Shear bond strength of veneering composite to high performance polymers

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High performance polymers like PEEK (polyetheretherketone) and FRC (fiberreinforced composite) could substitute metallic alloys for removable partial dentures. However, these polymers require aesthetic veneering. This study was to determine the bond strength to direct composite. Specimens made of PEEK and FRC were produced and air-abraded (50 μm aluminum-oxide). Specimens were allocated to four experimental groups: Luxatemp Glaze & Bond, Scotchbond Universal, SR Nexco Connect and iBond Universal. Specimens were divided into three subgroups for short-term, long-term and no artificial aging and shear bond strength (SBS) was evaluated. SBS of specimens made of PEEK with no artificial aging showed values between 10.79–14.00 MPa, short-term artificial aging resulted in values between 3.78–13.85 MPa and after long-term artificial aging SBS decreased to 0–8.75 MPa. SBS measurement of FRC specimens resulted in values between 9.83–12.1 MPa without aging, after short-term artificial aging values decreased to 8.36–11.98 MPa and after long-term aging SBS showed a degradation to 4.52–7.82 MPa.

Keywords: PEEK, Fiber-reinforced composite, Shear bond strength, Adhesion, EDS-analysis

INTRODUCTION

In many cases, prosthodontic dentures, such fixed dental prostheses (FDPs) and removable partial dentures, require a supporting substructure in order to increase mechanical stability and thus ensure longevity.

Usually, these frameworks for FDPs are made of metal alloys or ceramics. However, for the fabrication of FDPs with metal frameworks, a distinction must be made between alloys containing gold and alloys not containing precious metals. Chromium-cobalt molybdenum alloys and, less frequently, titanium are used as frameworks for various types of partial dentures. All these metals used for frameworks made it possible to apply a tooth-colored resin composite veneer or ceramic veneer.

The gold standard of metal-ceramic restorations has been replaced by all-ceramic restorations for aesthetically demanding, high-quality fixed dentures. Frameworks made of oxide ceramics meet both mechanical and esthetic requirements. But it is difficult to construct removable partial dentures without metal alloys as the framework material.

The desire for completely tooth-colored dental prostheses has grown mainly due to increasing aesthetic demands. In addition, there are also medically proven allergies and hypersensitivities to metallic alloys, which then force the dentist and dental technician to develop alternative solutions. The search, further development and scientific investigation of possible substitute materials, especially in the field of tooth-colored materials, is therefore necessary.

The production of polymer-based blanks for the CAD/CAM fabrication of dental prostheses is a logical extension of the therapeutic spectrum.

PEEK polymers belong to the group of thermoplastics and are further classified as polyaryl ether ketones. They differ from the polyetherketoneketones only by the ether groups.

PEEK was able to prove its chemical stability and thus its good biocompatibility in vitro but also in vivo. The good milliability and thus economical processing as well as the grey to white color of PEEK also make it interesting for applications in the dental field.

The attractiveness of PEEK in both orthopaedics and dental implantology is due to its bone-like modulus of elasticity. With pure PEEK, this is approximately 3–4 GPa and corresponds approximately to the lower modulus of elasticity of human bone (24.2 GPa).

In contrast to the positive properties, the connection to other dental and dental materials poses a problem. The problem is the inertness of the material, which makes it difficult to bond with other polymers. A direct chemical bond from PEEK to composite does not seem possible. All previous studies agree that an increase in surface roughness is necessary to achieve better wettability and additional bonding is necessary. Some studies are therefore focusing on different surface treatments and others on bonding agents to produce a durable bond.

Nevertheless, in recent years, PEEK has increasingly been used in dentistry due to its positive material properties. Examples are temporary implant abutments, framework materials for fixed and
removable dentures\textsuperscript{27} and retention and friction elements of various kinds. Further dental implant systems made of PEEK are currently being tested\textsuperscript{2,28}. All in contrast to PEEK, for fiber-reinforced composite (FRC) only few products of this type are currently available for prosthetic applications in the fabrication of dental prostheses. For instance, Trilor (Bioloren Srl, Sareno, Italy) and Trinia (Bicon Dental Implants, Boston, MA, USA) are currently available as millable materials. Trilor, which was used in this study, consists of multidirectional glass fibre mats embedded in an epoxy resin matrix. The millable blocks and discs are colored with titanium dioxide.

These composites basically consist of at least two components—a polymer matrix and fibers with differing fiber orientation, fiber content, and geometry\textsuperscript{29-32}. They offer several advantages, such as increased strength and stiffness, which makes them interesting for use in dentistry\textsuperscript{29}.

However, some clinically important parameters of this new material group have already been investigated. There are indications that FRC leads to a comparatively higher marginal gap for endocrowns in a \textit{in vitro} study compared to ceramic materials after CAD/CAM production\textsuperscript{33}. Nevertheless, studies on these two materials are rare overall\textsuperscript{34,35} and bonding strategies are needed. Both to tooth surface but also to direct composites for esthetic veneering.

This study was intended to assess the influence of different adhesive systems on the bond strength of composites to high-performance polymers (PEEK, FRC). Different periods of artificial aging and their influence on shear bond strength (SBS) should also be investigated. The null hypothesis that artificial aging has no influence on SBS was statistically evaluated.

### MATERIAls And METHODS

#### Fabrication of specimens

After a preliminary test and case number planning, the group sizes were set to \(n=12\) (data not shown). The specimens were designed with the support of computer-aided-manufacturing (CAM) software (Dental Softworks, Version 1.2, Dental Softworks, Wahlsburg, Germany). The size of the test specimens was set to 10 mm diameter and 5 mm thickness. Ninety-six specimens made of PEEK (LuxaCam PEEK, DMG, Hamburg, Germany; Lot No. 748023) blanks; 98 mm diameter) and 96 specimens made of FRC (Trilor, Bioloren; Lot No. 1303; 98 mm diameter) blanks (98 mm diameter) were produced via CAD/CAM. All specimens were air-abraded with 50 μm aluminum oxide particles at 10 mm distance and 2 bar pressure for 20 s.

#### Bonding procedure

The 156 specimens (diameter of 10 mm and thickness of 5 mm) of each material were randomly allocated to five experimental groups according to the adhesive system used: LG, Luxatemp Glaze & Bond (DMG); SR, SR Nexco Connect (Ivoclar Vivadent, Schaan, Liechtenstein); SU, Scotchbond Universal Adhesive (3M OralCare, Seefeld, Germany), and IU iBond Universal (Kulzer, Hanau, Germany) (Table 1). A negative control (NC) with air abrasion and no adhesives was only included in the tests without artificial aging. All adhesive systems were applied according to the manufacturer’s instructions and were polymerized. The veneering composite Nexco Paste (Ivoclar Vivadent) was applied manually in plexiglass tubes (inner diameter of 5 mm) and polymerized.

#### Artificial aging and SBS testing

The manufactured specimens were divided into three groups of artificial aging. One group was kept in a artificial saliva (Aqua bidest1 mol Potassium chloride, 150 mmol Calcium chloride, 90 mmol Potassium...
dihydrogen phosphate) for 24 h without any further methods of artificial aging. In the group for short-term artificial aging, specimens were stored for 14 days in artificial saliva at 37°C and then exposed to 5,000 thermal cycles between 5 and 55°C (THE10000, SD Mechatronik, Feldkirchen-Westerham, Germany). In long-term artificial aging, the specimens were stored in the solution for 200 days and then subjected to 37,500 cycles (5 and 55°C).

After artificial aging, SBS was evaluated with a universal testing machine (TA.HDplus, Stable Micro Systems, Godalming, UK) at constant crosshead speed of 2 mm/min (Fig. 1).

**Analysis of the failure mode**

Subsequently, the failure modes were analyzed by light-microscopy and classified as adhesive, cohesive or partially cohesive. Selected test specimens were additionally examined by scanning electron microscopy (SEM) coupled electron dispersive spectroscopy (EDS). SEM was carried out at 20 kV acceleration voltage using the backscattered electron detector. For EDS analysis, an Apollo XL detector (EDAX, Mahwah, NJ, USA) with the software Team V4.2.2 was used. The signal for silicium (Si) was used to detect adhesive and composite residuals and the signal for aluminum (Al) and titanium (Ti) for free specimen surfaces. In the case of FRC (Trilor), calcium (Ca) was additionally analyzed as an indication of exposed glass fiber structures. To analyze the entire specimen surface, 20 individual images were needed, which were then assembled using Adobe Photoshop (Adobe Photoshop CS6, Adobe Systems, San José, California, USA).

**Statistical analysis**

The SBS data were used to test the hypothesis that there is no difference between the methods of artificial aging when using an adhesive system.

The measured data were evaluated using GraphPad Prism (Version 8.31, GraphPad Software, La Jolla, CA, USA) as software. Normal distribution was checked using the Kolmogorov-Smirnov test. As data were normally distributed the one-way ANOVA with Tuckey correction was used for statistical evaluation. The significance level was determined to be $p \leq 0.05$.

**RESULTS**

**Measurement of SBS**

In a comparison of the bond strength values from the short- and long-term tests of composite to PEEK, all adhesive systems showed lower values after prolonged artificial aging (Fig. 2a, Table 2). Both PEEK and FRC specimens showed a decrease in SBS values after prolonged artificial aging. In most cases, these differences were also significant, the corresponding median values and levels of significance are shown in Fig. 2 and Tables 2 and 3. The highest SBS values from PEEK to composite were achieved with Scotchbond universal and Luxatemp Glaze & Bond. The adhesive bond seems to be convincing even with prolonged artificial ageing. Likewise, the SBS values between FRC and composite are highest and most durable with Scotchbond universal. The results of iBond
Table 2  Descriptive analysis (median, percentile, minimum, maximum, significance) of PEEK SBS (MPa) in comparison of no artificial aging, short-term and long-term tests sequences; significant differences are highlighted in gray

| Artificial aging       |  n  | Median  | 25% Percentile | 75% Percentile | Minimum | Maximum | Significance p≤0.05 |
|------------------------|-----|---------|----------------|----------------|---------|---------|-------------------|
| Luxatemp-Glaze & Bond  | non | 12      | 10.79          | 09.70          | 12.18   | 13.90   | 09.25             |
|                        | short| 12      | 10.01          | 08.76          | 10.71   | 06.73   | 13.39             | 0.0834 <0.0001 |<0.0001 |
|                        | long | 12      | 05.95          | 05.44          | 07.30   | 04.44   | 09.41             |
| SR Nexco Connect       | non | 12      | 11.99          | 09.47          | 13.34   | 08.97   | 14.99             | 0.0063 <0.0001 |<0.0001 |
|                        | short| 12      | 09.84          | 08.86          | 10.22   | 08.25   | 11.58             |<0.0001 <0.0001 |
|                        | long | 4*      | 01.91          | 01.84          | 01.97   | 01.83   | 01.97             |
| Scotchbond Universal   | non | 12      | 14.00          | 12.37          | 14.70   | 10.74   | 15.99             | 0.9216 <0.0001 |<0.0001 |
|                        | short| 12      | 13.85          | 12.76          | 15.10   | 10.08   | 15.75             |<0.0001 <0.0001 |
|                        | long | 12      | 08.75          | 07.42          | 09.82   | 04.58   | 12.80             |
| iBond Universal        | non | 12      | 11.27          | 09.28          | 12.48   | 08.45   | 13.05             |<0.0001 <0.0001 |
|                        | short| 12      | 03.78          | 00.63          | 03.96   | 00.23   | 04.73             |<0.0001 <0.0001 |
|                        | long | 3*      | 01.05          | 01.01          | 01.48   | 01.01   | 01.48             |0.3613 <0.0001 |
| Negative control       | non | 12      | 09.77          | 08.35          | 11.05   | 06.17   | 11.42             |— —                      |

Table 3  Descriptive analysis (median, percentile, minimum, maximum, significance) of FRC SBS (MPa) in comparison of no artificial aging, short-term and long-term tests sequences; significant differences are highlighted in gray

| Artificial aging       |  n  | Median  | 25% Percentile | 75% Percentile | Minimum | Maximum | Significance p≤0.05 |
|------------------------|-----|---------|----------------|----------------|---------|---------|-------------------|
| Luxatemp-Glaze & Bond  | non | 12      | 09.83          | 08.35          | 10.64   | 07.14   | 11.83             | 0.3412 0.0005 <0.0001 |
|                        | short| 12      | 08.36          | 06.30          | 10.37   | 05.16   | 12.20             |
|                        | long | 12      | 04.78          | 03.64          | 06.34   | 02.74   | 09.38             |
| SR Nexco Connect       | non | 12      | 11.14          | 09.83          | 12.14   | 08.46   | 13.24             | 0.0439 0.0001 <0.0001 |
|                        | short| 12      | 09.70          | 07.26          | 10.80   | 06.86   | 12.69             |<0.0001 <0.0001 |
|                        | long | 12      | 04.55          | 03.30          | 05.25   | 02.56   | 08.25             |
| Scotchbond Universal   | non | 12      | 12.10          | 11.38          | 13.98   | 10.18   | 16.74             | 0.5337 0.0181 0.0010 |
|                        | short| 12      | 11.49          | 09.14          | 13.11   | 08.01   | 17.44             |<0.0001 0.0010 |
|                        | long | 12      | 07.82          | 06.72          | 11.01   | 04.98   | 12.53             |
| iBond Universal        | non | 12      | 11.99          | 10.41          | 13.38   | 09.39   | 14.16             | 0.9373 <0.0001 |
|                        | short| 12      | 11.98          | 10.66          | 13.48   | 09.33   | 14.08             |<0.0001 |
|                        | long | 12      | 04.52          | 04.25          | 05.26   | 03.00   | 06.84             |
| Negative control       | non | 12      | 08.03          | 07.19          | 09.09   | 05.87   | 09.58             |— —                      |

*Less than 12 specimens were available for statistical analysis because failure occurred during thermal cycling.

Universal with PEEK led to not significant differences because only 3 complete specimens were available, and the adhesive bond of 9 specimens had already dissolved during thermal cycling.

Failure mode
For each test group, all specimens were analyzed for the failure mode after SBS measurement. No cohesive fracture of the specimen surface was detected. The adhesive and partially cohesive modes are shown in the following diagram (Fig. 3).

SEM and EDS analysis
Untreated and air-abraded specimens made of PEEK
Fig. 3  Percentage diagram of failure modes in the long-term test.

and Trilor were examined by SEM and EDS analysis prior to treatment with adhesive systems. In the first step, the relevant elements were identified (Fig. 4).

The images, assembled from twenty photographs, show the bonding area between PEEK and Luxatemp Glaze & Bond after SBS testing in the long-term trial. The test specimen showed a partially cohesive failure mode to the composite. The magenta-colored areas represent silicium, which indicates the remaining composite residues (Fig. 5a). The yellow areas show
titanium, which was contained in PEEK by the whitener titanium dioxide. An adhesive fracture occurred on these surfaces.

In this EDS analysis (Fig. 5b), aluminum is shown in addition to silicium. The aluminum particles on the test specimen surface were preserved by air abrasion with aluminum oxide. Due to the persistent aluminum elements, a cohesive fracture in the base material appears unlikely.

The SEM image shown in Fig. 5c shows the multidirectional glass fiber networks embedded in an epoxy resin matrix of FRC as well as approximately circularly persisting composite residues.

In the superimposed image (Fig. 5d) of the entire adhesive surface with the signal of silicium and calcium, the exposed glass fibers in red (calcium) and silicium confirmed composite residues are visible. Titanium (shown in yellow) is also clearly visible in the area of the epoxy resin matrix. The fracture analysis via the EDS image therefore indicates a partial, cohesive failure pattern.

**DISCUSSION**

The present study was conducted in vitro and therefore allows only limited conclusions to be drawn about the clinical behavior. In the oral cavity, teeth and of course dental materials are exposed to different stresses. The saliva can cause the materials to absorb water and temperature fluctuations, chemical influences and chewing forces can all contribute to material stress and material failure. These influences on dental materials should be simulated as well as possible in in vitro experiments. However, uniform standard for this type of in vitro material testing does not yet exist. Therefore, when comparing with other studies, the parameters of artificial aging as well as the type of adhesive bond measurement must always be taken into account.

Mostly, the methods of artificial aging consist of water storage and thermal cycling. The period of water storage and the exposure to thermal stress often differ in study design. In previous studies it has already been shown that thermocycling has the greatest influence on the adhesive bond of different materials. However, it has also been reported that a longer period of water storage can lead to a lower bond strength. In our study design, specimens were subjected to an ascending load by artificial aging. This consisted of water storage and thermocyclization. During water storage, not distilled water as usual, but a mineral solution similar to saliva was used. Evidence that artificial saliva leads to different results than distilled water during storage is still outstanding.

In general, the method of the SBS measurement has to be considered critically. In addition to various shear tests, tensile bond strengths (TBS) tests are also analyzed in studies. Some authors also see micro measurement techniques as superior to conventional SBS or TBS testing. The choice of material, the manufacturing process and the geometry of the test specimens also have an influence.

To come as close as possible to clinical use in material tests, it is highly important to adhere to a strict protocol during the production of the specimens, which also corresponds to a later validated workflow. In most studies, the specimens of material blocks are sawed for practical reasons. This appears unproblematic with homogeneous materials such as PEEK, since the surface can later be treated by further surface treatments, such as air abrasion or chemical etching, in accordance with the clinical requirements. In the case of a multiphase, millable material such as FRC, sawing is not appropriate for producing the specimens. The multidirectional fiber networks could be cut in different ways from specimen to specimen, resulting in irregular results in later investigations. For this reason, the specimens in this study were manufactured using CAD/CAM to simulate the dental technical processes as accurately as possible in later clinical use.

In the evaluation of in vitro experiments, the question often arises as to which results are necessary to recommend a clinical application. Unfortunately, this question cannot be conclusively clarified because the measurement of the bond strengths only reflects the clinical situation in a model manner. There are expert estimates that the average of SBS to a veneering should exceed 10 MPa. However, a study from the 1980s could provide a scientific approach to answer this question although this manuscript delivers low evidence. The authors state that that the bond between the dental materials should have shear bond strengths of 8–10 MPa. This assumption is justified by the occurring chewing forces, which are mainly perpendicular to the bonding surfaces. In the cited study, chewing forces of a maximum of 600 N are assumed. Assumed that the adhesion surfaces of a crown are approximately 60 mm², the measured bond strength values would have to be above 6 MPa in order to be suitable for clinical use. In more recent studies, lower chewing forces of approx. 200–300 N were also measured, which would result in lower demands on the bond strength of various materials.

To classify the results achieved in this study, similar studies must be consulted. To the authors’ knowledge, this is the first study on the bond between composite and FRC and the influence of different bonding systems. The present results are therefore not comparable with other available studies. However, the research findings on the connection of composites to PEEK are different, some literature already exists here.

Pretreatment with primers or adhesives is essential to achieve a durable bond between the polymer material and the composites. Stawarczyk et al. also described that the bond between veneering composites on PEEK with multifunctional adhesives containing methacrylates has the highest adhesion values. The key to a long-lasting bond—especially to PEEK—therefore seems to be not only the surface treatment but also the composition of the adhesive. In a comparable study, adhesives with multifunctional methacrylates such as...
Luxatemp Glaze & Bond showed TBS values of 15.0 MPa after 3 days storage and 12.9 MPa after 150 days storage\(^{23}\). A study by Lee et al.\(^{39}\) showed SBS values at 14.45 MPa. However, these values were achieved without artificial aging by thermal cycling.

The adhesive bond between Scotchbond Universal and PEEK has also been tested in other studies. In the study by Tsuka et al. the bond between PEEK and luting materials was investigated. Scotchbond Universal achieved bond strength values of 6.8 MPa\(^{39}\) after 24 h of water storage and air abrasion. Until now, the chemical composition of the adhesive seemed to be of particular importance. MDP did not show any positive effects on bond strength to PEEK. The reason for this seems to be the absence of metal oxides as found on surfaces of CoCrMo alloys. The phosphate group of the bifunctional molecule cannot therefore react chemically to PEEK or DMA\(^{23}\). Nevertheless, a very high adhesive bond was measured in our study. This could indicate that the phosphate groups of the MDP do not bind with PEEK but with the titanium oxide used as whitening in PEEK and FRC, which was shown before\(^{49}\). Another possibility would be that the composition of different substances in Scotchbond Universal would simply allow deeper penetration of the roughened polymer surface. Following these hypotheses the results for iBond Universal were surprising. Considering the ingredients of iBond Universal, according to the manufacturer, are very comparable to Scotchbond Universal. But the SBS values to PEEK and FRC are very low after long-term artificial aging. This may be due to different percentages of MDP or to the additional use of silane in Scotchbond Universal. The use of silane alone in combination with tribiochemical pretreatment did not provide satisfactory adhesion values\(^{29}\), but could be an additional factor in the composition of functional adhesive systems for high performance polymers.

**CONCLUSIONS**

Within the limitations of an in vitro study it can be stated that Luxatemp Glaze & Bond and Scotchbond Universal can be recommended as promising bonding methods to PEEK after air abrasion. Additionally, Scotchbond Universal showed promising bond strengths to the fiber-reinforced composite.

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**REFERENCES**

1) Sailer I, Pjetursson BE, Zwahlen M, Hämmerle CH. A systematic review of the survival and complication rates of all-ceramic and metal–ceramic reconstructions after an observation period of at least 3 years. Part II: fixed dental prostheses. Clin Oral Implants Res 2007; 18: 86-96.

2) Sailer I, Makarov NA, Thoma DS, Zwahlen M, Pjetursson BE. All-ceramic or metal-ceramic tooth-supported fixed dental prostheses (FDPs)? A systematic review of the survival and complication rates. Part I: Single crowns (SCs). Dent Mater 2015; 31: 603-623.

3) Pjetursson BE, Thoma D, Jung R, Zwahlen M, Zembic A. A systematic review of the survival and complication rates of implant-supported fixed dental prostheses (FDPs)’ after a mean observation period of at least 5 years. Clin Oral Implants Res 2012; 23: 22-38.

4) Kern M, Sasse M, Wolfart S. Ten-year outcome of three-unit fixed dental prostheses made from monolithic lithium disilicate ceramic. JADA 2012; 143: 234-240.

5) Priest G, Priest J. Promoting esthetic procedures in the prosthodontic practice. J Prosthodont 2004; 13: 111-117.

6) Kappert H, Eichner K. Zahnärztliche Werkstoffe und ihre Verarbeitung, Bd. 2. Werkstoffe unter klinischen Aspekten, Kap. Unerwünschte biologische Nebenwirkungen. Thieme; 2008.

7) Katzer A, Marquardt H, Westendorf J, Wening J, Von Foerster G. Polyetheretherketone —cytotoxicity and mutagenicity in vitro. Biomaterials 2002; 23: 1749-1759.

8) Morrison C, Macnair R, MacDonald C, Wykman A, Goldie I, Grant M. In vitro biocompatibility testing of polymers for orthopaedic implants using cultured fibroblasts and osteoblasts. Biomaterials 1995; 16: 987-992.

9) Barkamo S, Anderson M, Currie F, Kjellin P, Jimbo R, Johansson CB, et al. Enhanced bone healing around nanohydroxyapatite-coated polyetheretherketone implants: An experimental study in rabbit bone. J Biomater Appl 2014; 29: 737-747.

10) Rivard CH, Rhalmi S, Coillard C. In vivo biocompatibility testing of peek polymer for a spinal implant system: a study in rabbits. J Biomed Mater Res A 2002; 62: 488-498.

11) Schmidlin PR, Stawarczyk B, Wieland M, Attin T, Hämmerle CH, Fischer J. Effect of different surface pre-treatments and luting materials on shear bond strength to PEEK. Dent Mater 2010; 26: 553-559.

12) Panayotov IV, Orti V, Cuisinier F, Yachou J. Polyetheretherketone (PEEK) for medical applications. J Mater Sci Mater Med 2016; 27: 118.

13) Schwaitalla AD, Abo-Emara M, Spintig T, Lackmann J, Müller WD. Finite element analysis of the biomechanical effects of PEEK dental implants on the peri-implant bone. J Biomech 2015; 48: 1-7.

14) Schwaitalla A, Müller WD. PEEK dental implants: a review of the literature. J Oral Implantol 2015; 39: 743-749.

15) Nalla RK, Kruzic JJ, Kinney JH, Ritchie RO. Effect of aging on the toughness of human cortical bone: evaluation by R-curves. Bone 2004; 35: 1240-1246.

16) Hallmann L, Mehl A, Sereno N, Hämmerle CH. The improvement of adhesive properties of PEEK through different pre-treatments. Appl Surf Sci 2012; 258: 7213-7218.

17) Laemkemann N, Strickstrock M, Eichberger M, Zylla IM, Stawarczyk B. Impact of air-abrasion pressure and adhesive systems on bonding parameters for polyetheretherketone dental restorations. Int J Adhes Adhes 2018; 80: 30-38.

18) Sålthamnpatig P, Chaijareenegroon P, Tattakorn K, Banjongprasert C, Takahashi H, Arksornnukit M. Effect of surface pretreatments on resin composite bonding to PEEK. Dent Mater J 2016; 35: 668-674.

19) Stawarczyk B, Beuer F, Wimmer T, Jahn D, Sener B, Roos M, et al. Polyetheretherketone—a suitable material for fixed dental prostheses? J Biomed Mater Res B Appi Biomater 2013; 101: 1209-1216.

20) Stawarczyk B, Jordan P, Schmidlin PR, Roos M, Eichberger
M., Gernet W., et al. PEEK surface treatment effects on tensile bond strength to veneering resins. J Prosthet Dent 2014; 112: 1278-1288.

21) Sproesser O, Schmidlin PR, Uhrenbacher J, Eichberger M, Roos M, Stawarczyk B. Work of adhesion between resin composite cements and PEEK as a function of etching duration with sulfuric acid and its correlation with bond strength values. Int J Adhes Adhes 2014; 54: 184-190.

22) Keul C, Liebermann A, Schmidlin PR, Roos M, Sener B, Stawarczyk B. Influence of PEEK surface modification on surface properties and bond strength to veneering resin composites. J Adhes Dent 2014; 16: 383-392.

23) Kern M, Lehmann F. Influence of surface conditioning on bonding to polyetheretherketon (PEEK). Dent Mater 2012; 28: 1280-1283.

24) Stawarczyk B, Bähr N, Beuer F, Wimmer T, Eichberger M, Gernet W, et al. Influence of plasma pretreatment on shear bond strength of self-adhesive resin cements to polyetheretherketone. Clin Oral Investig 2014; 18: 163-170.

25) Lee KS, Shin MS, Lee JY, Ryu JJ, Shin SW. Shear bond strength of composite resin to high performance polymer PEKK according to surface treatments and bonding materials. J Adv Prosthodont 2017; 9: 350-357.

26) Tetelman ED, Babbush CA. A new transitional abutment for immediate aesthetics and function. Implant Dent 2008; 17: 51-58.

27) Zoidis P, Papathanasiou I, Polyzois G. The use of a modified poly-ether-ether-ketone (PEEK) as an alternative framework material for removable dental prostheses. A Clinical Report. J Prosthodont 2016; 25: 580-584.

28) Costa-Palau S, Torrents-Nicolas J, Brufau-de Barberà M, Cabratosa-Termes J. Use of polyetheretherketone in the fabrication of a maxillary obturator prosthesis: a clinical report. J Prosthet Dent 2014; 112: 680-682.

29) Basaran EG, Ayna E, Vallittu PK, Lassila LV. Load bearing capacity of fiber-reinforced and unreinforced composite resin CAD/CAM-fabricated fixed dental prostheses. J Prosthodont 2013; 108: 88-94.

30) Barbero Ed. Introduction to composite materials design. CRC press; 2017.

31) John J, Gangadhar SA, Shah I. Flexural strength of heat-polymerized polymethyl methacrylate denture resin reinforced with glass, aramid, or nylon fibers. J Prosthet Dent 2001; 86: 424-427.

32) Fajardo RS, Pruitt LA, Finzen FC, Marshall GW, Singh S, Curtis DA. The effect of E-glass fibers and acrylic resin thickness on fracture load in a simulated implant-supported overdenture prosthesis. J Prosthet Dent 2011; 106: 373-377.

33) El Ghoul WA, Özcan M, Ounsi H, Tohme H, Salameh Z. Effect of different CAD-CAM materials on the marginal and internal adaptation of endocrown restorations: An in vitro study. J Prosthet Dent 2020; 123: 128-134.

34) Bonfante EA, Suzuki M, Carvalho RM, Hirata R, Labelski W, Bonfante G, et al. Digitally produced fiber-reinforced composite substructures for three-unit implant-supported fixed dental prostheses. Int J Oral Maxillofac Implants 2015; 30: 321-329.

35) Ruschel GH, Gomes EA, Silva-Sousa YT, Pinelli RGP, Sousa-Neto MD, Pereira GKR, et al. Mechanical properties and superficial characterization of a milled CAD-CAM glass fiber post. J Mech Behav Biomed Mater 2018; 82: 187-192.

36) Wegner SM, Gerdes W, Kern M. Effect of different artificial aging conditions on ceramic-composite bond strength. Int J Prosthodont 2012; 15: 267-272.

37) Heikkinen T, Matinlinna J, Vallittu P, Lassila L. Long term water storage deteriorates bonding of composite resin to alumina and zirconia short communication. Open Dent J 2013; 7: 123-125.

38) Armstrong S, Geraldini S, Maia R, Raposo LH, Soares CJ, Yamagawa J. Adhesion to tooth structure: a critical review of “micro” bond strength test methods. Dent Mater 2010; 26: e50-62.

39) Tsuka H, Morita K, Kato K, Kawano H, Abe Kura H, Teaga K. Evaluation of shear bond strength between PEEK and resin-based luting material. J Oral Biosci 2017; 59: 231-236.

40) Matsumura H, Yanagida H, Tanoue N, Atsuta M, Shimoe S. Shear bond strength of resin composite veneering material to gold alloy with varying metal surface preparations. J Prosthodont 2001; 86: 315-319.

41) Jakob E, Marx R. Silanisierung der Klebebrückenflügel. Zahnarzt Praxis 1988; 17: 124.

42) Mornburg TR, Pröscheil PA. In vivo forces on implants influenced by occlusal scheme and food consistency. Int J Prosthodont 2002; 16: 481-486.

43) Tsuchimoto Y, Yoshida Y, Mine A, Nakamura M, Nishiyama N, Van Meerbeek B, et al. Effect of 4-MET-and 10-MDP-based primers on resin bonding to titanium. Dent Mater J 2006; 25: 120-124.