OSR
ORAL SCIENCES REPORTS

Original Article

The Effects of Solutions and Surface Treatments on the Shear Bond Strength Between Aged 3D-Printed Provisional Restorations and Repair Materials

Natthamol Aroonmanakun[1], Lapon Mutthapong[2], Boonchai Chaoklaiwong[2], Pisaisit Chaijareenont[2], Piriya Yavirach[2], Apichai Yavirach[2]

[1]Master of Science Program in Dentistry, Department of Prosthodontics, Faculty of Dentistry, Chiang Mai University, Thailand
[2]Department of Prosthodontics, Faculty of Dentistry, Chiang Mai University, Thailand

Received: December 12, 2025
Revised: March 7, 2025
Accepted: August 21, 2025

Corresponding Author:
Apichai Yavirach, Department of Prosthodontics, Faculty of Dentistry, Chiang Mai University, Chiang Mai 50200, Thailand
E-mail: apichai.y@cmu.ac.th

Abstract

Objectives: To evaluate the effects of different solutions, surface treatments, and repair materials on the shear bond strength (SBS) between aged 3D-printed provisional materials and repair materials.

Methods: This study printed samples with 3D-printed resin and divided them into 16 groups (n=10): non-immersion and three solutions (40% ethanol, heptane, and cola) × two surface treatments (no abrasion [NA] and sandpaper and sandblasting [SP&SB]) × two repair materials (Poly(methyl methacrylate) [PMMA] and bis-acryl). The samples were immersed in the solutions for six days and then surface-treated. Nine samples were randomly selected for surface examination, including surface roughness, surface characteristics, and contact angle. Then, they were bonded with the repair materials, followed by 2,500 cycles of thermocycling. SBS was determined using a universal testing machine, and failure modes were determined by stereomicroscope. A three-way ANOVA was conducted to evaluate the effects of the solution, surface treatment, and repair material on SBS. SBS, surface roughness, and contact angle were compared among groups using one-way ANOVA, followed by post-hoc Tukey's tests.

Results: The three-way ANOVA analysis revealed a significant interaction among solutions, surface treatments, and repair materials ($p<0.05$). The mean SBS did not differ significantly between immersed and non-immersed groups. Among the solutions, surface treatments, and repair materials, SBS significantly increased after SP&SB surface treatment ($p<0.05$) and was significantly higher in the bis-acryl group than in the PMMA group ($p<0.05$). Cohesive failure was primarily observed when SP&SB and/or bis-acryl was applied. The mean Ra and contact angle were significant different after applied SP&SB ($p<0.05$). Additionally, SP&SB groups exhibited an irregular surface with multiple porosities.

Conclusions: The solutions alone did not significantly affect the SBS between aged 3D-printed provisional materials and two repair materials. However, SBS differed significantly after SP&SB treatment of the aged 3D-printed provisional materials and/or when they were repaired with bis-acryl.

Keywords: bis-acryl, food-stimulating agents, PMMA, provisional crown, sandblasting

Introduction

The fabrication of the provisional restoration is one of the essential procedures in fixed prosthodontics treatment. For patients requiring full-mouth rehabilitation, especially those with parafunctional habits, long-term provisional restorations are crucial for comprehensively evaluating occlusion, function, and aesthetics over several months.[1,2] Provisional restorations must be durable but easily repairable since they may be worn or broken down due to prolonged use and functional forces.[3] Previously, provisional restorations were fabricated using conventional techniques, which had several drawbacks, including residual monomer, heat from exothermic reactions, and shrinkage after polymerization.[4] Currently, provisional restorations are commonly fabricated using computer-aided design (CAD) and manufacturing (CAM) technology. The CAD/CAM approach offers various advantages, including reduced material and manufacturing errors, shorter processing times, and decreased material usage.[5,6]

With CAD/CAM technology, provisional prostheses are fabricated using two techniques: subtractive manufacturing (SM) and additive manufacturing (AM) or 3D-printed technology.[7] In SM, a prefabricated block is milled using computer-controlled milling tools. However, this technique has drawbacks, such as challenges with recycling waste materials and addressing inaccessible areas due to the limited radius of the milling tool.[1,7,8] In contrast, AM involves building the material layer by layer, allowing more complex shapes to be produced, eliminating the wear of milling burs, and reducing material consumption.[1] Previous studies have found that the mechanical properties of 3D-printed provisional material were greater than those of poly(methyl methacrylate) (PMMA) and milled PMMA.[9-12] The accuracy of the 3D-printed provisional crown was comparable to SM and superior to the conventional technique.[13,14] Furthermore, Jain *et al*.,[15] demonstrated that 3D-printed provisional material was an alternative to long-term provisional material.

Long-term provisional restorations are subjected to biodegradation due to various contributing factors, including exposure to saliva, chemical components in the diet, and diverse mechanical and thermal stresses.[16-18] *In vitro* studies apply food-stimulating agents (FSAs) according to the US Food and Drug Administration standards to simulate the effects of food and beverages.[19] FSAs function as plasticizers by penetrating the polymer matrix and increasing intermolecular spacing, contributing to the enlargement and dissolution of polymer chains, thereby degrading the mechanical and physical properties of provisional materials.[20-23] Additionally, a previous study has found that acidic beverages can deteriorate the fracture resistance of bis-acryl composite crowns.[24] The biodegradation of provisional materials may also be initiated by fatigue caused by the relatively low but repetitive forces generated during normal chewing.[16] Physiologic occlusal forces in natural dentition and parafunctional habits, such as bruxism and nocturnal forces, typically range from 200 to 900 N; which is sufficient to deteriorate provisional crowns.[25,26] Furthermore, Luthardt *et al*.,[27] evaluated the clinical outcomes of 64 bis-acrylic provisional restorations in 32 patients, reporting fractures in four cases after a mean duration of 37.5 days. Therefore, chairside repairs remain necessary in clinical practice.

When repairing provisional materials, surface preparation prior to bonding has been recommended to enhance bond strength, as aged restorations exhibit fewer free radicals, fewer free carbon double bonds, and greater water absorption.[28,29] Mechanical surface treatments, such as sandblasting with aluminum oxide and grinding with a carbide bur, have been shown to increase the bond strength between 3D-printed materials and repair materials.[30-33] However, there is controversy regarding different repair materials. Monomethacrylates and dimethacrylates have frequently been used for the chairside repair of conventional provisional crowns.[34] Previous studies have reported that 3D-printed provisional materials had greater shear bond strength (SBS) with bis-acryl than PMMA.[31,35] However, Palavicini *et al*., reported the opposite.[36] Nonetheless, the effects of surface treatments and repair materials on SBS between aged 3D-printed provisional material and repair material have not been well established. Therefore, this study aimed to investigate the SBS between aged 3D-printed provisional material and repair materials, considering the effects of solutions, surface treatments, and repair materials. The first hypothesis was there was no significant different in SBS between repair materials and aged 3D-printed provisional after immersed in different solutions. The second was there was no significant difference in SBS between repair materials and aged 3D-printed provisional

restorations, regardless of whether surface treatment is applied. The third hypothesis was there was no significant difference in SBS among different types of repair materials.

Materials and Methods

This study used digital light processing (DLP) 3D-printed provisional material and two repair materials. Their details are provided in Table 1, and the experimental design is illustrated in Figure 1.

Sample size calculation

G*power software (version 3.1.9.7; Heinrich-Heine-Universität Düsseldorf, Düsseldorf, Germany) was used to determine the sample size. The effect size was determined from the pilot study, with a value of α=0.05 and a power of 0.95. The sample size was calculated to be 8, but in order to account for potential variability, this study elects to include 10 samples.

Sample preparation

The cylindrical shaped specimens were digitally

Table 1: Description of the 3D-printed provisional material and repair materials.

Material	Manufacturer	Composition	Type	Lot. number
NextDent C&B MFH	NextDent B.V., Soesterberg, Netherlands	Not applicable.	UV-light cured resin	WT162N03
UNIFAST™ Trad (PMMA)	GC America, Inc.	Powder: poly((ethyl methacrylate)-co-(methyl methacrylate)) poly(methyl methacrylate), dibenzoyl peroxide, titanium dioxide, iron(III) oxide, cellulose acetate Liquid: Methyl methacrylate, N,N dimethyl-p-toluidine.[37]	Self-cure resin	2212271
Protemp™ 4 (Bis-acryl)	3M ESPE, St. Paul, MN, USA	Catalyst Paste: ethanol, 2,2'-((1-methylethylidene) bis(4,1-phenyleneoxy)) bis-diacetate, benzyl-phenyl-barbituric acid, silane treated silica, tert-butyl peroxy- 3,5,5-trimethylhexanoate Base Paste: dimethacrylate (Bis-EMA 6), silane-treated amorphous silica, reaction products of 1,6-diisocyanatohexane with 2-((2-methacryloyl) ethyl) 6-hydroxyhexanoate and 2-hydroxyethyl methacrylate, silane-treated silica.[37]	Self-cure resin	9169729

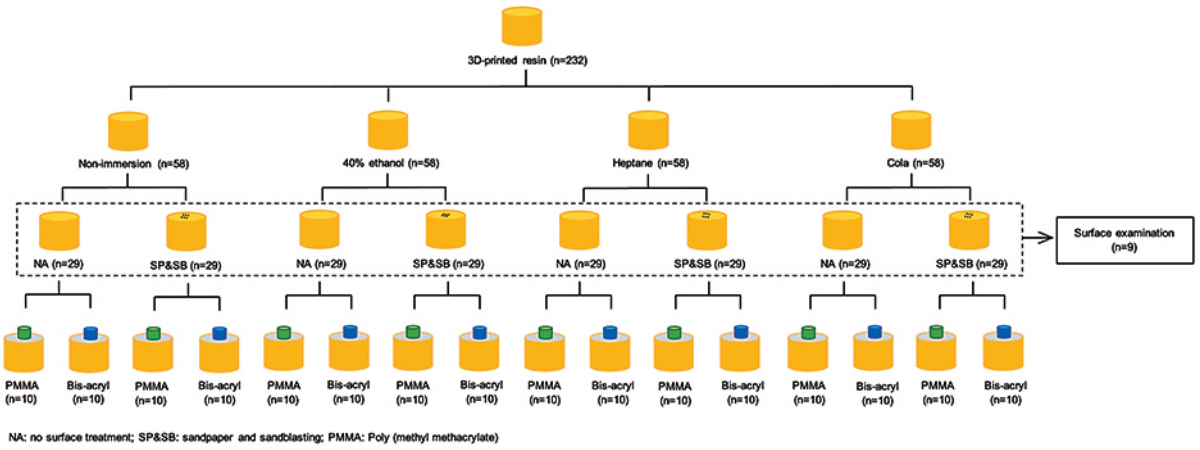

Figure 1: The experimental design.

designed using CAD software (Thinkercad, version 2024; Autodesk, Inc., San Francisco, CA, USA) with a diameter of 8 mm and thickness of 12 mm and exported in the Standard Tessellation Language (STL) format. Next, the STL files were transferred into the CAM software (3D Sprint; 3D Systems, Rock Hill, SC, USA). Then, 232 samples were printed in 50-µm layers with a 0° angle using photopolymerized resin (NextDent C&B MFH; NextDent B.V., Soesterberg, Netherlands) and a DLP 3D Printer (5100 3D Printer; NextDent B.V., Soesterberg, Netherlands). Next, the support structures were removed, and the specimens were cleaned with 91% isopropanol. Then, they were post-polymerized in a UV oven (LC-3DPrint Box; NextDent B.V., Soesterberg, Netherlands) for 40 minutes to promote the completion of the curing process. Finally, the samples were immersed in glycerin to complete the reaction of the remaining monomer. After fabrication, each sample's average surface roughness (Ra) was assessed using a contact profilometer (Surftest SJ-310; Mitutoyo, Kanagawa, Japan) to achieve a consistent surface roughness.

Aging processes of 3D-printed provisional materials

The 232 samples were categorized into four solution treatment groups (n=58/group): no immersion (None) and immersion in 40% ethanol (Eth), heptane (Hep), or cola. Here, 40% ethanol represented alcoholic beverages; heptane represented vegetable oils, butter, and meat-based oils; and cola represented acidic drinks. The samples were immersed in 200 mL of the solution for six days, corresponding to six months of intraoral use[38], in an incubator at 37°C to mimic oral cavity conditions. The pH was measured before and after immersion. The solutions were changed daily to avoid contamination. After six days, the samples were rinsed with distilled water and dried.

Surface treatments

The samples in each solution treatment group were divided into two surface treatment subgroups (n=29/group): no abrasion (NA) and grinding with 220 grit sandpaper (DCC waterproof abrasive paper; TOA, Thailand) followed by sandblasting with 50 µm aluminum oxide (SP&SB) using an airborne-particle abrasion device (Basic Classic Fine Sandblasting Unit; Renfert, Germany) for 10 seconds at a pressure of 0.2 MPa, maintaining 10 mm from the sample's surface. Then, the samples were subjected to ultrasonic cleaning in distilled water for five minutes to remove debris generated during the surface treatment process. Then, nine samples from each group were randomly selected for surface examination by scanning electron microscopy (SEM; fourth-generation VEGA; TESCAN, Czech Republic), surface roughness measurement using a contact profilometer (Surftest SJ-310; Mitutoyo, Kanagawa, Japan), and contact angle measurement using a contact angle meter (KINO, Boston, MA, USA).

Repair procedures

The remaining 20 samples in each surface treatment subgroup were further divided into two repair material subgroups (n=10/group): PMMA and bis-acryl. According to the ISO 29022:2013 standards, the procedure used a stainless steel (SS) mold measuring 3 mm in diameter and height, with the unexposed areas protected by masking tape. PMMA and bis-acryl were prepared according to the manufacturer's instructions. Next, the material was injected into the SS mold until it was completely filled and covered with a microscope glass slide. Polymerization was allowed to proceed for five minutes. Then, the SS mold and masking tape were removed and wiped with gauzed-soak alcohol to eliminate the smear layer formed by atmospheric oxygen. All specimens were immersed in distilled water at 37°C for a duration of 24 hours before thermocycling.

Thermocycling

Artificial aging was performed using a thermocycling system (HWB332R, CWB332R, TC301) designed to replicate the temperature fluctuations experienced in the oral cavity. Thermocycling was conducted for 2,500 cycles, alternating the temperature between 5°C and 55°C, with a dwell time of 30 seconds at each temperature. This process simulates the thermal conditions that occur in the oral cavity over three months.[39] The samples were immersed in distilled water at 37°C for 24 hours before measuring the SBS.

SBS and failure mode analysis

The samples were mounted into a testing jig compatible with a universal testing machine (model 5566; Instron, Norwood, MA, USA). Next, they were exposed to shear forces using a flat blade at a crosshead speed of 1.0 mm/min until failure occurred. The bond strength values (MPa) were determined by dividing the failure load (N) by the surface area of the cylindrical specimen (mm^2), as shown in the formula below. Then, the specimens were analyzed by optical microscope (Eclipse 50i; Nikon,

Tokyo, Japan) to determine the failure mode, which was classified into adhesive, mixed, and cohesive failure. Adhesive failure was defined when less than 10% of the repair resin remained. When over 50% of the temporary base material fragmented, cohesive failure was identified. Mixed failure served as the intermediary between the two failure modes.[31] 5 samples of each failure modes were randomly selected for analysis the surface characteristic by scanning electron microscope analysis (TESCAN VEGA's 4th, TESCAN, Czech Republic)

σ (MPa) = F / A, where F is the load at failure (N), and A is the repaired surface area (mm^2).

Statistical analysis

Each group's SBS (MPa), surface roughness (Ra), and contact angle were calculated and are reported as the mean±standard deviation. The data were analyzed using SPSS Statistics (version 25.0; IBM, Corp., Armonk, NY, USA). The effects of the solution, surface treatment, and repair material on SBS were examined using a three-way analysis of variance (ANOVA). The SBS, surface roughness, and contact angle were compared between groups using one-way ANOVA with post-hoc Tukey's tests. A $p<0.05$ was considered statistically significant.

Results

The three-way ANOVA analysis showed a significant interaction among the three factors—solution, surface treatment, and repaired material ($p<0.05$; Table 2). Additionally, there were significant interactions between solution and surface treatment ($p<0.001$; Table 2), and between solution and repaired material ($p<0.05$; Table 2). The interaction between surface treatment and repaired material was also significant ($p<0.001$; Table 2).

SBS

The mean and standard deviation of the SBS (MPa) between aged 3D-printed provisional material and repair materials, along with the p-values, were demonstrated in Table 3.

The mean SBS was greatest for aged 3D-printed provisional material immersed in 40% ethanol, followed by SP&SB surface treatment and repair with bis-acryl (Eth/SP&SB/Bis-acryl; 49.08±2.40 MPa) and lowest for aged 3D-printed provisional material immersed in 40% ethanol, followed by NA surface treatment and repaired with PMMA (Eth/NA/PMMA; 9.99±2.11 MPa).

The mean SBS did not differ significantly between the None/NA, Eth/NA, Hep/NA, and Cola/NA groups, regardless of the repair material. However, the mean SBS was significantly higher in the SP&SB group than in the NA group, regardless of the repair material and solution. In addition, the mean SBS was significantly higher in the NA/Bis-acryl group than in the NA/PMMA group. Similarly, the mean SBS was significantly greater in the SP&SB/Bis-acryl group than in the SP&SB/PMMA group.

Following SP&SB, the mean SBS differed significantly between the Eth/SP&SB/Bis-acryl group and the None/SP&SB/Bis-acryl group. Similarly, the mean SBS

Table 2: The three-way ANOVA analysis the effect of 3 factors: solutions, surface treatment and, repaired materials on SBS (MPa) with significant level of $p<0.05$.

Tests of between-subjects effects					
Dependent variable: shear bond strength					
source	**Type III Sum of Squares**	**df**	**Mean square**	**F**	**Sig.**
Corrected model	21132.659	15	1408.844	131.399	.0000
intercept	100560.784	1	100560.784	9379.033	.0000
Surface treatment	13684.081	1	13684.081	1276.277	.0000
Repair material	6025.789	1	6025.789	562.010	.0000
solution	116.018	3	38.673	3.607	.015
Surface treatment*repair material	482.122	1	482.122	44.966	.000
Surface treatment*solution	642.803	3	214.268	19.984	.000
Repair material*solution	87.107	3	29.036	2.708	.047
Surface treatment*repair material*solution	94.731	3	31.577	2.945	.035

Table 3: The mean and standard deviation of SBS (MPa) by solution, surface treatment, and repair material.

Solution	PMMA		Bis-acryl	
	NA	SP&SB	NA	SP&SB
None	12.70±2.62^{a}	24.05±4.01^{c,d,e}	22.89±2.77^{b,c,d}	38.00±1.82^{f}
Eth	9.99±2.11^{a}	28.41±4.30^{e}	18.64±1.40^{b}	49.08±2.40^{g}
Hep	10.91±2.36^{a}	26.83±4.85^{d,e}	19.57±2.67^{b,c}	41.58±3.41^{f}
Cola	12.11±3.35^{a}	26.49±4.52^{d,e}	19.78±4.46^{b,c}	40.10±2.76^{f}

Each same superscript letter indicates no significant difference between groups at $p>0.05$.; None: no immersion; Eth: 40% ethanol; Hep : heptane; PMMA: Poly(methyl methacrylate); NA: no surface treatment; SP&SB: sandpaper and sandblasting.

was greatest in the Eth/SP&SB/PMMA group, followed by the Hep, Cola, and None groups, regardless of the repair material.

Failure modes

The failure modes observed in each experimental group are illustrated in Figure 2. Regardless of the solution applied. The SP&SB/Bis-acryl groups predominantly exhibited cohesive failure, whereas the NA/PMMA and NA/Bis-acryl groups primarily demonstrated adhesive failure. However, the None/NA/Bis-acryl group predominantly showed mixed failure and the SP&SB/PMMA groups exhibited a predominance of mixed failure as well. SEM images of the failure modes are presented in Figure 3.

SEM micrographs

SEM images of the 3D-printed provisional materials are presented in Figure 4. The surface showed a smooth layer of printed polymer in the None group (Figure 4A). However, the surface exhibited a more irregular, visibly dissolved morphology and distinct polymer beads in the Eth, Hep, and Cola groups (Figure 4 B-D). Figure 5 shows visible crazing lines (arrows) on the surface in the Eth groups. The surface showed homogenous multiple porosities and irregularities in the SP&SB groups (Figure 4E-H). The surface in the Eth/SP&SB groups showed greater morphological variation, characterized by varied sizes and shapes, numerous porosities, and a distinctly roughened surface (Figure 4F).

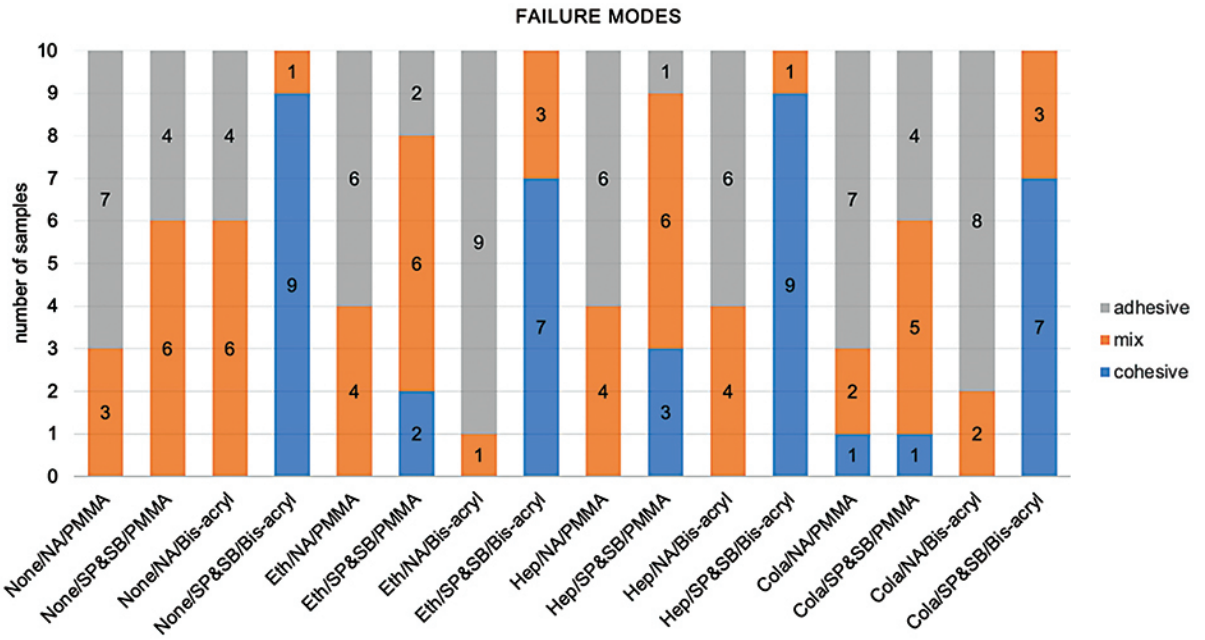

Figure 2: Distribution of failure modes in each experimental group.

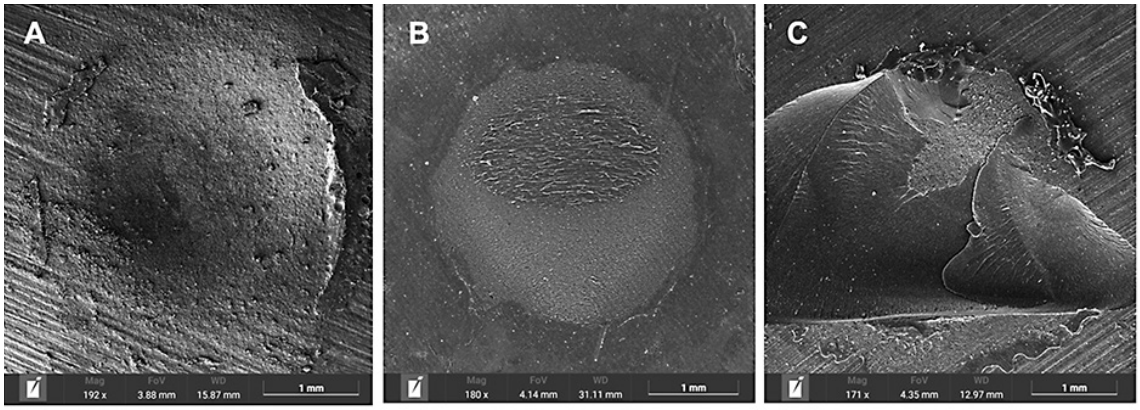

Figure 3: SEM micrographs of each failure mode. (A) Adhesive failure; (B) mixed failure; (C) cohesive failure.

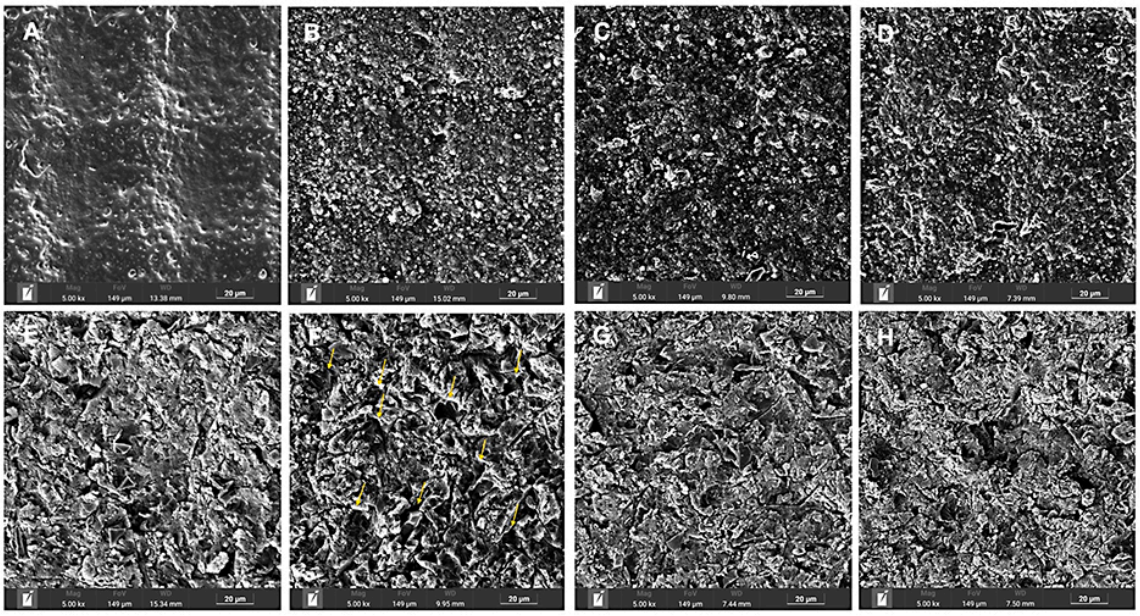

Figure 4: SEM micrographs of specimens treated with each solution and surface treatment (magnification: 5.00 kx). (A) None/NA; (B) Eth/NA; (C) Hep/NA; (D) Cola/NA; (E) None/SP&SB; (F) Eth/SP&SB (arrows indicate numerous porosities); (G) Hep/SP&SB; (H) Cola/SP&SB.

Surface roughness

The mean and standard deviation of surface roughness (μm) are presented in Table 4. The mean Ra was highest in the Eth/SP&SB group (3.48±0.30 μm) and lowest in the None/NA group (0.96±0.06 μm). Comparing the mean Ra between surface treatments, it was significantly higher in the SP&SB groups than in the NA groups. However, mean Ra showed no significant difference between the NA groups among solutions.

Contact angle

The mean and standard deviation of the contact angle are presented in Table 4. In all solutions, the contact angle was significantly lower in the SP&SB subgroup

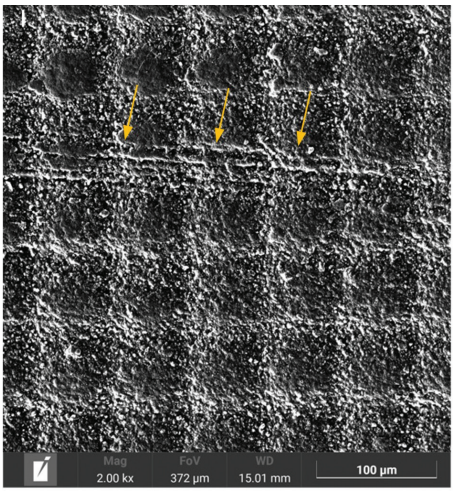

Figure 5: An SEM micrograph of a specimen in the Eth group (magnification: 2.00 kx). The arrows indicate crazing line.

compared to the NA subgroup. Among the SP&SB groups, the contact angle was the lowest in the Eth/SP&SB group (82.26±2.36), differing significantly from the None/SP&SB group. However, the contact angle did not differ significantly between solutions among the NA groups.

Discussion

Our study investigated the effects of solutions, surface treatments, and repair materials on the SBS between 3D-printed provisional materials and repair materials. According to the result. The first hypothesis was accepted, while the second and third one were rejected.

It demonstrated that solutions alone did not significantly impact the SBS between the 3D-printed provisional material and repair materials. In contrast, previous studies have reported that FSAs affected the hardness, flexural strength, and surface roughness of conventional provisional materials.[22,40,41] Additionally, FSAs were found to decrease the SBS between the conventional denture base and hard reline material.[20] Our study found that the surface roughness and contact angle of aged 3D-printed provisional materials did not differ significantly between the Eth, Hap, and Cola groups and the None group. Moreover, previous studies showed that the surface morphology of 3D-printed denture base materials demonstrated superior chemical stability compared to conventional and milled denture base materials.[32,42,43] Furthermore, the uppermost part of the 3D-printed provisional material showed greater polymerization than its foundation.[44]

In our study, SBS did not differ significantly between the Cola and None groups, consistent with previous studies.[20,21] The corrosive effects of acids are determined by their pH and pKa; a lower pKa signifies a stronger acid with an enhanced ability to donate protons.[45] Fatemi *et al*.,[20] found that acetic acid did not significantly affect the SBS between a conventional denture base and hard reline material. Similarly, citric acid is a weak acid with a relatively high pKa. Therefore, it was expected to have a negligible effect on the SBS of the materials.[20] In our study, phosphoric acid, the main acid in cola, is also a weak acid. Therefore, it might only slightly affect the surface roughness and integrity of 3D-printed provisional materials.

Whether repaired with PMMA or bis-acryl, the SBS and surface roughness differed significantly between the SP&SB and NA groups, consistent with previous studies.[31,35,43,46,47] SEM images also demonstrated a roughened surface with porosities. Grinding the surface with 220-grit sandpaper resembled using a carbide bur to eliminate contaminated surfaces that contain fewer free radicals.[48] Sandblasting promoted an irregular surface and increased the surface bonding area, enhancing micromechanical retention.[30] Furthermore, the contact angle significantly decreased after SP&SB, resulting in increased surface wettability, which facilitates the penetration of repair materials into the substrate. Moreover, the failure mode after SP&SB was predominantly cohesive failure. These results demonstrated that SP&SB was a reliable and effective technique for enhancing the SBS of aged 3D-printed provisional materials.

In our study, the mean SBS was highest in the Eth/SP&SB group among solutions, whether repaired with PMMA or bis-acryl. Moreover, SBS differed significantly between the Eth/SP&SB/Bis-acryl group and the None/SP&SB/Bis-acryl group. Previous studies have reported that ethanol caused a greater reduction in the mechanical properties of the provisional material than heptane since it exhibited a stronger plasticizing effect.[20,22,40] Solutions penetrated the interface layer due to the printed structure, where the interlayer bonding was weaker than the intralayer bonding, leading to the dissolution of the polymer chains.[44,49,50] As shown in the SEM images (Figure 5),

Table 4: Mean and standard deviation of surface roughness (Ra) and contact angle by solution and surface treatment.

Solution	Surface roughness (Ra)		Contact angle	
	NA	SP&SB	NA	SP&SB
None	0.96±0.06^{a}	2.01±0.23^{b}	96.04±1.22^{g}	82.26±2.36^{e,f}
Eth	1.17±0.15^{a}	3.48±0.30^{c}	92.84±2.56^{g}	73.70±3.21^{d}
Hep	1.45±0.08^{a}	2.36±0.04^{b}	90.74±1.03^{g}	78.18±1.06^{d,e}
Cola	1.29±0.03^{a}	2.1±0.23^{b}	89.10±4.31^{g}	80.06±2.86^{d,e}

Each same superscript letter indicates no significant difference between groups at $p>0.05$.; None: no immersion; Eth: 40% ethanol; Hep: heptane; PMMA: Poly(methyl methacrylate); NA: no surface treatment; SP&SB: sandpaper and sandblasting.

crazing lines were observed at the interface layer due to ethanol's plasticizing effect, compromising the structural integrity and potentially increasing susceptibility to pressure from sandblasting. Furthermore, previous studies have indicated that ethanol is a more effective polymer solvent for conventional provisional materials than heptane, as their solubility parameters are closer.[15,23,24] However, the solubility of 3D-printed materials has been insufficiently studied.

The SBS was significantly higher in the bis-acryl group than in the PMMA group within the same solutions and surface treatments, consistent with previous studies.[31,51] Jeong *et al*.,[31] reported that bis-acryl composites could achieve complex polymerization with 3D-printed resins. In contrast, 3D-printed resins are composed of photopolymerized resins with bifunctional monomers, which do not copolymerize with methyl methacrylate monomers.[52] Moreover, bis-acryl composites use an automix system that ensures a consistent mixture and minimizes the risk of air bubbles, resulting in fewer flaws and porosities.[51,53] The optimal SBS was also achieved when the repair materials had comparable chemical composition to the substrates.[54] The 3D-printed resin was primarily composed of ethoxylated bisphenol A dimethacrylate, urethan dimethacrylate, and bisphenol A-glycidyl methacrylate (Bis-GMA).[55,56] In addition, bis-acryl and Bis-GMA composites share similar chemical structures.[57] Therefore, the chemical composition of 3D-printed provisional resins might be more similar to bis-acryl composites than to conventional PMMA. similarity was further supported by the predominantly cohesive failures found in bis-acryl groups.

Based on the three-way ANOVA, an interaction was observed between solutions, surface treatments, and repair materials. The SBS was greatest in the Eth/SP&SB/Bis-acryl group and lowest in the Eth/NA/PMMA group. These findings suggest that SP&SB and/or bis-acryl significantly enhance the SBS of aged 3D-printed provisional materials, since SP&SB improved micromechanical retention by increasing surface roughness and wettability, the vinyl group in the Bis-acryl composite facilitated chemical bonding. A cohesive failure was mainly observed when bis-acryl and/or SP&SB were applied. In contrast, the solutions did not affect the SBS. However, 40% ethanol appeared to have a more pronounced effect on the structural integrity of the 3D-printed provisional materials than heptane and cola. According to the findings from our study, aged 3D-printed provisional materials should be ground and sandblasted before repairing, and bis-acryl was recommended as the repairing material for greater bond strength. However, using sandpaper might not be practical in a clinical setting, hence a previous study suggested grinding PMMA with a carbide bur before repairing PMMA for comparable results.[48]

Our study had several limitations. Firstly, it used an *in vitro* experimental design that tested only one type of 3D-printed provisional resin and two types of repair materials. Secondly, provisional crowns are not continuously immersed in solutions in the oral environment; they are exposed intermittently when the patient consumes foods and beverages. Thirdly, it did not simulate occlusal force or the presence of saliva. Therefore, *in vivo* studies should be conducted to evaluate the effects of the oral environment on 3D-printed provisional crowns. Furthermore, future studies should investigate other types of provisional crowns and repair materials.

Conclusions

Based on the findings of this *in vitro* study, solutions alone did not significantly impact the SBS between the 3D-printed provisional material and repair materials. However, the SBS differed significantly when the aged 3D-printed provisional material underwent SP&SB and/or was repaired with bis-acryl.

Acknowledgments

This study was supported by the Faculty of Dentistry at Chiang Mai University, Thailand. The authors would like to acknowledge the Science and Technology Park, Chiang Mai, Thailand, for technical support and assistance.

Conflict of Interest

The authors declare no conflicts of interest.

Funding

The Faculty of Dentistry at Chiang Mai University, Thailand.

References

1. Kessler A, Hickel R, Reymus M. 3D printing in dentistry-state of the art. Oper Dent. 2020;45(1):30-40.
2. Adulroj V CP, Yavirach A, Angkasith P. Semi-permanent restorations just temporary or long-lasting use?: a review of the literature. CM Dent J. 2023;44(1):13-21.
3. Rivera-Morales WC, Mohl ND. Restoration of the vertical dimension of occlusion in the severely worn dentition. Dent Clin North Am. 1992;36(3):651-64.
4. Albahri R, Yoon HI, Lee JD, Yoon S, Lee SJ. Shear bond strength of provisional repair materials bonded to 3D printed resin. J Dent Sci. 2021;16(1):261-7.
5. Charoenbhakdee S, Jiangkongkho P. Computer-aided design vs conventional design and bite transferring method for full mouth rehabilitation. CM Dent J. 2022;43(2):13-22.
6. Rexhepi I, Santilli M, D'Addazio G, Tafuri G, Manciocchi E, Caputi S, *et al*. Clinical applications and mechanical properties of CAD-CAM materials in restorative and prosthetic dentistry: a systematic review. J Funct Biomate. 2023;14(8):431.
7. Strub JR, Rekow ED, Witkowski S. Computer-aided design and fabrication of dental restorations: current systems and future possibilities. J Am Dent Assoc. 2006;137(9):1289-96.
8. Bosch G, Ender A, Mehl A. A 3-dimensional accuracy analysis of chairside CAD/CAM milling processes. J Prosthet Dent. 2014;112(6):1425-31.
9. Reeponmaha T, Angwaravong O, Angwarawong T. Comparison of fracture strength after thermo-mechanical aging between provisional crowns made with CAD/CAM and conventional method. J Adv Prosthodont. 2020;12(4): 218-24.
10. Taşın S, Ismatullaev A. Comparative evaluation of the effect of thermocycling on the mechanical properties of conventionally polymerized, CAD-CAM milled, and 3D-printed interim materials. J Prosthet Dent. 2022;127(1):173.e1-.e8.
11. Park SM, Park JM, Kim SK, Heo SJ, Koak JY. Flexural strength of 3D-printing resin materials for provisional fixed dental prostheses. Materials (Basel). 2020;13(18):3370.
12. Park JM, Ahn JS, Cha HS, Lee JH. Wear resistance of 3D printing resin material opposing zirconia and metal antagonists. Materials (Basel). 2018;11(6):1043.
13. Karasan D, Legaz J, Boitelle P, Mojon P, Fehmer V, Sailer I. Accuracy of additively manufactured and milled interim 3-unit fixed dental prostheses. J Prosthodont. 2022;31(S1):58-69.
14. Shabana F, Ahmed A, Mekkawi W. The outcome of 3D printing and CAD-CAM techniques on marginal accuracy of provisional crowns. Al-Azhar J Dent. 2024;11(4):1-6.
15. Jain S, Sayed ME, Shetty M, Alqahtani SM, Al Wadei MHD, Gupta SG, *et al*. Physical and mechanical properties of 3d-printed provisional crowns and fixed dental prosthesis resins compared to CAD/CAM milled and conventional provisional resins: a systematic review and meta-analysis. Polymers (Basel). 2022;14(13):2691.
16. Bettencourt AF, Neves CB, de Almeida MS, Pinheiro LM, Oliveira SA, Lopes LP, *et al*. Biodegradation of acrylic based resins: a review. Dent Mater. 2010;26(5):e171-80.
17. Gad MM, Abualsaud R. Effect of repair and surface treatments on the strength of digitally fabricated resin-based dental prostheses: a systematic review of *in vitro* studies. J Dent. 2024;141:104806.
18. Alqutaibi AY, Baik A, Almuzaini SA, Farghal AE, Alnazzawi AA, Borzangy S, *et al*. Polymeric denture base materials: a review. Polymers (Basel). 2023;15(15):3258.
19. Administration FaD. FDA guidelines for chemistry and technology requirements of indirect additive petitions. FDA, editor. Washington: FDA; 1976.
20. Fatemi FS, Vojdani M, Khaledi AAR. The effect of food-simulating agents on the bond strength of hard chairside reline materials to denture base resin. J Prosthodont. 2019;28(1):e357-e63.
21. Yesilyurt C, Yoldas O, Altintas SH, Kusgoz A. Effects of food-simulating liquids on the mechanical properties of a silorane-based dental composite. Dent Mater J. 2009;28(3):362-7.
22. Yap AU, Mah MK, Lye CP, Loh PL. Influence of dietary simulating solvents on the hardness of provisional restorative materials. Dent Mater. 2004;20(4):370-6.
23. Babaier R, Watts DC, Silikas N. Effects of three food-simulating liquids on the roughness and hardness of CAD/CAM polymer composites. Dent Mater. 2022;38(5):874-85.
24. Ribera OK, Mendes JM, Mendes J, Barreiros P, Aroso C, Silva AS. Influence of popular beverages on the fracture resistance of implant-supported bis-acrylic resin provisional crowns: an *in vitro* study. Polymers (Basel). 2023;15(16):3411.
25. Kiliaridis S, Kjellberg H, Wenneberg B, Engström C. The relationship between maximal bite force, bite force endurance, and facial morphology during growth. a cross-sectional study. Acta Odontol Scand. 1993;51(5):323-31.
26. Glaros AG, Rao SM. Effects of bruxism: a review of the literature. J Prosthet Dent. 1977;38(2):149-57.
27. Luthardt RG, Stössel M, Hinz M, Vollandt R. Clinical performance and periodontal outcome of temporary crowns and fixed partial dentures: a randomized clinical trial. J Prosthet Dent. 2000;83(1):32-9.
28. Patras M, Naka O, Doukoudakis S, Pissiotis A. Management of provisional restorations' deficiencies: a literature review. J Esthet Restor Dent. 2012;24(1):26-38.
29. Dewan H, Sayed ME, Jundus A, Gharawi M, Baeshen S, Alali M, *et al*. Shear strength of repaired 3D-printed and milled provisional materials using different resin materials with and without chemical and mechanical surface treatment. Polymers (Basel). 2023;15(21):4284.
30. Gad MM, Albazroun Z, Aldajani F, Elakel AM, El Zayat M, Akhtar S, *et al*. Repair bond strength of conventionally and

digitally fabricated denture base resins to auto-polymerized acrylic resin: surface treatment effects *in vitro*. Materials. 2022;15(24):9062.
31. Jeong KW, Kim SH. Influence of surface treatments and repair materials on the shear bond strength of CAD/CAM provisional restorations. J Adv Prosthodont. 2019;11(2): 95-104.
32. Park SJ, Lee JS. Effect of surface treatment on shear bond strength of relining material and 3D-printed denture base. J Adv Prosthodont. 2022;14(4):262-72.
33. Taokhampu N, Lekatana H, Palasuk J. Bond strength of aged provisional 3D-printed methacrylate resin with different surface treatments and repair materials. BMC Oral Health. 2025;25(1):789.
34. Revilla-León M, Meyers M, Zandinejad A, Özcan M. A review on chemical composition, mechanical properties, and manufacturing work flow of additively manufactured current polymers for interim dental restorations. J Esthet Restor Dent. 2019;31(1):51-7.
35. Lim NK, Shin SY. Bonding of conventional provisional resin to 3D printed resin: the role of surface treatments and type of repair resins. J Adv Prosthodont. 2020;12(5):322-8.
36. Palavicini J, Quin SL, Zakkour W, Zakkour K, Manafi Varkiani S, Xu X, *et al*. Bond strength of reline materials to 3D-printed provisional crown resins. Polymers (Basel). 2023;15(18):3745.
37. Prawatvatchara W, Yamockul S, Chaiteerapapkul P, Arunpraditkul S. Comparative radiopacity evaluation of eight provisional restoration materials. CM Dent J. 2023;44(3): 45-53.
38. Guler AU, Yilmaz F, Kulunk T, Guler E, Kurt S. Effects of different drinks on stainability of resin composite provisional restorative materials. J Prosthet Dent. 2005;94(2): 118-24.
39. Gale MS, Darvell BW. Thermal cycling procedures for laboratory testing of dental restorations. J Dent. 1999; 27(2):89-99.
40. Akova T, Ozkomur A, Uysal H. Effect of food-simulating liquids on the mechanical properties of provisional restorative materials. Dent Mater. 2006;22(12):1130-4.
41. Alalawi H, Al-Qanas S, Al-Ghamdi S, Al-Fuhaid R, Khan S, AlGhamdi MA, *et al*. Effect of dietary simulating solvents on the CAD-CAM provisional restorative materials' microhardness and color stability properties: an *in vitro* study. Clin Cosmet Investig Dent. 2024;16:237-48.
42. Wemken G, Burkhardt F, Spies BC, Kleinvogel L, Adali U, Sterzenbach G, *et al*. Bond strength of conventional, subtractive, and additive manufactured denture bases to soft and hard relining materials. Dent Mater. 2021; 37(5):928-38.
43. Li P, Krämer-Fernandez P, Klink A, Xu Y, Spintzyk S. Repairability of a 3D printed denture base polymer: effects of surface treatment and artificial aging on the shear bond strength. J Mech Behav Biomed Mater. 2021;114:104227.
44. Tahayeri A, Morgan M, Fugolin AP, Bompolaki D, Athirasala A, Pfeifer CS, *et al*. 3D printed versus conventionally cured provisional crown and bridge dental materials. Dent Mater. 2018;34(2):192-200.
45. Nelson DL, Cox MM. Lehninger principles of biochemistry: International edition. 7th ed. New York, NY: W.H. Freeman; 2017 2017.
46. Ha SR, Kim SH, Lee JB, Han JS, Yeo IS. Improving shear bond strength of temporary crown and fixed dental prosthesis resins by surface treatments. J Mater Sci. 2016;51(3):1463-75.
47. Soliman TA, Robaian A, Al-Gerny Y, Hussein EMR. Influence of surface treatment on repair bond strength of CAD/CAM long-term provisional restorative materials: an *in vitro* study. BMC Oral Health. 2023;23(1):342.
48. Lee YG, Moon SR, Cho YG. Effect of cutting instruments on the dentin bond strength of a self-etch adhesive. J Korean Acad Conserv Dent. 2010;35(1):13-9.
49. Gad MM, Alshehri SZ, Alhamid SA, Albarrak A, Khan SQ, Alshahrani FA, *et al*. Water sorption, solubility, and translucency of 3D-printed denture base resins. Dent J (Basel). 2022;10(3):42.
50. Es-Said O, Foyos J, Noorani R, Mendelson M, Marloth R, Pregger BA. Effect of layer orientation on mechanical properties of rapid prototyped samples. Mater Manuf Process. 2000;15:107-22.
51. Singh A, Garg S. Comparative Evaluation of flexural strength of provisional crown and bridge materials-an *in vitro* study. J Clin Diagn Res. 2016;10(8):ZC72-7.
52. Palitsch A, Hannig M, Ferger P, Balkenhol M. Bonding of acrylic denture teeth to MMA/PMMA and light-curing denture base materials: the role of conditioning liquids. J Dent. 2012;40(3):210-21.
53. Taşın S, Ismatullaev A, Usumez A. Comparison of surface roughness and color stainability of 3-dimensionally printed interim prosthodontic material with conventionally fabricated and CAD-CAM milled materials. J Prosthet Dent. 2022;128(5):1094-101.
54. Chen HL, Lai YL, Chou IC, Hu CJ, Lee SY. Shear bond strength of provisional restoration materials repaired with light-cured resins. Oper Dent. 2008;33(5):508-15.
55. Raszewski Z, Chojnacka K, Kulbacka J, Mikulewicz M. Mechanical properties and biocompatibility of 3D printing acrylic material with bioactive components. J Funct Biomater. 2023;14(1):13.
56. Altarazi A, Haider J, Alhotan A, Silikas N, Devlin H. Impact of artificial aging on the physical and mechanical characteristics of denture base materials fabricated via 3D printing. Int J Biomater. 2024;2024:8060363.
57. Hagge MS, Lindemuth JS, Jones AG. Shear bond strength of bis-acryl composite provisional material repaired with flowable composite. J Esthet Restor Dent. 2002;14(1):47-52.