

## RESEARCH AND EDUCATION

# Bond strength between a high-performance thermoplastic and a veneering resin

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High-performance thermoplastics such as polyetheretherketone (PEEK) and polyetherketoneketone (PEKK) are becoming popular in prosthetic dentistry. Both materials have adequate physical, mechanical, and biocompatible properties.<sup>1</sup> These high-performance thermoplastics have been used for removable partial dentures (RPDs)<sup>2-5</sup> and fixed partial dentures (FPDs)<sup>4,6-11</sup> for patients who are sensitive to metals or are seeking metal-free restorations.

An aryl-ketone polymer (Ultaire AKP) was recently introduced by Solvay Dental 360. According to the manufacturer, Ultaire AKP is indicated for RPDs and has a flexural strength of 148 MPa, an elastic modulus of 3500 MPa, and an impact strength of 9 kJ/m<sup>2</sup> as molded or 10.2 kJ/m<sup>2</sup> after conditioning. The material is supplied as a milling blank for processing by computer-aided design and computer-aided manufacturing (CAD-CAM) technology.

The overall performance of high-performance thermoplastics is driven by their composition and core

### ABSTRACT

**Statement of problem.** High-performance thermoplastics have been adopted as framework materials. However, their bond strength to an esthetic veneering material is unclear.

**Purpose.** The purpose of this in vitro study was to test the tensile bond strength (TBS) between an aryl-ketone polymer (Ultaire AKP) and veneering resins.

**Material and methods.** AKP substrates (N=324) were prepared, airborne-particle abraded (Al<sub>2</sub>O<sub>3</sub>, 50 μm, 0.2 MPa), and divided into 9 groups (n=36) with different bonding systems (visio.link, Adhese Universal, All-Bond Universal, CLEARFIL UNIVERSAL BOND, G-Premio BOND, iBOND Universal, ONE COAT 7 UNIVERSAL, Scotchbond Universal) and without a bonding system as a control. Each group was further divided for opaquer (n=18). Further subdivision followed according to flowable or paste veneering resin (n=9). Specimens were stored in distilled water for 24 hours at 37 °C and thermocycled (x5000, 5/55 °C). TBS was measured and analyzed with the Kolmogorov-Smirnov test and 3-way ANOVA with partial eta squared ( $\eta_p^2$ ), followed by the Kruskal-Wallis and Mann-Whitney-U tests. Relative frequency of failure types was analyzed with the Chi<sup>2</sup>-test and a Ciba-Geigy table.

**Results.** The highest impact on TBS was exerted by the adhesive ( $\eta_p^2=0.458$ ,  $P<.001$ ), followed by opaquer ( $\eta_p^2=0.288$ ,  $P<.001$ ). The binary combination of the 3 variables was significant for opaquer coupled with adhesive ( $\eta_p^2=0.173$ ,  $P<.001$ ). Visio.link showed the highest TBS followed by All-Bond Universal and Scotchbond Universal. Opaquer increased the TBS for all adhesives except for visio.link. Without adhesive, opaquer obtained comparable TBS to visio.link. Flowable veneering resin showed higher TBS than paste resin.

**Conclusions.** The application of opaquer increased TBS for all universal adhesives. Using opaquer and flowable veneering resin is beneficial for bonding to Ultaire AKP. (J Prosthet Dent 2019;■:■-■)

backbone chemistry. Different types and amounts of additives have been shown to influence appearance,<sup>12</sup> mechanical properties,<sup>13</sup> and roughness.<sup>14</sup> In addition to these performance metrics, the adhesion profile of high-performance thermoplastics is important if a veneering material is required for esthetics. Adhesion is challenging because of the stable chemical structure and

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## Clinical Implications

For veneering high-performance thermoplastics with veneering resin, an opaquer should be used when the surface of the high-performance thermoplastic is conditioned with a universal adhesive such as Scotchbond Universal or Adhese Universal.

the unreactive and inert surface character of high-performance thermoplastics.<sup>1</sup>

For PEEK, reliable bonding to dental composite resins has been reported after a surface treatment that combined surface roughening by airborne-particle abrasion with  $\text{Al}_2\text{O}_3$  and the application of methymethacrylate (MMA)-containing adhesives.<sup>15</sup> Additionally, surface etching with sulfuric acid,<sup>16-23</sup> a mixture of sulfuric acid and hydrogen peroxide,<sup>16,19,20,22</sup> plasma application,<sup>22-27</sup> and silicatization<sup>17,23,28</sup> have also been evaluated for bonding. However, airborne-particle abrasion has been reported to be the most effective method.<sup>15</sup>

Surface treatment protocols have been evaluated with different adhesives, with visio.link being studied for bonding to PEEK<sup>19,20,22,26,27,29-31</sup> and PEKK.<sup>23,24</sup> visio.link is a universal, light-polymerizing polymethyl methacrylate (PMMA) resin and composite resin primer developed to improve the bonding of PMMA denture resin and high-impact PMMA composite resin materials. It was reported to have the highest bond strength values, independent of the veneering resin or composite resin cement used.<sup>20</sup> The bond strengths were not affected by the size of the  $\text{Al}_2\text{O}_3$  particles<sup>29</sup> or varying pressure during airborne-particle abrasion.<sup>30</sup> In contrast, the universal adhesive Scotchbond Universal obtained comparable bond strength values with visio.link on PEEK<sup>29,30</sup> but showed higher survival rates with increasing airborne-particle abrasion pressure.<sup>29</sup> For PEKK, the universal adhesive Single Bond Universal (3M) was reported to be similar to visio.link.<sup>23</sup> Additionally, the use of an opaquer can enhance adhesion to high-performance thermoplastics.<sup>32</sup>

However, bonding between high-performance thermoplastics and dental composite resins is not fully understood. The differences in the chemistries of high-performance thermoplastics and their processing conditions complicate the issue, and the manufacturing process has a significant impact on the crystallinity of PEEK and thus affects its mechanical properties.<sup>33-35</sup>

The purpose of this *in vitro* study was to test the tensile bond strength between the newly introduced high-performance thermoplastic Utaire AKP and 2 different veneering resins after surface treatment. Both

veneering resins were based on urethane dimethacrylate (UDMA) but differed in viscosity. The surface treatment combined different universal adhesives and the alternative application of opaquer. The null hypothesis was that the tensile bond strength (TBS) between Utaire AKP and veneering resin would not be affected by the universal adhesive or the application of opaquer. Furthermore, the type of veneering resin would have no impact on the TBS to Utaire AKP.

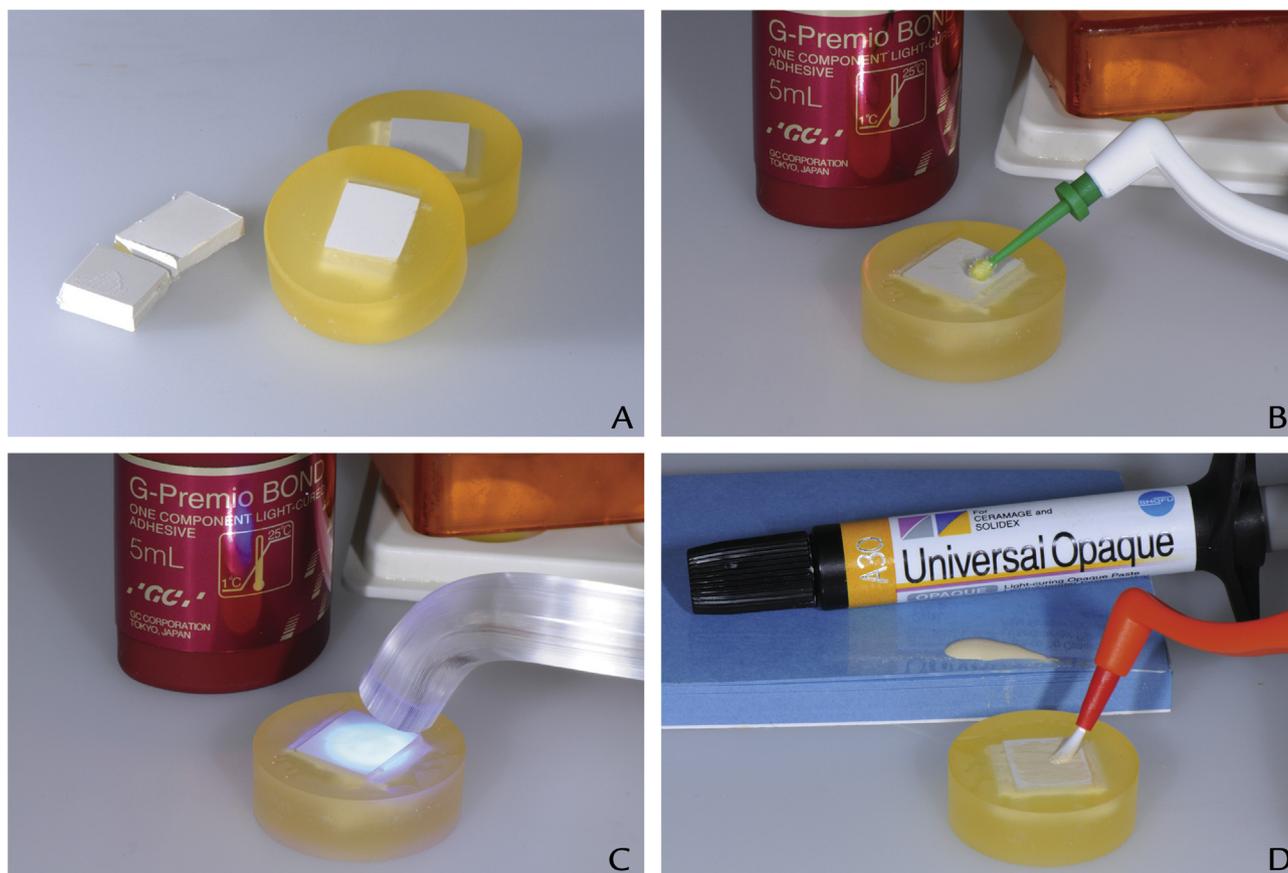
## MATERIAL AND METHODS

In total, 324 substrates were prepared from Utaire AKP (Dentivera Milling Discs; Solvay Dental 360). The milling blanks were cut into bars with handpiece and then into square specimens with an approximate surface area of 16 mm<sup>2</sup>. The specimens were embedded in acrylic resin (ScandiQuick A, ScandiQuick B; ScanDia) and polished up to P1200 by using silicon carbide paper (SiC Foil; Struers) for 20 seconds under water cooling with an automatic polishing device. The specimens were ultrasonically cleaned in distilled water (L&R Transistor/Ultrasonic T-14; L&R) and air-dried. The specimen surface was airborne-particle abraded (basis Quattro IS; Renfert) with alumina ( $\text{Al}_2\text{O}_3$ ) with a mean particle size of 50  $\mu\text{m}$  (Orbis Dental) at 0.2 MPa. The distance between the nozzle and specimen surface was 10 mm at an angle of 45 degrees. After ultrasonic cleaning for 60 seconds in distilled water, the specimens were divided into subgroups according to the conditioning (Fig. 1).

The specimens were divided into 9 subgroups according to the adhesives (Table 1, n=36/subgroup). One group was left without the application of an adhesive as a control. For all universal adhesives, a thin layer was applied on the substrate surface for 10 seconds by using a microbrush and dispersed with oil-free compressed air if recommended by the manufacturer. The thin layer of the universal adhesive was polymerized for 10 seconds at a 5-mm distance (Elipar S10; 3M). To guarantee sufficient polymerization, the light intensity of the polymerization unit (1250 mW/cm<sup>2</sup>) was measured by using a radiometer (Bluephase Meter II; Ivoclar Vivadent AG). Visio.link was polymerized for 90 seconds according to the manufacturer's recommendation (bre.Lux Power Unit; bredent).

Half of the specimens in each subgroup were coated with a thin layer of opaquer (Universal Opaque A30; Shofu) applied with a brush (n=18/subgroup). The application was made in lines from 2 directions: horizontal and vertical. The opaquer was polymerized for 180 seconds (Solidilite V; Shofu). The other specimens per subgroup were not coated with the opaquer (n=18/subgroup).

The conditioned groups were further divided into 2 groups of veneering resin (n=9/veneering resin) with either a flowable veneering resin (Ceramage flowable



**Figure 1.** Step-by-step specimen preparation. A, Sectioned and embedded specimens. B, Conditioning with adhesive. C, Polymerization of adhesive. D, Application of opaquer. E, Filling of centrally positioned acrylic resin cylinder with flowable veneering resin. F, Final specimen dimension. G, Specimen positioned in test device for tensile bond strength measurement.

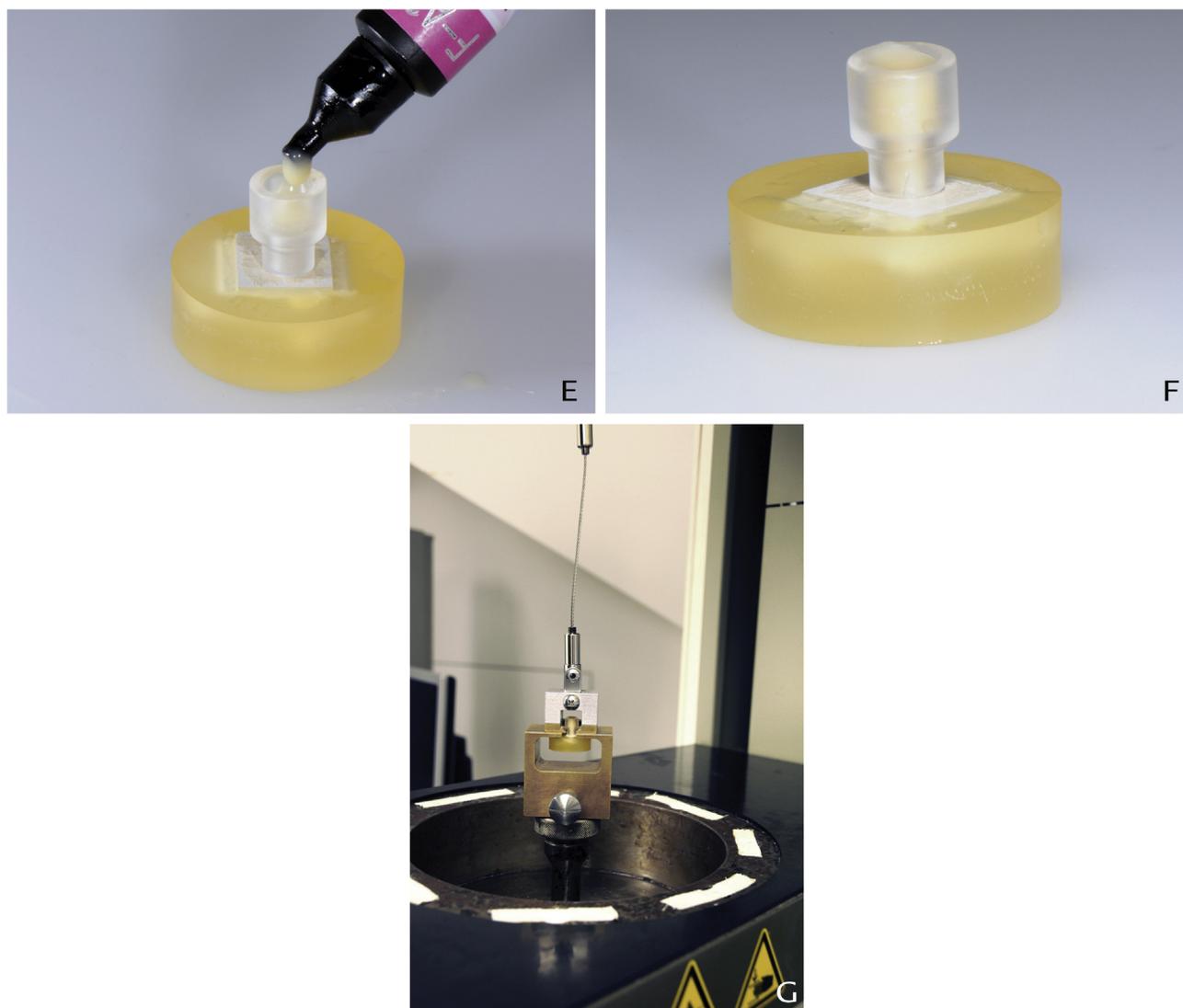
**Table 1.** Summary of materials used

Material	Product Name	Manufacturer	Lot No.
Thermoplastic polymer (AKP)	Dentivera Milling Discs Ultraire AKP	Solvay Dental 360	1641189007
OPAQUER	Universal Opaque A30	Shofu	121619
Adhesive	visio.link	breident	164371
	Adhese Universal	Ivoclar Vivadent AG	U52628
	All-Bond Universal	Bisco	1700000951
	CLEARFIL UNIVERSAL BOND	Kuraray Noritake Dental	CN0022
	G-Premio BOND	GC Europe	1608301
	iBOND Universal	Kulzer GmbH	10026
	ONE COAT 7 UNIVERSAL	Coltène	H39695
Veneering resin	Scotchbond Universal	3M	648274
	Ceramage flowable composite A3B	Shofu	091616, PN1921
	Ceramage dentine paste A3B	Shofu	061683, PN1903

composite; Shofu) or a paste veneering resin (Ceramage dentine paste; Shofu). To enable TBS measurements, a transparent acrylic resin cylinder (SD Mechatronik) with an inner diameter of 2.9 mm was placed in the center of

each substrate surface and filled with either flowable or paste veneering resin. Both groups were polymerized for 360 seconds (Solidilite V; Shofu), and excess veneering resin was removed with a scalpel.

All specimens were stored in distilled water for 24 hours at 37 °C (HeraCell 150; Kulzer GmbH), followed by additional thermocycling for  $\times 5000$  between 5 °C and 55 °C (Thermocycler THE 1100; SD Mechatronik). After artificial aging and storing for 2 hours at room temperature (24 °C), TBS measurements were performed. The specimens were positioned successively in a universal testing machine (RetroLine; Zwick/Roell), with the specimen surface perpendicular to the applied tensile stress. The TBS (MPa) was measured at a crosshead speed of 5 mm/min and calculated after fracture of the bonding area as follows: fracture load in N/bonding area in mm<sup>2</sup>. For each specimen, the failure type was examined by using a stereomicroscope at a magnification of  $\times 20$  (Carl Zeiss Axioskop 2 MAT; Zeiss). To assign the failure type, the following categories were defined: (1) adhesive, no veneering resin left on the Ultraire AKP surface; (2) cohesive, remnants of veneering resin



**Figure 1.** (continued). E, Positioning and filling of acrylic resin cylinder with veneering resin. F, Bonded specimen. G, Positioning of specimen in universal testing machine.

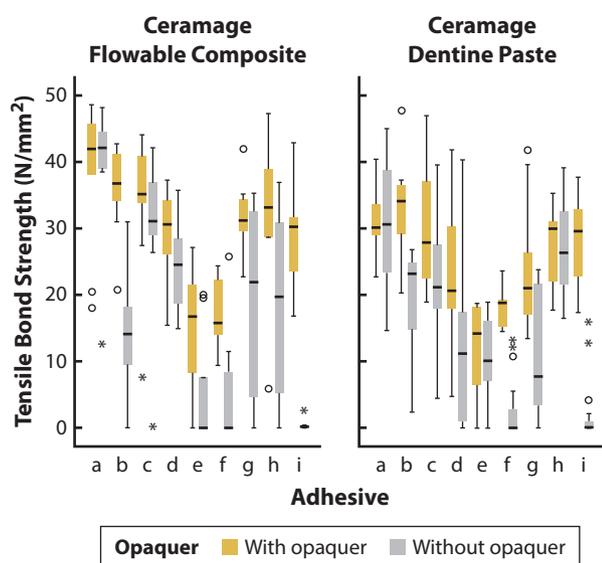
composite left on specimen surface; and (3) cohesive, cohesive failure in the Ultaire AKP polymer.

The measured data were analyzed by using descriptive statistics, including mean and standard deviation with 95% confidence intervals (95% CI). Normality of data distribution was tested by using the Kolmogorov-Smirnov test. Multivariate analysis with partial eta-squared ( $\eta_p^2$ ) followed by the Kruskal-Wallis and Mann-Whitney U-tests were performed to determine the significant differences among the tested groups. Partial eta-squared was used to determine the effects of independent variables and interactions on the result of TBS. The relative frequencies of failure types together with the corresponding 95% CI according to the Ciba Geigy tables were provided. A chi<sup>2</sup>-test was used to detect the differences in frequencies of failure types between groups.

The statistical tests were performed by using a statistical software program (IBM SPSS Statistics, v23.0; IBM Corp) ( $\alpha=.05$  for all tests except where Bonferroni correction was applied at  $\alpha=.0014$ ).

## RESULTS

The Kolmogorov-Smirnov test showed deviations from the normal distribution for 11% of all tested groups. Thus, nonparametric analysis with the Kruskal-Wallis and Mann-Whitney U test was computed. The highest influence on TBS was exerted by the adhesive ( $\eta_p^2=0.458$ ,  $P<.001$ ), followed by the application of opaquer ( $\eta_p^2=0.288$ ,  $P<.001$ ), and the influence of the veneering resin ( $\eta_p^2=0.031$ ,  $P=.01$ ) was not statistically significant. The effect of the binary combination of the 3 variables was



**Figure 2.** Box and whisker plots for tensile bond strength (N/mm<sup>2</sup>) according to flowable or paste veneering resin depending on conditioning with different adhesives and application of opaquer (with "\*" and "°" indicating statistical outliers). a: visio.link; b: Adhese Universal; c: All-Bond Universal; d: CLEARFIL UNIVERSAL BOND; e: G-Premio BOND; f: iBOND Universal; g: ONE COAT 7 UNIVERSAL; h: Scotchbond Universal; i: without adhesive.

significant only for opaquer coupled with adhesive ( $\eta_p^2=0.173$ ,  $P<.001$ ). The ternary combination of the variables did not affect the TBS results ( $\eta_p^2=0.033$ ,  $P=.171$ ).

In terms of the TBS of the adhesive, visio.link had the highest strength, followed by All-Bond Universal and Scotchbond Universal (Fig. 2). CLEARFIL UNIVERSAL BOND, ONE COAT 7 UNIVERSAL, and Adhese Universal all registered TBS values in the middle of the range of the adhesives measured. The lowest TBS was achieved when iBOND Universal, G-Premio BOND, or no adhesive was used. In general, the use of the opaquer increased the TBS values ( $P<.001$ ). Within the type of veneering resin, significant differences between the adhesives were found ( $P<.001$ ), with a strong dependence on the alternative coating with opaquer. All differences are indicated in Table 2. The TBS values of the negative control group (without the application of adhesive) were comparable with visio.link when the opaquer was used.

The relative frequency (95% CI) of the failure type is shown in Table 3. According to the  $\chi^2$ -test, different failure types between the tested groups were observed ( $P<.001$ ). All groups showed predominant adhesiveness (11% to 100%) or cohesiveness in the veneering resin material (0% to 89%). However, cohesive failures in the Ultraire AKP material were not observed.

## DISCUSSION

High-performance thermoplastics typically require an esthetic veneer to improve appearance. For this, a reliable

**Table 2.** Descriptive statistics of TBS (N/mm<sup>2</sup>) listed by means with standard deviations (SD)

Veneering Resin	Adhesive	Means $\pm$ Standard Deviation	
		With Opaquer	Without Opaquer
Flowable	visio.link	38.3 $\pm$ 11.4 <sup>b</sup>	39.6 $\pm$ 10.6 <sup>c</sup>
	Adhese Universal	35.8 $\pm$ 6.8 <sup>b</sup>	13.6 $\pm$ 9.8 <sup>a,b,c</sup>
	All-Bond Universal	33.6 $\pm$ 11.0 <sup>b</sup>	30.3 $\pm$ 12.6 <sup>d,e</sup>
	CLEARFIL UNIVERSAL BOND	28.9 $\pm$ 7.7 <sup>b</sup>	24.3 $\pm$ 6.6 <sup>c,d</sup>
	G-Premio BOND	15.4 $\pm$ 8.1 <sup>a</sup>	5.7 $\pm$ 8.4 <sup>a,b</sup>
	iBOND Universal	17.1 $\pm$ 5.0 <sup>a</sup>	5.1 $\pm$ 8.9 <sup>a,b</sup>
	ONE COAT 7 UNIVERSAL	31.8 $\pm$ 5.4 <sup>b</sup>	18.3 $\pm$ 14.8 <sup>b,c,d</sup>
	Scotchbond Universal	32.2 $\pm$ 11.5 <sup>b</sup>	18.8 $\pm$ 13.6 <sup>b,c,d</sup>
	Without adhesives	28.8 $\pm$ 7.6 <sup>b</sup>	0.4 $\pm$ 0.8 <sup>a</sup>
	Paste	visio.link	30.8 $\pm$ 5.6 <sup>c</sup>
Adhese Universal		33.0 $\pm$ 8.0 <sup>c</sup>	19.4 $\pm$ 8.2 <sup>b,c</sup>
All-Bond Universal		29.9 $\pm$ 8.7 <sup>c</sup>	22.4 $\pm$ 10.5 <sup>d,e</sup>
CLEARFIL UNIVERSAL BOND		23.1 $\pm$ 9.7 <sup>a,b</sup>	11.5 $\pm$ 11.0 <sup>a,b</sup>
G-Premio BOND		12.3 $\pm$ 6.9 <sup>a</sup>	10.1 $\pm$ 7.1 <sup>a,b</sup>
iBOND Universal		18.2 $\pm$ 3.1 <sup>a,b</sup>	2.7 $\pm$ 4.9 <sup>a</sup>
ONE COAT 7 UNIVERSAL		23.0 $\pm$ 8.4 <sup>b,c</sup>	11.7 $\pm$ 10.2 <sup>a,b</sup>
Scotchbond Universal		28.0 $\pm$ 6.0 <sup>c</sup>	27.2 $\pm$ 6.8 <sup>d,e</sup>
Without adhesives		27.8 $\pm$ 7.1 <sup>c</sup>	2.3 $\pm$ 5.0 <sup>a</sup>

Lowercase letters indicate significant differences between adhesives within one group according to results of Mann-Whitney U test. \*Nonnormal distributed groups.

bonding protocol is necessary. The null hypothesis that neither the universal adhesive nor the opaquer affects the bond strength between Ultraire AKP and a veneering resin was rejected as the type of veneering resin had no impact on the bonding results.

The flowable veneering resin resulted in higher bond strength values than the paste veneering resin (Fig. 2). This result is consistent with recently published data<sup>24</sup> and could be explained by differences in viscosities of the veneering resins. A lower viscosity veneering resin can easily flow into micromechanical retentions, while paste veneering resins require a certain pressure during processing to adapt to the bonding area. Additionally, the ratio of the matrix polymer and the filler particles might be of importance. It is assumed that the filler particles do not bond to the high-performance thermoplastic surface, but the matrix polymer does. Paste veneering resins have higher filler content.

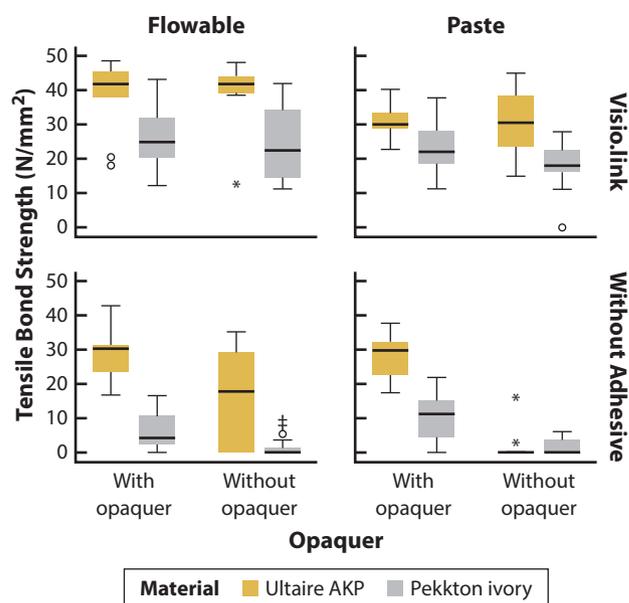
For most of the adhesives, increased bond strength values were observed when the opaquer was applied between Ultraire AKP and veneering resin (Fig. 2). This observation is consistent with previous results<sup>24,32</sup> and is also reflected by the frequency of failure types (Table 3). Even the application of opaquer without additional adhesive resulted in comparable bond strength values with visio.link. Opaquer materials are composed of inorganic filler particles such as zirconium silicate, various dimethacrylates (DMAs) such as urethane dimethacrylate (UDMA), stabilizer, pigments, and initiators. In comparison, visio.link is mainly based on MMA (25% to 50%). Thus, the present findings cannot conclusively

**Table 3.** Relative frequency of failure types (%) with 95% CI listed by failure types

Veneering Resin	Adhesive	Failure Type				
		With Opaquer		Without Opaquer		
		Adhesive	Cohesive	Adhesive	Cohesive	
Flowable	visio.link	11 (0; 49)	89 (50; 100)	56 (20; 87)	44 (12; 79)	
	Adhese Universal	44 (12; 79)	56 (20; 87)	78 (38; 98)	22 (1; 61)	
	All-Bond Universal	67 (28; 93)	33 (6; 71)	67 (37; 89)	33 (10; 62)	
	CLEARFIL UNIVERSAL BOND	78 (38; 98)	22 (1; 61)	77 (45; 95)	23 (4; 54)	
	G-Premio BOND	89 (64; 99)	11 (0; 35)	100 (65; 100)	0 (0; 34)	
	iBOND Universal	100 (65; 100)	0 (0; 34)	100 (65; 100)	0 (0; 34)	
	ONE COAT 7 UNIVERSAL	100 (65; 100)	0 (0; 34)	86 (56; 99)	14 (0; 43)	
	Scotchbond Universal	89 (64; 99)	11 (0; 35)	67 (28; 93)	33 (6; 71)	
	Without adhesives	56 (20; 87)	44 (12; 79)	100 (65; 100)	0 (0; 34)	
	Paste	visio.link	22 (1; 61)	78 (38; 98)	33 (8; 66)	67 (33; 91)
		Adhese Universal	67 (28; 93)	33 (6; 71)	100 (65; 100)	0 (0; 34)
All-Bond Universal		56 (20; 87)	44 (12; 79)	85 (53; 99)	15 (0; 46)	
CLEARFIL UNIVERSAL BOND		78 (38; 98)	22 (1; 61)	100 (77; 100)	0 (0; 22)	
G-Premio BOND		100 (65; 100)	0 (0; 34)	100 (65; 100)	0 (0; 34)	
iBOND Universal		100 (65; 100)	0 (0; 34)	100 (77; 100)	0 (0; 22)	
ONE COAT 7 UNIVERSAL		100 (65; 100)	0 (0; 34)	100 (65; 100)	0 (0; 34)	
Scotchbond Universal		67 (28; 93)	33 (6; 71)	62 (30; 87)	38 (12; 69)	
Without adhesives		100 (65; 100)	0 (0; 34)	100 (77; 100)	0 (0; 22)	

attribute higher bonding strength values to either MMA or DMA.

The occurrence of cohesive failure types is used as a metric to underscore the high bond strength values as these 2 variables are often proportional in their occurrence. This trend is reflected in this study (Table 3). For the flowable veneering resin, visio.link, G-Premio BOND, and specimens without adhesive showed more frequent cohesive failure types when coated with the opaquer. For the paste veneering resin, the same trend was observed for Adhese Universal and CLEARFIL UNIVERSAL BOND. To provide context for the results (Table 2), a comparison of the bond strength values of the present study (Ultaire AKP) was drawn with the results of a previous study<sup>24</sup> that tested PEKK (Pekkton ivory; Cendres Métaux) (Fig. 3). Both high-performance thermoplastics were adhered to a flowable and a paste veneering resin when the substrate surface was either conditioned with visio.link or left without an adhesive.



**Figure 3.** Box and whisker plots for comparison of tensile bond strength (N/mm<sup>2</sup>) between flowable and paste veneering resin and AKP versus PEKK<sup>24</sup> with and without opaquer according to conditioning using either visio.link or without adhesive (with "\*" and "o" indicating statistical outliers). AKP, aryl-ketone polymer; PEKK, polyetherketoneketone.

For both groups (visio.link and without adhesive), the bond strength values were higher for Ultaire AKP than for PEKK, with one exception: without adhesive, without opaquer, and paste veneering resin. This might indicate certain differences between the interactions of the veneering resin, the opaquer, the adhesive, and the substrate materials. The explanation behind the difference in the bond strength results (Fig. 3) requires further investigation. Differences in the core chemistries and amount of crystallinity of the polymer system (if any) and the chemistry of the adhesion system can all affect the type and strength of the interaction between the adhesion system and the characteristically nonpolar, high-performance thermoplastic surfaces. Possible differences in the crystallinity of thermoplastics are not assumed to be influential variables because a previous bond strength study did not detect differences between an amorphous and crystalline PEKK.<sup>28</sup>

The photoinitiator system and solvent are further possible influential variables on bond strength. One difference between visio.link and the other tested universal adhesives was the photoinitiator as well as the time of exposure during the light polymerizing. The polymerization of visio.link and G-Premio BOND is initiated by the Type 1 photoinitiator diphenyl(2,4,6-trimethylbenzoyl)phosphine oxide (TPO). All other adhesives contain camphor quinone (CQ), a Type 2 photoinitiator that has a maximum absorption wavelength at 470 nm. TPO has a maximum absorption wavelength of 385 nm, but only visio.link was

polymerized by using a light polymerizing unit with an aligning wavelength profile (370 to 500 nm, breLux Power Unit; bredent) to the ideal conditions of TPO. Although not directly measured, this circumstance likely promoted a maximum dissociation of the TPO into free radicals<sup>36</sup> and so might have increased the propagation efficiency of the MMA in visio.link, as well as the DMA in the opaquer, yielding a strong bond strength. However, G-Premio BOND was polymerized with a light source that was red-shifted from the absorption maximum (430 to 480nm) of the TPO in Elipar S10. Thus, the TPO radical formation was not optimized and resulted in inadequate bond strength for G-Premio BOND. The use of the Elipar S10 light-polymerization unit for the G-Premio BOND specimens was driven by the manufacturer requirement of polymerization with a light intensity of 1250 mW/cm<sup>2</sup>.

All other tested universal adhesives with CQ as initiator were polymerized with the Elipar S10 light-polymerizing unit, which had an emission wavelength that falls within CQ's optimal adsorption maxima (430 to 480 nm). Despite being polymerized at an optimal wavelength, the mean bond strengths for CQ specimens were below those of visio.link. This result might either be explained by the difference in the total energy exposed to a certain adhesive (exposure time×intensity) or by the fact that even at its optimal wavelength, CQ has a poor radical formation efficiency because the energy absorption at the absorption maximum of CQ at 470 nm is inadequate to facilitate a direct dissociation of CQ molecules into free molecules. To combat this, amines are typically added to increase the efficiency of radical formation.<sup>36</sup> Regarding the tested universal adhesives, only Scotchbond Universal and Adhese Universal have added amines in their formulation according to the information provided by the manufacturer. Thus, their superior performance over the other CQ-initiated adhesives might be explained.

The alignment between the optimal photoinitiator wavelength and the light-polymerizing unit wavelength should be carefully considered to optimize the bond strength of thermoplastic dental materials. Specific testing should be performed to confirm this conjecture.

## CONCLUSIONS

Based on the findings of this in vitro study, the following conclusions were drawn:

1. Flowable veneering resin resulted in significant higher bond strength values than paste veneering resin.
2. The application of the opaquer increased bond strength values for all tested universal adhesives, except for visio.link.

3. A single application of the opaquer led to bond strength values comparable with those of visio.link, irrespective of the veneering resin.
4. CQ-initiated adhesives with added amines such as Scotchbond Universal and Adhese Universal showed bond strength values comparable with those of visio.link.
5. An alignment between the optimal initiator wavelength and the light-polymerizing wavelength should be carefully considered to optimize the bonding strengths of thermoplastic dental materials.
6. G-Premio BOND should be retested with a light-polymerizing unit that better matches its photoinitiator TPO.

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