Shear bond strength of the metal bracket on the porcelain surface using three silane coupling agents: a laboratory-based experimental study

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Abstract. This study aims to assess differences in shear bond strength using three materials of silane coupling agents with various organosilane compositions. The samples were 21 porcelain plates categorized into three groups as follows: (a) Monobond Plus (agent A); (b) Ultradent Silane (agent B); and (c) Porcelain Repair Primer (agent B). 37% phosphoric acid etching, silane coupling agents and Transbond XT adhesive were applied to the porcelain surface, followed by 24-h immersion in distilled water before measuring shear bond strength. The results revealed statistically significant differences in shear bond strength among the three silane coupling agents. Agent A had the highest shear bond strength (12.827 ± 1.228 MPa) and B had the lowest shear bond strength (6.295 ± 0.642 MPa) and 6–8 MPa fulfilled the minimum criteria of shear bond strength. Per the Adhesive Remnant Index scores, agent B revealed a clean porcelain surface, whereas agent A and C displayed the presence of bonding adhesive on the entire surface of the porcelain. While agent A and C could be used if the porcelain is replaced, agent B could be used if porcelain is not replaced.

1. Introduction
With growing understanding of maintaining oral health, an increasing number of patients from all age groups seek orthodontic treatment for condition such as malocclusion and oral conditions [1,2]. Typically, adults have complex oral conditions, including periodontal tissue abnormalities, tooth loss, dental caries, and dental restorations such as porcelain restorations. Porcelain restorations are generally used for correcting large cavities, post-root canal teeth, and replacing missing teeth [1]. As porcelain restoration is more expensive than other types of restorations, dentists should handle the porcelain diligently [3–6].

Apparently, the handling of porcelain restorations in orthodontic treatments comprises bonding and debonding bracket processes. The bonding process is a critical step to obtain good orthodontic treatments [4]. Reportedly, brackets bonding on the surface of porcelain restorations tend to damage
the restoration, which is avoidable [3,7–9]. Notably, coarsening or grinding glaze and etching applications are required, where all processes include the mechanical bonding mechanism to produce good bonding with the surface of the porcelain restoration [3,8]; this process may result in cracks and fractures in the restoration porcelain, warranting expensive replacement. As the entire situation leaves patients disadvantaged, orthodontists should have expertise in effective and efficient bonding techniques on porcelain restorations. Reportedly, a chemical bonding mechanism helps to maintain the integrity of the porous surface and does not require restoration replacement [6,7,10,11]. Chemically, the bonding mechanism comprises the use of a silane coupling agent, and the bonding produced by a silane coupling agent is known to be affected by several factors, one being its organosilane concentration [12]. Thus, it is imperative for orthodontists to know the composition of the silane coupling agent used to produce an adequate bond strength (6–8 MPa) between metal brackets and porcelain restorations [8]. At present, silane coupling agents of several brands are commercially available with variable organosilane compositions (e.g., Monobond Plus, <2.5% organosilane composition [Ivoclar Vivadent]; Ultradent Silane, 5%–15% organosilane composition [Ultradent Products]; Porcelain Repair Primer, 15%–20% organosilane composition [Ormco Corp.]).

In orthodontic treatment, various mechanisms and directions of force, including tension, compression, and shear, are significantly influenced by the malposition state of each tooth [10,13,14]. Tensile strength is an object’s ability to resist tensile force originating perpendicular to the object’s surface, such as the debonding force. The shear bond strength is an object’s ability to resist the shear/friction force originating from a direction parallel to the surface of the object, e.g., the force at which it will intrude, extrude, distalize, or mesialize the teeth [10,13,14]. In orthodontic treatments, the shear bond strength that is applied exceeds the tensile strength.

Hence, based on this background, this study aims to assess the differences in the shear bond strength of metal bracket to the porcelain surface using three silane coupling agents, Monobond Plus, Ultradent Silane, and Porcelain Repair Primer.

2. Methods
2.1 Study design and materials
This experimental laboratory study was conducted at the Dental Material Laboratory of Faculty of Dentistry, Universitas Indonesia, (Depok West Java, Indonesia) from February to March 2014. We examined 21 specimens based on the following inclusion criteria: cylindrical porcelain plate (diameter, 8 mm; thickness, 3 mm) that has been glazed on its surface, no damage or porosity on the porcelain plate, and the flat plate surface. Tools and materials used in this experiment were bracket gauge, bracket tweezers, air and water spray, explorer, low-speed brush, light curing, stopwatch, plastic jar, stirring paper, plastic brush, PVC cylinder (diameter, 18.8 mm; height, 10 mm), plastic filling, incubator, Shimadzu AG-5000 Universal Testing Machine, stereomicroscope, ultrasonic cleaner, decorative resin, Monobond Plus, Ultradent Silane, Porcelain Repair Primer, metal bracket for incisive teeth right upper center (Resolve), Dentsply GAC, fine pumice powder, Transbond XT (3M Unitek), etching of 37% phosphoric acid (Ultraetch; Ultradent Products), aquadest, and red wax (Figure 1).
2.2 Experiment
In this study, 21 porcelain specimens were categorized into the following three groups based on the application of the silane coupling agent: Monobond Plus (A); Ultradent Silane (B); and Porcelain Repair Primer (C). In addition, the upper maxillary right incisive bracket (Dentsply, GAC) was divided equally into three groups (seven each group). The surface of 21 cylindrical porcelain specimens (diameter, 8 mm; height, 3 mm) was coated with red wax and then planted into a PVC cylinder (diameter, 18.8 mm; height, 10 mm) with a decorative resin. Then, the surface of 21 specimens was cleaned using a pumice powder with a low-speed brush, rinsed with water, and then dried. After that, 21 specimens were inserted into an ultrasonic cleaner and then dried. Etching solution was applied to specimens using 37% phosphoric acid for 60 s and rinsed with water and then dried; group A (seven specimens), applied with silane coupling agent A for 60 s and dried with air spray; group B (seven specimens), applied with silane material coupling agent B for 60 s and dried with air spray; group C (seven specimens) applied with silane coupling agent C for 60 s and dried with air spray, followed by applying the bonding material to the mesh of bracket. The excess of the bonding material was discarded, and then the bonding was irradiated by light curing for 20 s each from the mesial, distal, occlusal, and cervical directions, before storing the specimens in aquadest at 37°C for 24 h. On the second day, the shear bond strength was measured using the Universal test apparatus Shimadzu AG-5000 Testing Machine with a speed of 0.5 mm/min and the maximum load of 50 kg. Finally, the recorded force was obtained.

2.3 Statistical analysis
The shear bond strength of each specimen was measured with loads used at 50 kgf and a cross-head speed of 0.5 mm/min. The results of the measurement tool were expressed in kgf units, which were then converted into MPa (megapascal) by dividing the measurement results with the metal bracket cross-sectional area of 11.786 mm² and multiplied by 9.8 Mpa/kg/mm².

In this study, statistical analysis was performed with SPSS software. The univariate analysis was performed to obtain the mean, median, maximum, minimum, and standard deviation (SD) of each group. In addition, the data normality test of the shear bond strength of the metal bracket to the porcelain surface using each silane coupling agent A, B, and C was performed by using the Shapiro-Wilk normality test data because the number of samples per group was less than 50. Besides the data normality test, the data variance of the shear bond strength of the metal bracket to the porcelain surface using each silane coupling agent A, B, and C was tested by Levene’s test. Furthermore, the bivariate analysis was performed to assess the shear strength differences in the three types of silane coupling agents using one-way ANOVA and post-hoc because the data distribution was normal with no data variance.
3. Results

The results revealed that groups A, B, and C had normal data distribution ($P > 0.05$; Table 1).

**Table 1.** Data normality test for shear bond strength of the metal bracket to the porcelain surface using three silane coupling agents A, B, and C (MPa)

| Group | $P$          |
|-------|--------------|
| A     | 0.824        |
| B     | 0.176        |
| C     | 0.723        |

$P > 0.05$, normal data distribution

The data variance test revealed no difference in the variance among the three groups ($P = 0.315$). After all measurements were completed, the mean and SD of metal brackets’ shear bond strength on porcelain surfaces with each silane coupling agent A, B, and C was obtained (Table 2). The mean of the shear strength and SD was $12.827 \pm 1.228$ MPa (group A), $6.295 \pm 0.642$ MPa (group B), and $11.098 \pm 0.646$ MPa (group C), suggesting that group A had the highest shear strength, whereas group B had the lowest shear strength bond. Furthermore, all three groups exhibited a substantial shear bond strength that fulfilled the minimum shear bond strength criteria of 6–8 MPa per according to Whitlock and Reynolds.

**Table 2.** The mean and SD of metal brackets’ shear bond strength on porcelain surfaces using three silane coupling agents A, B, and C (MPa)

| Group | N  | Mean ± SD       |
|-------|----|-----------------|
| A     | 7  | 12.827 ± 1.228  |
| B     | 7  | 6.295 ± 0.642   |
| C     | 7  | 11.098 ± 0.646  |

SD, standard deviation

**Table 3.** One-way ANOVA test result in the differences in the shear bond strength of metal brackets on porcelain surfaces in the three groups of silane coupling agents (MPa)

| Silane Coupling Agent | N | Mean ± d.s. | $P$ |
|-----------------------|---|-------------|-----|
| A                     | 7 | 12.827 ± 1.228 | < 0.001 |
| B                     | 7 | 6.295 ± 0.642   |     |
| C                     | 7 | 11.098 ± 0.646  |     |

$P < 0.05$, (statistically different)

The results of the one-way ANOVA exhibited $P < 0.001$ ($P < 0.05$), showing that the difference in the shear bond strength of metal brackets in the porcelain surface existed when using three silane coupling agents A, B, and C (Table 3). Based on these findings, the post-hoc test was performed to determine which silane coupling agent exhibited a significant difference, revealing that a significant difference existed between the application of silane coupling agent A and silane coupling agent B ($P < 0.001$); between the application of silane coupling agent A and silane coupling agent C ($P = 0.005$); between the application of silane coupling agent B and silane coupling agent C ($P < 0.001$; Table 4).
Table 4. Post-hoc Bonferroni test to analyze the differences in shear bond strength of metal brackets on porcelain surfaces in the three groups of silane coupling agents (MPa)

| Group   | P     | Explanation |
|---------|-------|-------------|
| A–B     | 0.000 | $P < 0.05$  |
| A–C     | 0.005 | $P < 0.05$  |
| B–C     | 0.000 | $P < 0.05$  |

$P < 0.05$, (statistically different)

Besides the shear bond strength measurements, the remaining adhesive material on the bracket and porcelain surface was evaluated visually using a stereomicroscope; the results of these observations were assessed using the Adhesive Remnant Index (ARI) calculation (Figure 2).

![Figure 2. Adhesive Remnant Index (Source: Sant’Anna, 2002) [15]](image)

The ARI system was based on a pilot study of 20 extracted teeth and used the following criteria [16]:
0 = no adhesive material left on the surface of the tooth/another substrate
1 = <50% of the adhesive material left on the surface of the tooth/another substrate
2 = >50% of adhesive material left on the surface of the tooth/another substrate
3 = all the adhesive material left on the surface of the tooth/another substrate, characterized by a primary imprint of the bracket.

Table 5. The Adhesive Remnant Index

| Group | Adhesive Remnant Index |
|-------|------------------------|
|       | 0 | 1 | 2 | 3 |
| A     | 0 | 0 | 6 | 1 |
| B     | 5 | 2 | 0 | 0 |
| C     | 0 | 0 | 5 | 2 |

The results in Table 5 revealed that in group A, the ARI score of six specimens was 2 and that of one specimen was 3. In group C, the ARI score of five specimens was 2, and that of two specimens was 3. In group B, the ARI score of five specimens was 0, and that of two specimens was 1. In addition, the results revealed that in groups A and C, the remainder of the adhesive material was almost entirely attached to the porcelain surface, whereas in group B, only a small part/absence of the adhesive material remained on the porcelain surface.
4. Discussion

In orthodontic treatments, the movement of the teeth is essential to correct the malposition of teeth into the desired dental arch. The movement of the teeth is ensured by the interaction between the bracket attached to the teeth and wire on the bracket slot. Thus, the bonding bracket to the tooth surface should withstand the orthodontic force to render the treatment effective and efficient [4]. The principle of bonding the bracket to the tooth surface is through the presence of microporosity in the enamel layer, obtained by the application of etching of phosphoric acid. Once the tooth surface has been restored to obtain its integrity, the formation of microporosity for the bonding process becomes challenging, which is usually observed in restorations with dental ceramic materials. In the anterior teeth that require high aesthetic, ceramic materials used are feldspathic ceramic or porcelain type. The porcelain crown is a restoration that is more expensive than other types of restorations. Thus, in the process of bonding the bracket on porcelain restorations, orthodontists should notice two things, to get enough bonding power and maintain the integrity of the porcelain after the completion of the orthodontic treatment.

The application of silane coupling agents in the bonding process resulted in the sufficient bonding strength but maintained the porcelain integrity. To enhance the bonding strength, the rule of using commercial silane coupling agent products recommends acid etching applications before silane applications. Several factors are known to indirectly affect the bonding strength of the silane concentration, solvent, and temperature.

In group A, the silane coupling agent was Monobond Plus comprising the organosilane content (MPS) at >2.5%, ethanol at 50%–100%, and methacrylated phosphoric acid ester at >2.5%. In group B, the silane coupling agent was Ultradent Silane consisting of the organosilane content (MPS) at 5%–15%, isopropyl alcohol at 92%, and acetic acid at >1%. In group C, the silane coupling agent was Porcelain Repair Primer with comprising the organosilane content at 15%–20% and ethyl alcohol at 80%–85%.

Group A with the lowest organosilane content (<2.5%) exhibited the highest shear bond strength compared to groups B and C with more organosilane content, which could be attributed to the presence of methacrylated phosphoric acid ester of <2.5% in the preparation of a silane coupling agent. Methacrylated phosphoric acid ester is the active ingredient in primary self-etching solution. Phosphoric acid and methacrylate groups are combined into a molecule that can simultaneously function as etching and primers. Thus, the methacrylated phosphoric acid ester material could bind to the adhesive and porcelain resin material, thereby increasing the covalent bond between the materials, resulting in the increased shear bond strength between the metal bracket and the porcelain surface.

Group B with 5%–15% organosilane (MPS) content displayed the lowest shear bond strength compared to groups A and C. Silane coupling agent B had an additional composition of acetic acid, which is used for the acceleration process of silanol condensation to oligomers to maximize the formation of oligomers [12]. Such conditions automatically increase the covalent bond between the oligomers and the inorganic substance OH groups (porcelain), which likely results in an increase in the shear bond strength of the metal bracket on the porcelain surface. However, compared to group A, which had higher shear bond strength with lesser organosilane content, the addition of methacrylated phosphoric acid ester is probably more effective than the addition of acetic acid. However, when compared to group C, which had higher shear bond strength with more organosilane content, the addition of acetic acid might be less effective to produce the maximum shear bond strength. Group C with the highest organosilane content (15%–20%) had higher shear bond strength than group B and lower than group A. In group C, no additional ingredients, other than organosilane and main solvent, were present. When compared to group A, which had the higher shear bond strength and lower organosilane content, the addition of methacrylated phosphoric acid ester is probably effective in increasing the shear strength of the shear so that it is equivalent to group C with organosilane content of 15-20.
Figure 3. Observation results of the remaining adhesive materials

The accuracy of ARI measurements is imperative. The ARI value correlates with the bonding strength of the bracket and other teeth or material. The lower the ARI score, the lower the bonding strength; however, the debonding bracket and the cleaning of the tooth surface or material are easier, and the incidence of porcelain fracture is lower [16]. This study established that the mean of the shear bond strength of the three study groups was in accordance with the minimum shear strength criteria of 6–9 MPa according to Whitlock and Reynolds. Thus, when viewed from the integrity of the porcelain surface, group B exhibited the best results because of the shear bond strength was sufficient in withstanding the orthodontic force, only a little adhesive material remained on the porcelain surface, and the fracture potential of porcelain was the least of all groups (Figure 3).

5. Conclusion
This study established that using three silane coupling agents fulfilled the criteria of the minimal shear bond strength in orthodontic treatments. While silane coupling agent A exhibited the highest shear bond strength, silane coupling agent B exhibited the lowest shear bond strength. Overall, silane coupling agent B exhibited the best results because the shear bond strength was sufficient in withstanding the orthodontic force and only a little adhesive material remained on the porcelain surface.

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