{c/A}	10.4;20.9	2.1 (1.2;3.3) ^{b/A}	17.6 (13.0;23.5) ^{c/AB}
Telio CAD	none	1.1 \pm 2.6 ^{a/A}	-0.6;2.8	0.2 (0.1;0.4) ^{a/A}	0.1 (0.0;0.4) ^{a/A}
	roughening	8.4 \pm 4.6 ^{b/C}	5.4;11.3	1.1 (0.5;1.8) ^{b/A}	8.4 (4.7;14.6) ^{b/A}
	Al ₂ CO ₃ air-abrasion	15.8 \pm 4.7 ^{c/AB}	12.8;18.8	4.0 (2.4;6.2) ^{c/A}	17.5 (15.0;20.4) ^{c/AB}
	SiO ₂ coating	15.0 \pm 5.2 ^{c/A}	11.7;18.3	3.4 (2.0;5.3) ^{c/A}	16.7 (14.0;20.0) ^{bc/A}
Everest C-Temp	none	9.4 \pm 5.3 ^{a/C}	6.0;12.8	1.8 (1.0;2.9) ^{a/B}	10.5 (7.4;14.6) ^{a/C}
	roughening	21.1 \pm 2.1 ^{bc/BC}	19.7;22.6	11.0 (7.0;17.0) ^{b/C}	22.1 (20.8;23.4) ^{b/C}
	Al ₂ CO ₃ air-abrasion	16.2 \pm 5.6 ^{b/AB}	12.6;19.8	3.2 (2.0;4.9) ^{ab/A}	18.1 (14.8;21.8) ^{b/AB}
	SiO ₂ coating	26.0 \pm 6.3 ^{c/B}	21.9;30.0	5.5 (3.3;9.0) ^{b/AB}	28.2 (25.2;31.5) ^{c/C}
LAVA Ultimate	none	4.2 \pm 2.4 ^{a/AB}	2.6;5.8	1.9 (1.1;3.0) ^{a/B}	4.7 (3.3;6.5) ^{a/B}
	roughening	15.9 \pm 5.3 ^{b/B}	12.5;19.3	3.8 (2.2;6.2) ^{ab/B}	17.7 (15.0;20.7) ^{bc/B}
	Al ₂ CO ₃ air-abrasion	14.4 \pm 3.3 ^{b/AB}	12.2;16.5	5.3 (3.2;8.3) ^{b/A}	15.6 (13.8;17.6) ^{b/A}
	SiO ₂ coating	18.8 \pm 5.1 ^{b/AB}	15.5;22.1	4.5 (2.7;7.1) ^{ab/AB}	20.7 (18.0;23.7) ^{c/AB}
Filtek Supreme XTE (control)	none	8.8 \pm 2.7 ^{a/BC}	7.0;10.6	3.8 (2.3;6.1) ^{a/B}	9.7 (8.2;11.4) ^{a/C}
	roughening	23.8 \pm 5.5 ^{b/C}	20.2;27.3	4.9 (3.0;7.7) ^{a/BC}	25.9 (22.8;29.3) ^{b/C}
	Al ₂ CO ₃ air-abrasion	19.9 \pm 4.6 ^{b/B}	16.9;22.8	5.1 (3.1;8.0) ^{a/A}	21.6 (19.1;24.4) ^{b/B}
	SiO ₂ coating	21.8 \pm 6.5 ^{b/AB}	7.7;26.0	4.6 (2.6;7.7) ^{a/AB}	23.7 (20.8;27.0) ^{b/BC}

Significant differences between the different surface pretreatments within one material are marked with different small letters. Significant differences between the different materials within the same surface pretreatment are marked by different capital letters.

Table 3: Relative frequencies of failures (95% confidence intervals) in the different subgroups.

Material	Repair pretreatment	Adhesive (%)	Cohesive (%)	Mixed (%)
Ambarino	none	100 (72;100)	0 (0;27)	0 (0;27)
	roughening	50 (20;79)	0 (0;27)	50 (20;79)
	Al ₂ CO ₃ air-abrasion	17 (1;49)	33 (8;66)	50 (20;79)
	SiO ₂ coating	8 (0;39)	75 (41;95)	17 (1;49)
artBloc-Temp	none	100 (72;100)	0 (0;27)	0 (0;27)
	roughening	100 (72;100)	0 (0;27)	0 (0;27)
	Al ₂ CO ₃ air-abrasion	100 (72;100)	0 (0;27)	0 (0;27)
	SiO ₂ coating	100 (72;100)	0 (0;27)	0 (0;27)
CAD-Temp	none	100 (72;100)	0 (0;27)	0 (0;27)
	roughening	100 (72;100)	0 (0;27)	0 (0;27)
	Al ₂ CO ₃ air-abrasion	67 (33;91)	0 (0;27)	33 (8;66)
	SiO ₂ coating	83 (50;98)	0 (0;27)	17 (1;49)
Telio CAD	none	100 (72;100)	0 (0;27)	0 (0;27)
	roughening	100 (72;100)	0 (0;27)	0 (0;27)
	Al ₂ CO ₃ air-abrasion	100 (72;100)	0 (0;27)	0 (0;27)
	SiO ₂ coating	100 (72;100)	0 (0;27)	0 (0;27)
Everest C-Temp	none	100 (72;100)	0 (0;27)	0 (0;27)
	roughening	33 (8;66)	0 (0;27)	67 (33;91)
	Al ₂ CO ₃ air-abrasion	42 (14;73)	0 (0;27)	58 (26;85)
	SiO ₂ coating	17 (1;49)	0 (0;27)	83 (50;98)
LAVA Ultimate	none	100 (72;100)	0 (0;27)	0 (0;27)
	roughening	67 (33;91)	0 (0;27)	33 (8;66)
	Al ₂ CO ₃ air-abrasion	67 (33;91)	0 (0;27)	33 (8;66)
	SiO ₂ coating	67 (33;91)	0 (0;27)	33 (8;66)
Filtek Supreme XTE (control)	none	100 (72;100)	0 (0;27)	0 (0;27)
	roughening	25 (4;58)	50 (20;79)	25 (4;58)
	Al ₂ CO ₃ air-abrasion	0 (0;27)	25 (4;58)	75 (41;95)
	SiO ₂ coating	8 (0;39)	67 (33;91)	25 (4;58)

Cohesive failures occurred solely in the substrate and not in the repair composite.