Bond strength between a veneering composite resin and zirconia frameworks with attached mechanical retentive devices

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The effects of mechanical retentive devices and various surface treatments on the shear bond strength between a veneering composite resin and zirconia was investigated. Zirconia disks were classified into three surface-treatment groups: airborne-particle abrasion, overglazing, and overglazing with white alumina particles of three different grain sizes (50, 70, and 105 μm) attached onto zirconia disks (ZR-50, ZR-70, and ZR-105, respectively). They were further divided into four groups (n=44): unprimed, Clearfil Porcelain Bond Activator (CA), Clearfil Photo Bond (CB), and CA+CB. An indirect composite resin was bonded to zirconia specimens. Shear bond strengths were measured. For the ZR-70 and ZR-105 groups, the CB and CA+CB specimens exhibited higher bond strengths than the other two specimens after thermocycling. The ZR-70 and ZR-105 groups achieved micromechanical interlocking, and priming with a phosphate monomer (MDP) yielded stable bond strengths between the composite resin and zirconia with alumina particles attached as retentive devices.

Keywords: Bond strength, Composite resin, Glaze, Mechanical device, Zirconia

INTRODUCTION

Zirconia restorations have become popular and effective treatment alternatives to metal–ceramic restorations for tooth- and implant-supported prostheses owing to their excellent physical properties, esthetics, and biocompatibility1-3). Although systematic reviews have indicated that zirconia restorations have stable and promising survival rates, chipping of veneering porcelain is frequently observed as the major technical complication1,2). To prevent the chipping of veneering porcelain, several methods have been introduced. These include overpressing4), the use of veneering indirect composite resin5), and employing a monolithic structure for zirconia restorations6). Monolithic zirconia restorations are prevalent in fixed prostheses owing to their advantages of lower frequency of porcelain chipping, preservation of the tooth structure, and low cost7). However, medium- and long-term clinical outcomes are still limited2,7).

Indirect composite resins have been used as a veneering material for fixed dental prostheses, including implant-supported prostheses. Prostheses with layered composite resin bonded to a framework (resin-veneered restorations) have good aesthetics and yield promising clinical results8,9). Previous studies have suggested that the use of resin-veneered restorations with metallic frameworks for implant-supported prostheses eases the occlusal force or stress distribution around the implant10,11). However, composite resins have drawbacks, such as their low wear resistance12), low fracture resistance13), discoloration14), and facilitated plaque accumulation15). Resin-veneered restorations with zirconia frameworks have been introduced, and favorable results have been achieved with regard to the fracture resistance16,17) and the bond strength of the veneering composite resin to zirconia frameworks18,19).

Composite resin veneers have been applied to fixed prostheses as restorative materials for the facial surface. For enhancing the mechanical retention of resin veneers to metal frameworks, mechanical retentive devices such as retention beads are attached onto the metal frameworks20-22). Although the retentive devices are expected to enhance the mechanical retention between the zirconia frameworks and the composite resin veneers, few studies have focused on determining the effect of attaching retentive devices onto zirconia frameworks on the bond strength between the resin veneer and zirconia. Additionally, a combination of mechanical and chemical retention or bonding has been advocated for enhancing the durability of resin veneers21).

Accordingly, the objective of this laboratory study was to evaluate the effects of mechanical retentive devices and various surface treatments on the shear bond strength between a veneering composite resin and zirconia frameworks. Two null hypotheses were tested: (1) the mechanical retentive devices attached onto the zirconia frameworks would not affect the shear bond strength and (2) there would be no difference in shear bond strength among the various surface treatments.

MATERIALS AND METHODS

Specimen preparation

The assessed materials and a flowchart of the present study are presented in Table 1 and Fig. 1, respectively.
Table 1 Materials assessed in the present study

| Material                        | Abbreviation | Manufacturer                          | Components                                                                 |
|---------------------------------|--------------|---------------------------------------|---------------------------------------------------------------------------|
| Zirconia ceramic material       |              | Kuraray Noritake Dental, Tokyo, Japan | 94.4% ZrO₂, 5.4% Y₂O₃                                                     |
| Indirect composite resin        |              | Kuraray Noritake Dental               | UTMA, methacrylate, photo initiator, pigment, filler (glass, macro-alumina) |
| Estenia C&B Dentin DA2          |              | Kuraray Noritake Dental               | Bis-GMA, methacrylate, photo initiator, pigment, filler (quartz, composite, others) |
| Estenia C&B Opaque OA2          |              | Kuraray Noritake Dental               |                                                                           |
| Feldspathic porcelain           |              | Kuraray Noritake Dental               |                                                                           |
| White alumina                   |              | Akiyama Sangyo, Osaka, Japan          | Al₂O₃                                                                     |
| Priming agent                   |              | Kuraray Noritake Dental               | Catalyst: MDP, HEMA, Bis-GMA                                               |
| Clearfil Photo Bond             | CB           | Kuraray Noritake Dental               | Universal: accelerators, ethanol                                           |
| Clearfil Porcelain Bond         | CA           | Kuraray Noritake Dental               | 3-TMSPMA                                                                  |
| Activator                       |              |                                       |                                                                           |

UTMA: urethane tetramethacrylate; Bis-GMA: bisphenol-A-diglycidyl methacrylate; MDP: 10-methacryloyloxydecyl dihydrogen phosphate; HEMA: 2-hydroxyethyl methacrylate; 3-TMSPMA: 3-trimethoxysilylpropyl methacrylate

Fig. 1 Experimental procedure. Refer to the legend of Table 1 and the main text for the definitions of the abbreviations.

A total of 440 zirconia disks (diameter of 11.0 mm and thickness of 2.5 mm) were industrially fabricated from pre-sintered zirconia blocks (Katana Zirconia HT, Kuraray Noritake Dental, Tokyo, Japan). The zirconia disks were wet-ground and airborne-particle abraded as shown in Fig. 1A and B, respectively. The disks were grouped into the following surface-treatment groups (n=88 each): airborne-particle abrasion (ZR-AB), overglazing (ZR-GL), and overglazing with white alumina particles (Alumina WA-050, WA-150, and WA-105, Akiyama Sangyo, Osaka, Japan) of three different grain sizes (50, 70, and 105 μm) attached to the zirconia.
disks (ZR-50, ZR-70, and ZR-105, respectively) (Fig. 1C).

**ZR-GL group**
The bonding area was determined by using plastic tape with a round hole (diameter of 5.0 mm) taped onto the surfaces of the zirconia disks. The glazing material (Cerabian ZR E glaze, Kuraray Noritake Dental) was thinly applied onto the bonding area of the zirconia disks. After removal of the plastic tape, and the zirconia disks were fired with a vacuum furnace as shown in Fig. 1D.

**ZR-50, ZR-70, and ZR-105 groups**
A thin layer of the glazing material was layered on the bonding area of the zirconia disks as stated above. Alumina particles (Alumina WA-050, WA-150, and WA-105) with average particle sizes of 50, 70, and 105 μm, respectively, as mechanical retentive devices were then incorporated onto the glazing material. The zirconia specimens were fired under the same firing schedule that was used for the ZR-GL group (Fig. 1D).

**Bonding protocol**
The bonding area of the zirconia disks was specified using a double-coated tape with a 5-mm diameter hole after the surface treatments. The zirconia disks were additionally assigned into the following four subgroups (n=44 each) (Fig. 1E): unprimed (UP), Clearfil Porcelain Bond Activator (CA; Kuraray Noritake Dental), Clearfil Photo Bond (CB; Kuraray Noritake Dental), and CA+CB. These primers contain one or more functional monomers as listed in Table 1. For the CA+CB group, equal amounts of CA and CB were mixed.

Each priming agent (CA, CB, or CA+CB) was applied to the surface of the zirconia disks using a microbrush (Micro Tip Applicator, GC, Tokyo, Japan) (Fig. 1E), and then the disks were dried gently.

An opaque resin (Estenia C&B Body Opaque OA2, Kuraray Noritake Dental) was placed onto the zirconia disks and light-polymerized for 90 s using an apparatus (Fig. 1F). A stainless ring (diameter of 6.0 mm and thickness of 2.5 mm) was fixed onto the zirconia disks. A composite resin was packed into the ring with a force of 5 N and then light-polymerized for 5 min. This was followed by heat-activated polymerization using an oven (Fig. 1F).

**Shear bond testing**
The specimens were divided into two groups: storing in purified water at 37°C for 24 h (0 thermocycle) (Fig. 1G) and thermocycling for 5,000 cycles (Fig. 1H). The specimens were mounted in a shear bond testing jig (ISO TR11405, Tokyo Giken, Tokyo, Japan). The shear bond strength was measured using a universal testing machine (Type 5567, Instron, Canton, MA, USA) at a crosshead speed of 0.5 mm/min (Fig. 1I).

**Statistical analysis**
The normality of the data distribution was assessed using the Shapiro–Wilk test (IBM SPSS Statistics, version 24.0, IBM, Armonk, NY, USA). The homogeneity of the variance was evaluated by using the Levene test. The tests revealed a non-normal distribution (p=0.007) and did not confirm homoscedasticity (p=0.005). The data were analyzed using the Kruskal–Wallis and Steel–Dwass multiple comparison tests (Kyplot 5.0, KyensLab, Tokyo, Japan). The Mann–Whitney U-test was performed to compare the samples before and after thermocycling (α=0.05).

**Surface analysis**
To determine the failure mode, the fractured surfaces of the specimens were observed at 32× magnification using a stereoscopic microscope (Stemi DV4, Carl Zeiss, MicroImaging, Göttingen, Germany). The failure modes were categorized as follows: (A) adhesive failure at the zirconia/composite resin interface, (B) combination of adhesive failure at the zirconia/composite resin interface and cohesive failure within the composite resin, (C) adhesive failure at the zirconia/glazed layer interface, (D) combination of adhesive failure at the zirconia/glazed layer interface and cohesive failure within the glazed layer, (E) adhesive failure at the glazed layer/composite resin interface, (F) combination of adhesive failure at the glazed layer/composite resin interface and cohesive failure within the composite resin, and (H) cohesive failure within the composite resin.
failure at the glazed layer/composite resin interface and cohesive failure within the glazed layer, (G) combination of adhesive failure at the glazed layer/composite resin interface and cohesive failure within the composite resin, and (H) cohesive failure within the composite resin (Fig. 2).

Representative specimens were sputter-coated with osmium (HPC-IS, Vacuum Device, Mito, Japan) and imaged by scanning electron microscope (SEM; S-4300, Hitachi High-Technologies, Tokyo, Japan). The representative specimens were also analyzed using an X-ray diffractometer (Miniflex, Rigaku, Tokyo, Japan) with Cu Kα radiation by scanning over the diffraction angle (2θ) range of 3°–90°.

RESULTS

The results of the shear bond testing and statistical analyses are presented in Table 2. The shear bond strengths of the ZR-70 and ZR-105 groups of the UP specimen were significantly higher than those of the other groups both before and after thermocycling. For the ZR-70 and ZR-105 groups, the CB and CA+CB specimens exhibited significantly higher bond strengths than the other two specimens after thermocycling. The shear bond strengths of the CB and CA+CB specimens were significantly higher than those of the UP and CA specimens in the ZR-AB group both before and after thermocycling.

For the ZR-GL group, the UP and CB specimens exhibited significantly lower bond strengths than the CA and CA+CB specimens.

As shown in Table 3, the Mann–Whitney U-test revealed that the shear bond strengths of the CA specimen of the ZR-70 and ZR-105 groups decreased significantly with the application of thermocycling. However, no significant differences in the bond strengths measured before and after thermocycling were detected for the CB and CA+CB specimens of the ZR-70 and ZR-105 groups.

Table 4 presents the results of failure mode assessment after shear bond testing. For the ZR-GL group, no cohesive failures were observed within the glazed layer after thermocycling. A combination of adhesive failure at the zirconia/glazed layer interface and cohesive failure within the glazed layer was observed in the ZR-50, ZR-70, and ZR-105 groups regardless of the application of thermocycling. After thermocycling, no adhesive failure between the glazed layer and the composite resin was observed in the CA+CB specimen of the ZR-70 and ZR-105 groups.

Figure 3 shows representative SEM images of the zirconia surface obtained with various surface treatments. A rough and sharpened surface of a zirconia specimen from the ZR-AB group is shown in Fig. 3A. Figure 3B shows the smooth surface of a specimen from the ZR-GL group. Figures 3C–E show that the exposed surface of the ZR-AB group both before and after thermocycling.

Table 2 Results of shear bond testing (in MPa) and statistical analyses

| Specimen | ZR-AB group | ZR-GL group | ZR-50 group | ZR-70 group | ZR-105 group |
|----------|-------------|-------------|-------------|-------------|-------------|
|          | Median (IQR) | Category    | Median (IQR) | Category    | Median (IQR) | Category    |
| 0 thermocycles |             |             |             |             |             |
| UP       | 0.4 (0.3; 0.8) | a, A        | 0.3 (0.3; 0.4) | d, A        | 5.0 (3.4; 5.3) | g, B        |
| CA       | 8.8 (7.6; 9.4) | b, D        | 10.1 (8.9; 12.3) | f, D, E     | 10.4 (9.4; 12.7) | h, D, E     |
| CB       | 16.1 (14.7; 17.3) | c, H    | 0.7 (0.4; 1.0) | e, G        | 13.4 (11.6; 15.8) | b, H        |
| CA+CB    | 14.2 (13.4; 15.7) | c, J   | 9.5 (9.2; 12.8) | f, I        | 17.4 (16.6; 19.4) | i, J, K     |
| 5,000 thermocycles |             |             |             |             |             |
| UP       | 0.2 (0.2; 0.3) | an, L      | 0.2 (0.2; 0.3) | ee, L       | 2.4 (1.9; 3.0) | gg, M       |
| CA       | 9.1 (7.4; 9.5) | bb, O      | 10.1 (9.3; 10.4) | ff, O, P   | 11.2 (9.4; 12.8) | hh, O, P    |
| CB       | 16.1 (15.1; 17.8) | cc, Q    | 0.3 (0.2; 0.3) | ee, R       | 12.0 (10.5; 13.4) | hh, S       |
| CA+CB    | 12.5 (11.0; 13.8) | dd, T    | 10.9 (10.1; 11.6) | ff, T       | 15.8 (14.9; 17.7) | ii, U       |

Refer to the legend of Table 1 and the main text for the definitions of the abbreviations. Identical uppercase letters in the same row indicate that the values are not statistically different (Steel–Dwass test; p>0.05). Identical lowercase letters in the same column indicate that the values are not statistically different (Steel–Dwass test; p>0.05). IQR: interquartile range
Table 3  Results of the Mann–Whitney U-test for shear bond strengths between 0 and 5,000 thermocycles

| Specimen     | p value | Reduction (%) |
|--------------|---------|---------------|
| ZR-AB group  |         |               |
| UP           | 0.000*  | 66.7          |
| CA           | 0.847   | 8.5           |
| CB           | 0.949   | 0.6           |
| CA+CB        | 0.023*  | 15.2          |
| ZR-GL group  |         |               |
| UP           | 0.040*  | 33.3          |
| CA           | 0.949   | 3.8           |
| CB           | 0.000*  | 57.1          |
| CA+CB        | 0.847   | 3.6           |
| ZR-50 group  |         |               |
| UP           | 0.001*  | 40.9          |
| CA           | 1.000   | 0.9           |
| CB           | 0.217   | 11.0          |
| CA+CB        | 0.193   | 8.1           |
| ZR-70 group  |         |               |
| UP           | 0.699   | 3.6           |
| CA           | 0.047*  | 11.6          |
| CB           | 0.332   | 5.1           |
| CA+CB        | 0.056   | 11.5          |
| ZR-105 group |         |               |
| UP           | 0.438   | 8.5           |
| CA           | 0.000*  | 18.3          |
| CB           | 0.519   | 3.6           |
| CA+CB        | 0.151   | 10.8          |

Refer to the legend of Table 1 and the main text for the definitions of the abbreviations.

*Significant difference between 0 and 5,000 thermocycles (Mann–Whitney U-test; p<0.05).

area of the glazing material decreased as the grain size of the alumina particles increased.

Representative SEM images of the cross section of the specimens before shear bond testing are presented in Fig. 4. As shown in Fig. 4A, the opaque resin was in a shallow undercut for the ZR-50 group. SEM images of the specimens for the ZR-70 and ZR-105 groups indicate that the opaque resin penetrated the increased undercuts owing to the larger grain size of the alumina particles (Figs. 4B and C, respectively).

Figure 5 shows representative SEM images of the debonded surfaces after shear bond testing. For the CA+CB specimen of the ZR-105 group, the glazing material on the zirconia surface was observed as failure mode D (Fig. 5A). The UP specimen in the ZR-105 group exhibited adhesive failure at the glazed layer/composite resin interface (failure mode E), which was observed in the glazing material and alumina particles (Figs. 4B and C, respectively).

Figures 6 and 7 present the X-ray diffraction (XRD) patterns of the representative specimens. The peaks corresponding to amorphous glass (2θ=20.965°, 21.565°, and 27.094°) were observed for the glazing materials (Figs. 6A and 7A). The XRD pattern of zirconia exhibited ZrO₂ peaks at 2θ=30.364°, 34.789°, and 55.342° (Fig. 6B). The XRD pattern of the CA+CB specimen in the ZR-105 group (failure mode D) exhibited peaks corresponding to the glazing material and zirconia (Fig. 6C). The peaks corresponding to alumina particles were detected at 2θ=25.427°, 35.005°, and 43.225° (Fig. 7B). Peaks corresponding to alumina and the glazing material were both confirmed on the surface of the UP specimen in the ZR-105 group as a fracture mode (E) (Fig. 7C).

DISCUSSION

To assess the clinical applicability of resin-veneered zirconia restorations with mechanical retentive devices, the effects of mechanical retentive devices and various surface treatments for zirconia frameworks on the shear bond strength between a veneering composite resin and zirconia frameworks was investigated in an in vitro study. The first null hypothesis—that the mechanical retentive devices attached to the zirconia frameworks would not affect the shear bond strength—was disproved. The obtained results indicated that the sizes of the mechanical retentive devices, i.e., alumina particles, significantly affected the shear bond strength between the veneering composite resin and zirconia frameworks. The CB and CA+CB specimens exhibited significantly higher bond strengths than the UP and CA specimens for the ZR-70 and ZR-105 groups. Therefore, the second null hypothesis, namely, that there would be no difference in shear bond strength among the various surface treatments, was also rejected.

The bond strengths of the UP specimens in the ZR-70 and ZR-105 groups were significantly higher than those of the specimens in the other groups tested before and after thermocycling. The results indicate that the larger grain size of the alumina particles achieved micromechanical interlocking between the glazed layer and the composite resin. These findings were supported by the SEM observation that the undercuts of the
| Specimen | A | B | C | D | E | F | G | H |
|----------|---|---|---|---|---|---|---|---|
| ZR-AB group | UP | 11 | 0 | 0 | 0 | 0 | 0 | 0 |
| | CA | 5 | 6 | 0 | 0 | 0 | 0 | 0 |
| | CB | 3 | 8 | 0 | 0 | 0 | 0 | 0 |
| | CA+CB | 3 | 8 | 0 | 0 | 0 | 0 | 0 |
| ZR-GL group | UP | 0 | 0 | 0 | 0 | 11 | 0 | 0 |
| | CA | 0 | 0 | 0 | 0 | 8 | 3 | 0 |
| | CB | 0 | 0 | 0 | 0 | 11 | 0 | 0 |
| | CA+CB | 0 | 0 | 0 | 0 | 9 | 2 | 0 |
| TC0 | UP | 0 | 0 | 0 | 0 | 5 | 6 | 0 |
| | CA | 0 | 0 | 0 | 5 | 2 | 4 | 0 |
| | CB | 0 | 0 | 0 | 6 | 1 | 4 | 0 |
| | CA+CB | 0 | 0 | 0 | 6 | 0 | 5 | 0 |
| ZR-50 group | UP | 0 | 0 | 0 | 0 | 3 | 8 | 0 |
| | CA | 0 | 0 | 0 | 6 | 2 | 3 | 0 |
| | CB | 0 | 0 | 0 | 6 | 1 | 4 | 0 |
| | CA+CB | 0 | 0 | 0 | 7 | 0 | 4 | 0 |
| ZR-70 group | UP | 0 | 0 | 0 | 0 | 3 | 8 | 0 |
| | CA | 0 | 0 | 0 | 7 | 1 | 3 | 0 |
| | CB | 0 | 0 | 0 | 7 | 0 | 4 | 0 |
| | CA+CB | 0 | 0 | 0 | 8 | 0 | 3 | 0 |
| ZR-105 group | UP | 11 | 0 | 0 | 0 | 0 | 0 | 0 |
| | CA | 6 | 5 | 0 | 0 | 0 | 0 | 0 |
| | CB | 4 | 7 | 0 | 0 | 0 | 0 | 0 |
| | CA+CB | 3 | 8 | 0 | 0 | 0 | 0 | 0 |
| ZR-AB group | UP | 0 | 0 | 0 | 0 | 11 | 0 | 0 |
| | CA | 0 | 0 | 0 | 8 | 3 | 0 | 0 |
| | CB | 0 | 0 | 0 | 11 | 0 | 0 | 0 |
| | CA+CB | 0 | 0 | 0 | 8 | 3 | 0 | 0 |
| ZR-GL group | UP | 0 | 0 | 0 | 0 | 5 | 6 | 0 |
| | CA | 0 | 0 | 0 | 5 | 3 | 3 | 0 |
| | CB | 0 | 0 | 0 | 5 | 3 | 3 | 0 |
| | CA+CB | 0 | 0 | 0 | 6 | 2 | 3 | 0 |
| TC5000 | UP | 0 | 0 | 0 | 0 | 4 | 7 | 0 |
| | CA | 0 | 0 | 0 | 5 | 2 | 4 | 0 |
| | CB | 0 | 0 | 0 | 5 | 1 | 5 | 0 |
| | CA+CB | 0 | 0 | 0 | 7 | 0 | 4 | 0 |
| ZR-50 group | UP | 0 | 0 | 0 | 0 | 3 | 8 | 0 |
| | CA | 0 | 0 | 0 | 6 | 2 | 3 | 0 |
| | CB | 0 | 0 | 0 | 6 | 1 | 4 | 0 |
| | CA+CB | 0 | 0 | 0 | 7 | 0 | 4 | 0 |
| ZR-70 group | UP | 0 | 0 | 0 | 0 | 11 | 0 | 0 |
| | CA | 0 | 0 | 0 | 8 | 3 | 0 | 0 |
| | CB | 0 | 0 | 0 | 11 | 0 | 0 | 0 |
| | CA+CB | 0 | 0 | 0 | 8 | 3 | 0 | 0 |
| ZR-105 group | UP | 0 | 0 | 0 | 0 | 5 | 6 | 0 |
| | CA | 0 | 0 | 0 | 5 | 3 | 3 | 0 |
| | CB | 0 | 0 | 0 | 5 | 3 | 3 | 0 |
| | CA+CB | 0 | 0 | 0 | 6 | 2 | 3 | 0 |

Refer to the legends of Table 1, Fig. 2 and the main text for the definitions of the abbreviations.

Surfaces of the specimens were enlarged as the grain size of the alumina particles increased, and the opaque resin penetrated the enlarged undercuts (Figs. 4B and 4C). The results contradict those of previous studies, in which the “small beads” (350 or 490 μm) provided mechanical retention superior to that of the “large beads” (430 or 695 μm, respectively)\(^20\)\(^21\). The differences are likely due to the different forms and grain sizes of the mechanical retentive devices and materials assessed in the studies.

The results of this in vitro study suggest that priming with a hydrophobic phosphate monomer (MDP) yields stable bond strengths between a composite resin and zirconia with attached retentive devices (alumina particles). For the ZR-70 and ZR-105 groups, the CB and CA+CB specimens exhibited significantly higher bond strengths than the other two specimens after thermocycling. Additionally, the bond strengths of the CB and CA+CB specimens in the ZR-70 and ZR-105 groups did not significantly decrease with the application of 5,000 thermocycles. The SEM images indicated that...
the exposed area of alumina particles increased after the application of alumina particles with diameters of 70 and 105 μm (Figs. 3C–E). This phenomenon is supported by the results obtained in previous studies, in which applying a functional phosphate monomer provided a durable bond between the alumina and the resin material.23,24 Furthermore, the results of this study were confirmed by the failure mode after shear bond testing, in which adhesive failure between the glazed layer and the composite resin was either observed or not observed in a single specimen (Table 4).

In a previous study, the strengths of bonds between an indirect composite resin and porcelain-coated zirconia were evaluated, and no adhesive failure or combination of adhesive and cohesive failure was observed at the interface.18 In the current study, a combination of adhesive failure at the zirconia/glazed layer interface and cohesive failure within the glazed layer (failure mode D) was observed for CA, CB, and CA+CB specimens in the ZR-50, ZR-70, and ZR-105 groups, regardless of the application of thermocycling.
The probable reason for these findings is the formation of strong bonds between the composite resin and zirconia with the attached retentive devices (alumina particles). Additionally, the zirconia/glazing-material interface should be strengthened to enhance the bond durability of the system described herein.

For the ZR-GL group, the surface treatments with the primer containing 3-TMSPMA, namely, the CA and CA+CB specimens, improved the shear bond strengths between the glazed layer on the zirconia and the composite resin. It is likely that 3-TMSPMA plays a positive role in the bonding of composite resin to the glazed layer including silica. These findings are consistent with those of previous studies\(^{18,25}\). However, the shear bond strengths of the CA specimens in the ZR-70 and ZR-105 groups were significantly lower than those of the CB and CA+CB specimens. These findings indicated that the silane was not effective for bonding between the retentive devices (alumina particles with diameters of 70 and 105 μm) attached to the zirconia and composite resin, which may have been related to the reduced area of the glazing material on surface of the specimens in the ZR-70 and ZR-105 groups.

In this study, the median bond strengths of the CB and CA+CB specimens in the ZR-70 and ZR-105 groups reached levels of >10–13 MPa, which can be suggested as a clinical acceptable range of bond strengths for composite–ceramics and composite–metal bonds\(^{26,27}\). Although no in vivo data for the clinically acceptable bond strength are available, the use of the CB and CA+CB specimens in the ZR-70 and ZR-105 groups tested might have potential to be a promising approach for resin-veneered zirconia restorations with mechanical retentive devices.

To the best of our knowledge, this study represents a first attempt to evaluate the effect of attaching retentive devices to zirconia on the bonding performance. However, the effects of different particle forms, grain sizes, and material types on the bonds between the retentive devices attached to zirconia and the composite resins...
remain unclear. Therefore, future in vitro studies should include additional clinically relevant parameters, and clinical trials are needed to advance recommendations for clinical protocols for general clinical use.

Within the limitations of this laboratory study, it can be concluded that the specimens in the ZR-70 and ZR-105 groups exhibited significantly higher bond strengths than those in the other groups tested and achieved micromechanical interlocking between the glazed layer and the composite resin. Priming with a hydrophobic phosphate monomer (MDP) can yield stable bond strengths between a composite resin and zirconia with attached retentive devices (alumina particles).

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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