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RESEARCH AND EDUCATION

Bond strength of recently introduced computer-aided design and computer-aided manufacturing resin-based crown materials to polyetheretherketone and titanium

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ABSTRACT

Statement of problem. Several additively and subtractively manufactured resin-based materials indicated for interim and definitive fixed dental prostheses have been launched. However, knowledge of the bond strength of these materials to different implant abutment materials is limited.

Purpose. The purpose of this in vitro study was to evaluate the shear bond strength (SBS) of additively and subtractively manufactured resin-based materials to different implant abutment materials.

Material and methods. One hundred and ten disk-shaped specimens (Ø3×3 mm) were fabricated either additively from 2 resins indicated for definitive use (Crowntec; AM_CT and VarseoSmile Crown Plus; AM_VS) and 1 resin indicated for interim use (FREEPRINT temp; AM_FP) or subtractively from a nanographene-reinforced polymethyl methacrylate (G-CAM; SM_GC) and a high-impact polymer composite (breCAM.HIPC; SM_BC). After allocating 2 specimens from each group for scanning electron microscope evaluation, the specimens were divided according to the abutment material (CopraPeek; polyetheretherketone, PEEK and Dentium Superline Pre-Milled Abutment; titanium, Ti) (n=10). All specimens were airborne-particle abraded with 50-μm aluminum oxide. After applying a resin primer (Visio.link) to PEEK and an adhesive primer (Clearfil Ceramic Primer Plus) to Ti specimens, a self-adhesive resin cement (PANAVIA SA Cement Universal) was used for cementation. All specimens were stored in distilled water (24 hours, 37 °C), and a universal testing device was used for the SBS test. SBS data were analyzed with 2-way analysis of variance and Tukey honestly significant difference tests, while the chi-squared test was used to evaluate the difference among the abutment-resin pairs in terms of failure modes (α=.05).

Results. The interaction between the material type and the abutment type and the main factor of material type affected the SBS ($P<.001$). SM_BC-PEEK and SM_GC had the lowest SBS followed by SM_BC-Ti, whereas AM_VS-PEEK had the highest SBS ($P\leq.001$). AM_CT-Ti had higher SBS than AM_FP-PEEK ($P=.026$). SM_GC had the lowest and AM_VS had the highest SBS, while AM_CT and AM_FP had higher SBS than SM_BC ($P\leq.004$). The distribution of failure modes was significantly different among tested material-abutment pairs, and only for AM_CT among tested materials ($P\leq.025$). Most of the material-abutment pairs had a minimum of 80% adhesive failures.

Conclusions. Regardless of the abutment material, additively manufactured specimens had higher bond strength and one of the subtractively manufactured materials (SM_GC) mostly had lower bond strength. The abutment material had a small effect on the bond strength. Adhesive failures were observed most frequently. (J Prosthet Dent xxxx;xxx:xxx-xxx)

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Clinical Implications

The tested additively manufactured resins may be more resistant to debonding than nanographene-reinforced polymethyl methacrylate and high-impact polymer composite when cemented on polyetheretherketone and titanium abutments.

Early and immediate loading of implants has become a common treatment option to maintain esthetics and provide favorable soft tissue healing,[1] increasing the importance of interim restorations.[2] For implant-supported restorations, titanium (Ti) has been the preferred abutment material[3]; however, esthetic issues might be encountered because of its grayish color, particularly in those with a high smile line or thin phenotype.[4] High-performance polymers with their tooth-like color have been introduced as an alternative to Ti.[5] Polyetheretherketone (PEEK) is a commonly used high-performance polymer with favorable mechanical properties, biocompatibility, and chemical stability[1] and has been used as an interim abutment for implant-supported restorations.[6] However, achieving an adequate bond strength to PEEK has been reported to be challenging given the material's low surface energy and hydrophobicity.[7]

The range of restorative materials has shown a parallel increase with computer-aided design and computer-aided manufacturing (CAD-CAM) technologies,[8] and new materials have become available for implant-supported restorations.[9] Subtractively manufactured (SM) nanographene-reinforced polymethyl methacrylate (PMMA) is among these newly introduced materials[10] and has been shown to have favorable mechanical and optical properties associated with the presence of graphene particles.[11–13] Another new material that can also be SM is a high-performance polymer that consists of cross-linked composite resin and is referred to as high-impact polymer composite (breCAM.HIPC; bredent Medical GmbH & Co KG).[14] Additive manufacturing (AM) has emerged as an alternative to subtractive manufacturing with reported advantages, and interim restorations can be fabricated with this technology.[15,16] Recently introduced AM definitive composite resins are also indicated for interim restorations[17] and may be suitable for long-term interim restorations.

Even though the bond strength of AM resins for interim use has been evaluated,[15,16,18–21] knowledge on that of the AM composite resins for definitive use[8,22,23] and the SM resin-based materials is limited. In addition, previous studies on the bond strength of AM resins for interim use did not consider the abutment material as a factor.[15,16,18–21] Because the knowledge of the bond strength between the restorative material and various abutment materials would elaborate on the applicability of newly introduced CAD-CAM resins for implant-supported restorations, the present study aimed to evaluate the shear bond strength (SBS) of additively or subtractively manufactured resin-based materials to PEEK and Ti specimens by simulating abutment materials and the failure modes. The null hypotheses were that the material and abutment type would not affect the SBS or the failure modes.

MATERIAL AND METHODS

A total of 110 disk-shaped specimens (Ø3×3 mm) were fabricated from 3 additively (Crowntec; Saremco DENTAL AG [AM_CT], FREEPRINT temp; Detax [AM_FP], and Varseosmile Crown Plus; Bego [AM_VS]) and 2 subtractively (G-CAM; Graphenano Dental [SM_GC] and breCAM.HIPC; bredent Medical GmbH & Co KG [SM_BC]) manufactured CAD-CAM materials (n=22) (Table 1). To fabricate AM_CT, AM_FP, and

Table 1. List of restorative materials tested

Material	Material Type	Chemical Composition	Manufacturer
Crowntec (AM_CT)	Additively manufactured composite resin for definitive use	Esterification products of 4.4′- isopropylphenol, ethoxylated and 2- methylprop–2enoic acid, silanized dental glass, pyrogenic silica, initiators. Total content of inorganic fillers: 30–50 wt%	Saremco Dental AG
FREEPRINT temp (AM_FP)	Additively manufactured resin for interim use	45 - <60 wt% Iso- propylidenediphenol Peg–2 Dimethacrylat, 1 - <5 wt% 2 Hydroxyethylmethacrylat, 1 - <5 wt% Diphenyl (2,4,6 trimethylbenzoyl) phosphinoxid, 1 - <5 wt% Hydroxypropylmethacrylat, < 1 wt% Phenyl-bis(2,4,6-trimethylbenzoyl)- phosphinoxid	Detax
VarseoSmile Crown Plus (AM_VS)	Additively manufactured composite resin for definitive use	Esterification products of 4.4′- isopropylphenol, ethoxylated and 2- methylprop–2enoic acid, silanized dental glass, methyl benzoylformate, diphenyl (2,4,6-trimethylbenzoyl) phosphine oxide. Total content of inorganic fillers: 30–50 wt%	Bego
G-CAM (SM_GC)	Subtractively manufactured nanographene-reinforced polymethyl methacrylate	Not disclosed	Graphenano DENTAL
breCAM.HIPC (SM_BC)	Subtractively manufactured high-impact polymer composite	Not disclosed	bredent Medical GmbH & Co KG

AM_VS specimens, a disk-shaped standard tessellation language (STL) file was designed with a software program (Meshmixer v3.5.474; Autodesk Inc), transferred into a nesting software program (Composer v1.3; ASIGA), and placed vertically on the build platform. The supporting structures were generated automatically, and this design was duplicated for standardization. A digital light processing technology-based 3-dimensional (3D) printer (MAX UV; ASIGA) was used to fabricate each specimen with a layer thickness of 50 μm. After fabrication, the residual resin on the AM_CT specimens was removed with ethanol-soaked cloths, while AM_FP and AM_VS specimens were ultrasonically cleaned either in isopropanol (AM_FP, precleaning: 3 minutes, main cleaning: 3 minutes) or ethanol (AM_VS, precleaning: 3 minutes, main cleaning: 2 minutes). The support structures of the AM_CT specimens were removed before cleaning, those of AM_FP were removed after precleaning, and those of AM_VS were removed after main cleaning. AM_FP specimens were polymerized for 4000 light exposures (2000 × 2) under nitrogen oxide gas atmosphere with a xenon polymerization unit (Otoflash G171; NK Optik). The surfaces of AM_CT and AM_VS specimens were abraded by using 50-μm glass beads (Rolloblast; Renfert) at 0.15-MPa and polymerized either for 4000 (AM_CT, 2000 × 2) or 3000 light exposures (AM_VS, 1500 × 2) with the same polymerization unit.[24–26] To fabricate the SM_GC and SM_BC specimens, a Ø3×15-mm cylinder was designed in the same software program, and imported into the nesting software program (PrograMill CAM V4.2; Ivoclar AG) of a 5-axis milling unit (PrograMill PM7; Ivoclar AG). The cylinders were wet sliced (Mecatome T180; Presi Metallography) into Ø3×3-mm disks. After fabrication, the bonding surfaces of all the specimens were standardized with the silicon carbide abrasive papers (Atlas Waterproof Sheet, 600–1200 grit; Saint-Gobain Abrasives) under water. Then, the specimens of each restorative material group were randomly (Excel; Microsoft Corp) divided into 2 subgroups based on the abutment material for cementation (n=10). The number of specimens per group was calculated with a priori power analysis (α=95%, 1-β=80%, and effect size f=0.42),[27] and 8 specimens per group were adequate. To increase the statistical power, 10 specimens per group were fabricated.

Fifty rectangular (7×7×2 mm) PEEK specimens (CopraPeek; Whitepeaks Dental Solutions GmbH) were prepared by using the same water-cooled precision cutter. Additionally, 50 disk-shaped (Ø15.8×2 mm) Ti specimens were prepared by cutting premilled Ti implant abutment blanks (Dentium Superline Pre-Milled Abutment; Dentium) with the same precision cutter under water cooling. All specimens were embedded into autopolymerizing acrylic resin (Meliodent; Heraulz Kulzer GmbH) cylinders (20×30 mm), wet ground with silicon carbide abrasive papers, and divided into 5 groups by using the randomization function of a software program (Excel; Microsoft Corp) (n=10).

The bonding surfaces of all restoration and abutment specimens were airborne-particle abraded (0.2 MPa pressure for 10 seconds from 10 mm) with 50 μm aluminum oxide (Cobra; Renfert) and steam cleaned (Vap-8 Steamer; Zhermack GmbH) for 10 seconds. The surface topography of a representative nonabraded and airborne-particle abraded specimen for each restorative material group was evaluated with a scanning electron microscope (SEM) (SU 1510; Hitachi High-Technologies Corp) at ×2500 magnification after sputter-coating with gold nanoparticles. Then, a thin layer of adhesive primer (Clearfil Ceramic Primer Plus; Kuraray Europe GmbH) that contained 10-methacryloyloxydecyl dihydrogen phosphate (MDP) was applied to the bonding surfaces of the restorative materials and the Ti framework specimens. Ten seconds after adhesive application, the surfaces were dried with oil-free air. The bonding surfaces of the PEEK specimens were treated with a resin primer (Visio.link; bredent Medical GmbH & Co KG) and polymerized with a polymerization unit (Labolight DUO; GC Corp) for 90 seconds[7] A self-adhesive dual-polymerizing resin cement (PANAVIA SA Cement Universal; Kuraray Europe GmbH) was applied to the bonding surfaces of the restorative materials with a refillable syringe, and the restorative material specimens were cemented either to PEEK or Ti. A loading device was used to apply a standardized 2-N force onto the restorative materials during cementation.[8] The excess cement was removed with a disposable brush, and the resin cement was light polymerized (Elipar S10; 3M) with 1200 mW/cm^2 power output for 10 seconds. Any excess was then removed with a scalpel. Four minutes after mixing the resin cement, the force was removed, and all specimens were stored in distilled water for 24 hours at 37 °C. All surface treatment and cementation procedures were performed by a single operator (A.S.K.).

A universal testing device (AGS-10 kNX; Shimadzu Co) was used to conduct the SBS test. Each restorative material abutment complex was placed on the lower holder of the testing device, and a knife-edged tip applied a force to the bonding interface between the restorative material and the abutment material at a crosshead speed of 1 mm/minute until failure (Fig. 1). The maximum force at failure (N) was divided by the bonding surface area (mm^2) to calculate the SBS values in megapascals (MPa). Failure modes were examined under ×200 magnification with a stereomicroscope (Leica SP1600; Leica Biosystems Nussloch GmbH) and described as adhesive (residue on the abutment surface after debonding ≤33%), mixed (33% <residue on the abutment surface after debonding ≤66%), or cohesive (residue on the abutment surface after debonding >66%).[1]

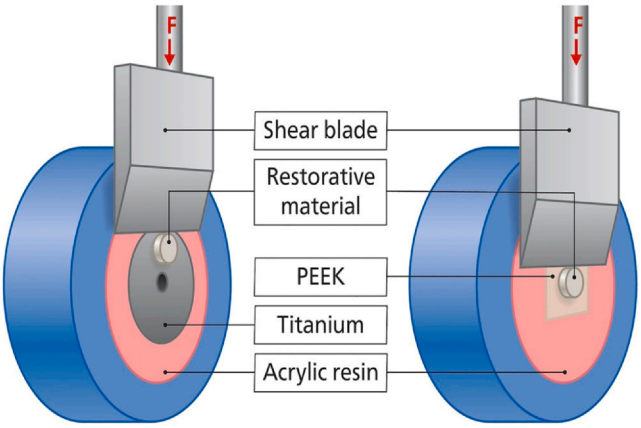

Figure 1. Schematic representation of shear bond strength test.

The Shapiro-Wilk test was used to evaluate the normality of the SBS data, which did not refute normal distribution. Therefore, a 2-way analysis of variance (ANOVA) and Tukey honestly significant difference tests were performed. The chi-squared test was used to evaluate the difference among tested material-abutment pairs in terms of failure modes.[28] A statistical analysis software program (IBM SPSS Statistics, v23; IBM Corp) was used for all analyses (α=.05).

RESULTS

The SEM images of both airborne-particle abraded and nonabraded specimens had porous and rough surfaces with irregularities and cavities, which were more prominent and intense on the airborne-particle abraded ones. The AM specimens had many small and superficial surface irregularities, but the SM specimens had larger and deeper irregularities (Fig. 2).

The 2-way ANOVA showed that the material type (P<.001), abutment type (P=.014), and their interaction (P<.001) affected the SBS (Table 2). However, post hoc tests revealed that the difference between PEEK and Ti abutments was not statistically significant (P=.450). Among tested material-abutment pairs, AM_VS-PEEK had the highest SBS (P≤.001). SM_BC-PEEK and SM_GC had the lowest SBS followed by SM_BC-Ti (P<.001). Also, AM_FP-PEEK had lower SBS than AM_CT-Ti (P=.026). Among the tested materials, AM_VS had the highest and SM_GC had the lowest SBS (P≤.004). In addition, SM_BC had lower SBS than AM_CT and AM_FP (P<.001) (Table 3).

Table 4 shows the distribution of the failure modes within each material-abutment pair, while Figures 3 and 4 show representative specimens from tested materials within each abutment type. The chi-squared test showed a significant difference among material-abutment pairs in terms of the failure modes (P=.008). Among tested materials, the distribution of failure modes was only significant for AM_CT (P=.025), which had 80% adhesive failures and no cohesive failures. No cohesive failures were observed, and a minimum of 80% adhesive failure was observed within most of the restorative material-abutment pairs. For AM_VS-PEEK, the failures were 40% adhesive and 60% mixed, whereas for AM_CT-Ti and AM_VS-Ti, the failures were 60% adhesive and 40% mixed.

DISCUSSION

Regardless of the abutment material, AM specimens had significantly higher SBS values than SM specimens (P<.05). SM_BC had higher SBS values when cemented to Ti, and AM_VS had higher values when cemented to PEEK. Considering these results, the null hypothesis that the material would not affect the SBS was rejected.

A 5-MPa minimum SBS value between a resin-based material and a substrate is specified by the International Organization for Standardization (ISO) 10477–2020 standard.[29] The mean SBS values of all groups (5.80 MPa to 17.56 MPa) were above this threshold value. In addition, the SBS of AM specimens (12.91 MPa to 17.56 MPa) were above a reported minimum clinical

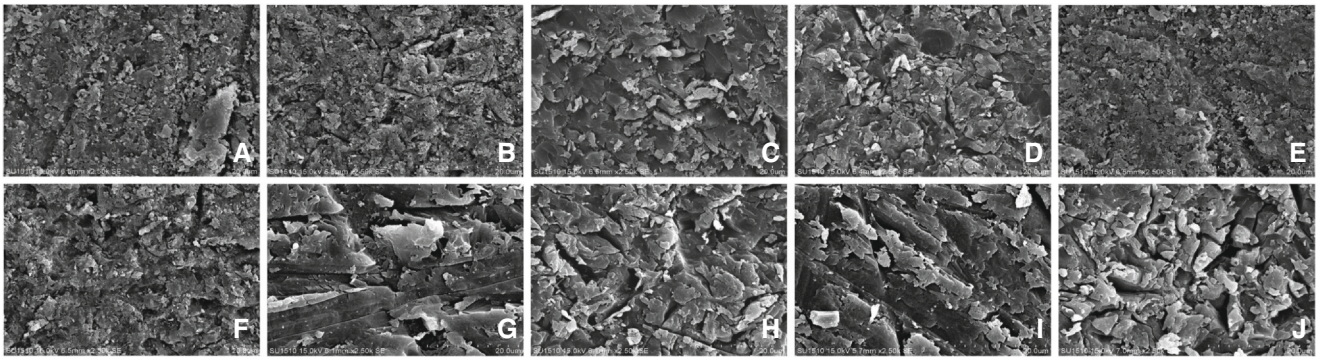

Figure 2. SEM images (original magnification ×2500) of additively (AM) and subtractively manufactured (SM) CAD-CAM restorative resin materials. Nonabraded and airborne-particle abraded Crowntec (A, B), Freeprint temp (C, D), VarseoSmile Crown Plus (E, F), G-CAM (G, H) and breCAM HIPC (I, J) groups.

Table 2. Results of 2-way analysis of variance test

	Type III Sum of Squares	df	Mean Square	F	*P*	Partial Eta Squared
Material type	1631.149	4	407.787	239.962	<.001	.914
Abutment type	10.719	1	10.719	6.308	.014	.065
Material type × Abutment type	105.736	4	26.434	15.555	<.001	.409

R^2=.920 (Adjusted R^2=.911)

Table 3. Mean ± standard deviations values with 95% confidence intervals (CI) for SBS values (MPa) within each restorative material-abutment pair

	Polyetheretherketone	Titanium	Total
Material	**Mean ±Standard Deviation (95%CI)**	**Mean ±Standard Deviation (95%CI)**	**Mean ±Standard Deviation (95%CI)**
AM_CT	14.13 ±1.83^{CD} (12.82–15.43)	14.94 ±1.73^{D} (13.70–16.17)	14.43 ±1.34^{c} (13.42–15.06)
AM_FP	12.91 ±0.84^{C} (12.31–13.51)	14.59 ±1.16^{CD} (13.76–15.42)	13.80 ±1.22^{c} (13.23–14.37)
AM_VS	17.56 ±1.69^{E} (16.35–18.77)	14.79 ±1.04^{CD} (14.05–15.53)	16.18 ±1.83^{d} (15.32–17.03)
SM_GC	5.80 ±1.33^{A} (4.86–6.76)	5.88 ±0.85^{A} (5.27–6.48)	5.89 ±1.02^{a} (5.42–6.37)
SM_BC	6.09 ±0.96^{A} (5.40–6.78)	9.57 ±1.12^{B} (8.77–10.37)	7.83 ±1.99^{b} (6.90–8.76)
Total	11.30 ±4.76* (9.94–12.65)	11.95 ±3.80* (10.87–13.04)	

Different superscript lowercase letters indicate significant differences among tested material-abutment pairs. Different superscript uppercase letters indicate significant differences among materials, while different superscript symbols indicate significant differences between abutments. Total values derived from pooled data (*P*<.05)

Table 4. Distribution of failure modes (n and %) within each restorative material-abutment pair

	Polyetheretherketone			Titanium			Total		
	Adhesive	**Mixed**	**Cohesive**	**Adhesive**	**Mixed**	**Cohesive**	**Adhesive**	**Mixed**	**Cohesive**
AM_CT	10 (100%)	0 (0%)	0 (0%)	6 (60%)	4 (40%)	0 (0%)	16 (80%)	4 (20%)	0 (0%)
AM_FP	9 (90%)	1 (10%)	0 (0%)	8 (80%)	2 (20%)	0 (0%)	17 (85%)	3 (15%)	0 (0%)
AM_VS	4 (40%)	6 (60%)	0 (0%)	6 (60%)	4 (40%)	0 (0%)	10 (50%)	10 (50%)	0 (0%)
SM_GC	8 (80%)	2 (20%)	0 (0%)	10 (100%)	0 (0%)	0 (0%)	18 (90%)	2 (10%)	0 (0%)
SM_BC	8 (80%)	2 (20%)	0 (0%)	10 (100%)	0 (0%)	0 (0%)	18 (90%)	2 (10%)	0 (0%)
Total	39 (78%)	11 (22%)	0 (0%)	40 (80%)	10 (20%)	0 (0%)			

value of 10 MPa,[30] regardless of the abutment material. Therefore, even though there were significant differences among tested restorative materials, the SBS of all restorative materials should be clinically acceptable. However, given that all restorative material specimens received a standardized pretreatment that involved air-borne-particle abrasion and MDP-containing primer application and that a single resin cement was used for luting, the differences among tested materials may have been related to the surface topography. SM resins are fabricated under standardized conditions with high temperature and pressure to minimize defects and increase structural integrity,[2,31] whereas AM resins are fabricated by the chemical bonding of consecutive layers and postpolymerization procedures.[31] The surface of AM specimens may have had irregularities and voids caused by the improper bonding between layers that improved penetration and interlocking of the resin cement.[1,31] Such irregularities and voids were seen in the SEM images (Fig. 2). In addition, while there were fewer adhesive residues on the abutments in the stereomicroscope images of AM specimens, the adhesive remnants were more prominent in the images of SM specimens (Figs. 3, 4). The differences in failure modes led to the rejection of the null hypothesis that the material and abutment type would not affect the failure mode. These differences can also be attributed to the better bonding of AM specimens to the tested adhesive agent. However, future studies should investigate the surface roughness and wettability of tested restorative materials for corroboration.

The only significant difference among the SBS of tested AM resin-based materials was observed when AM_VS was bonded to PEEK (*P*<.05). In addition, only the SBS of AM_VS to PEEK was higher than its SBS to Ti among the tested AM resin-based materials. A possible explanation for these results may be the chemical composition[2] and postpolymerization process[31] of AM_VS. AM_VS has a similar chemical composition to AM_CT with only slight differences. Even though all AM specimens were fabricated according to the respective manufacturer's recommendations, AM_VS was postpolymerized for a shorter time than AM_CT or AM_FP. Therefore, AM_VS may have had a more porous surface

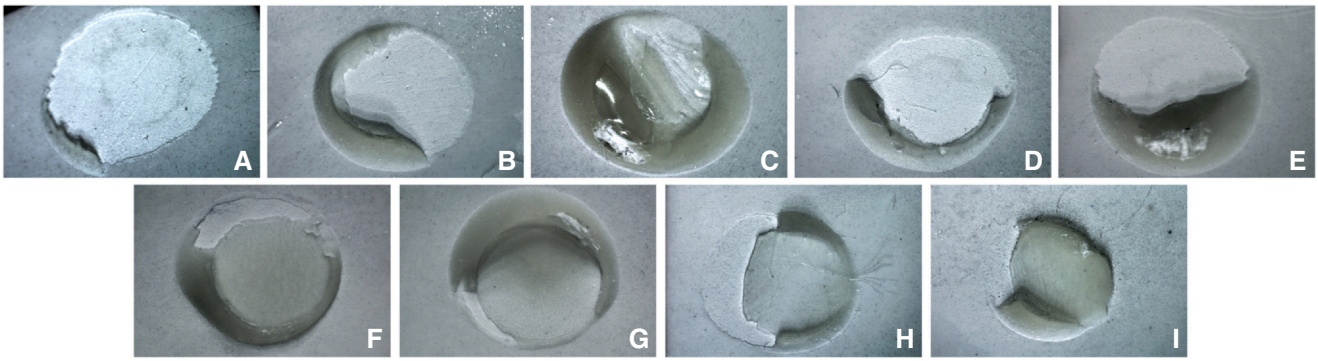

Figure 3. Representative stereomicroscope images (original magnification ×200) of polyetheretherketone abutment specimens after shear bond strength testing. Adhesive type fracture of Crowntec (A), adhesive and mixed type fractures of Freeprint temp (B, C), VarseoSmile Crown Plus (D, E), G-CAM (F, G) and breCAM HIPC (I, J) restorative material groups.

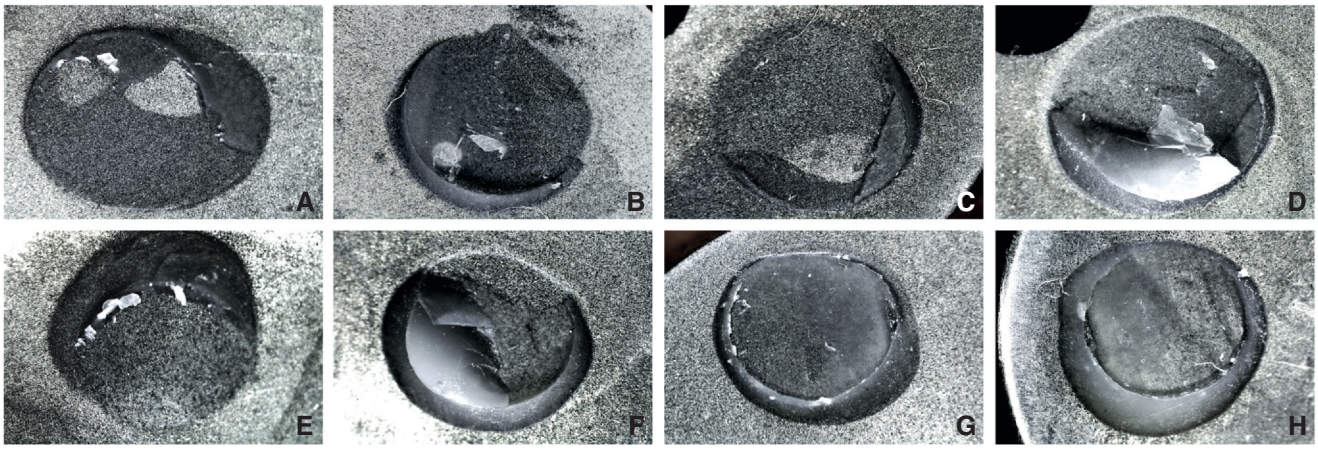

Figure 4. Representative stereomicroscope images (original magnification ×200) of titanium abutment specimens after shear bond strength testing. Adhesive and mixed type fractures of Crowntec (A, B), Freeprint temp (C, D), VarseoSmile Crown Plus (E, F), and adhesive type fractures of G-CAM (G), and breCAM HIPC (H) restorative material groups.

that was further roughened by the airborne-particle abrasion as seen in the SEM images (Fig. 2). Airborne-particle abrasion not only increased the surface irregularities but also severed polymer chains that generated free radicals, new binding sites for the adhesive agent and resin material.[28,32]

The bonding performance of polymer-based restorative materials to different frameworks has been evaluated in recent studies,[7,28] and it has been stated that the dimethacrylate- (DMA) based veneering material had better bonding to polyaryletherketone than the PMMA veneering material, attributed to the similar chemical composition of DMA veneering and resin cement materials.[28] The multifunctional molecules of DMA-based resin materials provide cross-linked connections with adhesives, whereas the monofunctional molecules and linear structures in PMMA-based resins may be accountable for the lower SBS.[33] In the present study, SM_BC had significantly higher SBS than SM_GC when cemented to a Ti abutment ($P<.05$). Even though the precise chemical composition of SM_BC and SM_GC was not disclosed by their manufacturers, the presence of graphene in SM_GC, which possibly leads to a more heterogeneous structure, might be related to the lower SBS when bonded to Ti.

The authors are unaware of a previous study on the SBS of the tested SM materials; therefore, comparison with previous studies on these materials was not possible. However, the bond strength of AM resins for definitive[8,22,23] and interim restorations[15,16,18–21] has been investigated. One of the studies on resins for definitive use evaluated the SBS of AM_CT and AM_VS to different substrates (dentin and Ti) and concluded that the differences between the materials were not significant.[8] Even though this result was consistent with the findings of the present study, Donmez et al[8] also reported that tested SM polymer-infiltrated ceramic network had higher SBS values, regardless of the substrate. This contradiction may be related to the differences in tested materials and resin cements. The higher

SBS of the SM polymer-infiltrated ceramic network when compared with AM_VS was also reported in another study, which evaluated the pull-off bond strength values of crown-shaped specimens.[23] The other study on AM definitive resins showed that different pretreatments affected the SBS of the 2 resins, one of which had a similar chemical composition to that of AM_VS.[22] The studies on the bond strength of AM interim resins have been investigated for the effect of material type,[18–20] print orientation,[15] cleaning methods,[16] and surface treatments.[16,18,19,21] Nevertheless, a direct comparison of the present study might be misleading because of methodologic differences.

Limitations of the present study included that only one milling unit and one 3D printer were used. All AM specimens were fabricated with a standardized and manufacturer-recommended layer thickness and build orientation, and different results may be achieved if these settings are changed. To standardize the cementation procedures between different abutment materials and CAD-CAM restorative materials, PEEK specimens were also airborne-particle abraded with aluminum oxide, and different surface treatments have been proposed for PEEK.[7] A single resin cement was used to perform cementation, and different resin cements with different polymerization methods may have affected these results. In addition, the study only focused on the inherent SBS of tested materials, and the absence of aging is another limitation. The SBS test does not require any additional steps after cementation. However, localized high-stress areas that result in underestimated bond strength values might be generated during SBS testing[34]; thus, these results should be substantiated with other bond strength tests such as tensile bond strength. Future studies focusing on the mechanical and optical properties of tested resin-based materials when cemented on abutments of different materials with different resin cement after aging are needed to elaborate this study's findings.

CONCLUSIONS

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

1. The tested additively manufactured resins had higher bond strength than the subtractively manufactured ones, regardless of the abutment material.
2. One of the additively manufactured resins (VarseoSmile Crown Plus) mostly had higher and subtractively manufactured nanographene-reinforced polymethylmethacrylate mostly had lower shear bond strength values. The abutment material had a small effect on measured shear bond strength values.
3. Adhesive failures were observed more frequently, and no cohesive failures were observed.

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