Novel testing method to evaluate the mechanical strength of self-adhesive resin cements with reflection of cement thickness

Mitsunobu KAWASHIMA1,2, Satoshi YAMAGUCHI1, Atsushi MINE3, Hefei LI1 and Satoshi IMAZATO1

This study aimed to propose an evaluation method for testing the mechanical strength of film-formed self-adhesive resin cements (SARCs) while reflecting cement layer thickness. Three commercially available dual-cure type SARCs were used for tensile and shear tests using specimens with varying thicknesses (0.05, 0.2, and 0.4 mm). There were no significant differences in tensile strengths among the various specimen thicknesses. In the shear test, there was a significant decrease in the strength with a reduction in specimen thickness. Stress distribution and fracture patterns were analyzed using in silico nonlinear dynamic finite element analysis. Finite element analysis demonstrated that stress distribution on the specimen surface was homogeneous even with different thicknesses in the tensile test, whereas it was inhomogeneous and induced different fracture patterns on the 0.05-mm-thick specimen in the shear test. These results suggest that the tensile test is useful for testing the mechanical strength of film-formed SARCs.

Keywords: Resin cements, Tensile strength, Film form, Self-adhesive, Finite element analysis

INTRODUCTION

Resin cements are a type of dental cement that are used for the luting of fixed prosthesis and are widely used in clinical practice to prevent fracture and debonding of dental prosthesis as well as improve their esthetic properties. Currently, a self-adhesive resin cement (SARC) has been developed by manufacturers and is being used in routine clinical practice. SARCs do not require a primer and/or bonding agent because of the inclusion of adhesive monomers in the cement paste. Several studies have described the bonding effectiveness of SARCs1-4). Sarr et al. evaluated the bonding effectiveness of nine resin cements including five SARCs used to lute ceramic to dentin and reported sufficient immediate bond strength even with simply use SARCs compared with conventional adhesive cements with primer5).

The mechanical properties of SARCs have been categorized into various properties, such as compressive strength5,6), flexural strength5,7), tensile strength8), diametral tensile strength9), and Vickers hardness9). Piwowarczyk and Lauer tested the compressive and flexural strengths of 12 luting cements, such as resin cements, resin-modified glass ionomer cements, glass ionomer cements, and zinc phosphate cements. They reported that high compressive and flexural strengths were achieved with SARC5). Kim et al. compared the compressive strength, diametral tensile strength, and microhardness of six SARCs using different curing modes (self-cured and light-cured) and testing times (immediately, after 24 h, and thermocycling). They concluded that all the tested cements demonstrated clinically suitable compressive and diametral tensile strengths9).

With increasing variation among SARC products, ISO/TS 16506: 2017 “Dentistry —Polymer-based luting materials containing adhesive components” was established as a technical specification for the testing methods of SARC5). In this specification, flexural strength using a rectangular specimen measuring 25×2.0×2.0 mm was adopted as an evaluation method to assess the mechanical strength of SARCs and has been used for flexural strength tests5,7). This test method follows the method specified by ISO 4049: 2019 “Dentistry —Polymer-based restorative materials”10), which has been widely used as the evaluation method for resin composites and resin cements that do not contain an adhesive component5,7). However, due to the luting cement applied for fixed prosthesis is formed as a thin layer, and a new evaluation method has been required to test the mechanical strength of cements cured in film form as a cement layer.

Therefore, in the present study, we proposed an evaluation method to test the mechanical strength of film-formed SARCs with respect to cement thickness. Tensile and shear tests were conducted for film-formed specimens of varying thicknesses (0.05, 0.2, and 0.4 mm) using three commercially available dual-cure type SARC. For comparison, a three-point flexural strength test specified in ISO/TS 16506: 2017 was performed. In addition, the stress distribution and fracture patterns of film-formed SARCs were analyzed using in silico nonlinear dynamic finite element analysis (FEA).
MATERIALS AND METHODS

Materials
Three commercially available dual-cure type SARCs were used for in vitro tensile, shear, and three-point bending tests: PANAVIA SA Cement Plus (PC; Kuraray Noritake Dental, Tokyo, Japan), iCEM Self Adhesive (IC; Kulzer, Hanau, Germany), and BisCem (BC; Bisco, IL, USA). The material compositions of each SARC are summarized in Table 1.

Tensile test
Rectangular specimens were fabricated with the following dimensions: width, 3.0 mm; length, 13.2 mm; and thickness, 0.05, 0.2, or 0.4 mm, using polyester molds for 0.05-mm-thick specimens and polytetrafluoroethylene molds for 0.2-mm and 0.4-mm-thick specimens. The paste of each SARC was filled in the molds and pressed with glass plates using 50-μm-thick polyester films from the upper and lower sides. These SARC pastes were light-cured for 10 s (PC), 40 s (IC), and 20 s (BC) with PENCURE 2000 (Morita, Kyoto, Japan) according to the manufacturer’s instructions. Irradiation was performed from the upper and lower sides of the specimens under the maximum light intensity of normal mode, that is, 1,000 mW/cm². Each specimen was immersed in a water bath at 37±2°C for 15 min for post-polymerization with self-cure (dual-cured group). SARC pastes not subjected to light irradiation were stored in a thermostatic chamber at 37±2°C for 1 h (self-cured group). The specimens were removed from each mold and polished using a waterproof abrasive paper with a grit size of #1000 (Nihon Kenshi, Hiroshima, Japan) to avoid the influence of flashes on the measurements. Each specimen (Fig. 1a) was immersed in distilled water at 37±2°C for 1 day.

The specimens were glued on jigs for the microtensile bond strength test with cyanoacrylate (MODEL REPAIR II BLUE, Dentsply Sirona, Tokyo, Japan), and their maximum forces were measured using a universal testing machine (EZ Test EZ-SX, Shimadzu, Kyoto, Japan) at a crosshead speed of 1.0 mm/min (Fig. 2). The tensile strength $\sigma_t$ (MPa) was calculated using the following equation (1)\(^\text{11}\).

$$\sigma_t = \frac{F}{bh}$$

where $F$ indicates the maximum load at failure (N), $b$ indicates the specimen width (mm), and $h$ indicates the specimen thickness (mm).

![Fig. 1 Photographs of the specimens in each test. (a) Film-formed specimen (thickness: 200 μm), (b) Specimen in the shear strength test (thickness: 200 μm), (c) Specimen in the flexural strength test](image)

Table 1  SARCsn used in this study (information as disclosed by the manufacturers)

| Material                  | Manufacturer            | Lot No. | Composition                                                                                                                                                                                                 |
|---------------------------|-------------------------|---------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| PANAVIA SA Cement Plus    | Kuraray Noritake Dental | 268     | Paste A: MDP, Bis-GMA, TEGDMA, hydrophobic aromatic dimethacrylate, HEMA, silanated barium glass filler, silanated colloidal silica, CQ, peroxide, catalysts, pigments. Paste B: hydrophobic aromatic dimethacrylate, hydrophobic aliphatic dimethacrylate, silanated barium glass filler, surface treated sodium fluoride, accelerators, pigments. The total amount of inorganic filler is ca. 63 wt%. The particle size of inorganic fillers ranges from 0.02 μm to 20 μm. |
| iCEM Self Adhesive (IC)   | Kulzer                  | KO10050 | Acidified urethane, di-, tri-, and multifunctional acrylate monomers, 49 wt% filler of sub-micron and micron sized particles. Base: Bis-GMA, proprietary, glass filler. Catalyst: bis[2-(methacryloyloxy)ethyl] phosphate, HEMA, bis(glyceryl 1,3 dimethacrylate)phosphate, dibenzoyl peroxide, glass fillers. Glass fillers have particle sizes from 0.02 to 5 μm (average), Base; 60 wt%, Catalyst; 62 wt% |
| BisCem (BC)               | BISCO                   | 1800006535 | MDP: 10-methacryloyloxydecyl dihydrogen phosphate; Bis-GMA: bisphenol A diglycidyl methacrylate; TEGDMA: triethyleneglycol dimethacrylate; HEMA: 2-hydroxyethyl methacrylate; CQ: DL-camphorquinone. |

MDP: 10-methacryloyloxydecyl dihydrogen phosphate; Bis-GMA: bisphenol A diglycidyl methacrylate; TEGDMA: triethyleneglycol dimethacrylate; HEMA: 2-hydroxyethyl methacrylate; CQ: DL-camphorquinone.
Shear test

Cylindrical specimens were fabricated measuring 10 mm diameter and 0.05, 0.2, or 0.4 mm thick using polyester or polytetrafluoroethylene molds. The SARC pastes were filled in the mold and pressed by glass plates with 50-μm-thick polyester films from the upper and lower sides. These SARC pastes were light-cured for 10 s (PC), 40 s (IC), and 20 s (BC) with PENCURE 2000 according to the manufacturer’s recommendation. Irradiation was administered from the upper and lower sides of the specimens under the maximum light intensity of the normal mode: 1,000 mW/cm². Each specimen was immersed in a water bath at 37±2°C for 15 min for post-polymerization with self-cure (dual-cured group). The SARC pastes that were not subjected to irradiation were stored in a thermostatic chamber at 37±2°C for 1 h (self-cured group). Each specimen (Fig. 1b) was immersed in distilled water at 37±2°C for 1 day.

The maximum force was measured using the method reported by Yamazaki et al. The specimen was set on the jigs and was punched out using a stainless-steel cylindrical rod with a diameter of 3 mm using a universal testing machine (Autograph AG-Xplus, Shimadzu) at a crosshead speed of 1 mm/min (Fig. 3). The shear strength σₛ (MPa) was calculated using the following equation (2):

$$\sigma_s = \frac{F}{\pi dh}$$  \hspace{1cm} (2),

where F indicates the maximum load at failure (N), πd indicates the circumference of cylindrical rod (mm), and h indicates the thickness of the specimen (mm).

Three-point bending test

The test was conducted as per the ISO/TS 16506: 2017. Rectangular specimens were fabricated with the following dimensions: width, 2 mm; height, 2 mm; and length, 25 mm, using a stainless-steel mold. The SARC pastes were filled in the mold and pressed with glass plates using 50-μm-thick polyester films from the upper and lower sides. These SARC pastes were light-cured by irradiation with PENCURE 2000 in the three overlapped sections per specimen using the ø9-mm irradiation window. The exposure time at each section was set to 10 s (PC), 40 s (IC), and 20 s (BC) according to the manufacturer’s instructions. Irradiation was administered from the upper and lower sides of the specimens under the maximum light intensity of the normal mode: 1,000 mW/cm². Each specimen was immersed in a water bath at 37±2°C for 15 min for post-polymerization with self-cure (dual-cured group). The specimens were removed from the molds and polished using a waterproof abrasive paper with a grit size of #1000 to avoid the influence of flashes on the measurements. Each specimen (Fig. 1c) was immersed in distilled water at 37±2°C for 1 day.

A universal testing machine (Autograph AG-Xplus) was used with a span length of 20 mm between the two support rods and at a crosshead speed of 0.5 mm/min. The flexural strength σƒ (MPa) was determined using the following equation (3):

$$\sigma_f = \frac{3Fl}{2bh^2}$$  \hspace{1cm} (3),

where F indicates the maximum load at failure (N), l indicates the span length between the support rods (mm), b indicates the specimen width (mm), and h indicates the specimen height (mm).
Nonlinear dynamic FEA
To compare the stress distribution and fracture pattern in tensile and shear tests using film-formed specimens, we performed in silico nonlinear dynamic FEA. According to the in vitro tensile tests, three rectangular computer-aided design (CAD) models (3×13.2 mm) with different thicknesses (0.05, 0.2, and 0.4 mm) were designed using CAD software (Solidworks Simulation 2011, Dassault Systèmes Solidworks, Waltham, MA, USA) (Fig. 4a). Elastic modulus, Poisson’s ratio, density, and fracture strain of PC cured using the dual-cure mode were determined as per a previous study (Table 2) and set for each model. A constant displacement of 0.05 mm was applied to a jig along the longitudinal axis, and another jig was fixed for all the directions. The specimen and jigs were perfectly bonded. The number of deformable elements for models with different thicknesses was as follows: 15840 for 0.05-mm thickness, 63360 for 0.2-mm thickness, and 126720 for 0.4-mm thickness.

According to the in vitro shear tests, three cylindrical CAD models (ø10 mm) with different thicknesses (0.05, 0.2, and 0.4 mm) were designed using CAD software (Fig. 4b). Material properties same with that in the tensile analysis were set for each model. A constant displacement of 0.06 mm was applied to the cylindrical rod along the vertical axis in the downward direction at the center of cylinder. The sliding contact condition was defined among the specimen, jigs, and cylindrical rod. The number of deformable elements for models with different thicknesses (0.05, 0.2, and 0.4 mm) was 24220, 96880, and 193760, respectively.

Nonlinear dynamic FEA was performed using FEA software (LS-DYNA, LSTC, Livermore, CA, USA). The maximum principal stress distribution was analyzed and the fracture patterns were compared.

Statistical analyses
The mean and standard deviation for each load at failure were subjected to statistical analyses with one-way analysis of variance, Tukey’s test, and Student’s t-test (KaleidaGraph Version 3.6, HULINKS, Tokyo, Japan), with a level of significance of 0.05.

RESULTS
Tensile strength
Horizontal fracture for the longitudinal direction of the specimen was observed in the region between the edges of jigs (Fig. 2b). For PC and IC, the tensile strengths of the self-cured or dual-cured groups were not significantly different among the specimen thicknesses (PC: self-cured; p=0.20687, dual-cured; p=0.4484, IC: self-cured; p=0.222, dual-cured; p=0.13889, Table 3). In contrast, the tensile strength in the dual-cured group were significantly greater than that in the self-cured group (PC: 0.05 mm; p<0.0001, 0.20 mm; p<0.0001, 0.40 mm; p<0.0001, IC: 0.05 mm; p<0.0001, 0.20 mm; p<0.0001, 0.40 mm; p<0.0001). With respect to BC, the tensile strength of the self-cured group and the dual-cured group did not show significant differences among the specimen thicknesses (self-cured; p=0.76663, dual-cured; p=0.7546). Moreover, there was no significant difference between the tensile strength of the two groups (0.05 mm: p=0.9682, 0.20 mm: p=0.5652, 0.40 mm: p=0.8152).

Shear strength
As for PC, IC, and BC, the shear strengths in the self-cured group or the dual-cured group were lower with thinner specimens (PC: self-cured; p<0.0001, dual-cured; p<0.0001, IC: Self-cured; p<0.0001, dual-cured; p<0.0001, BC: self-cured; p<0.0001, dual-cured; p<0.0001).
Table 3  Tensile strengths (MPa) of SARCs

|                  | Self-cured       | Dual-cured       |
|------------------|------------------|------------------|
|                  | 0.05 mm  | 0.20 mm  | 0.40 mm  | 0.05 mm  | 0.20 mm  | 0.40 mm  |
| PANAVIA SA Cement Plus Automix (PC) | 57.5ab (2.8) | 59.5aA (4.0) | 56.7aA (3.5) | 68.6aA (6.9) | 70.8aA (2.9) | 68.1aA (4.0) |
| iCEM Self Adhesive (IC)   | 27.1b (3.1) | 25.4b (2.4) | 25.4b (1.7) | 62.6bA (4.2) | 59.4b (4.7) | 62.3b (2.4) |
| BisCem (BC)   | 40.9c (5.2) | 42.1c (7.3) | 42.8c (4.4) | 39.0d (4.8) | 38.2c (4.4) | 39.8c (5.5) |

( ): SD. Different upper case letters in each resin cement indicate significant differences, and different lower case letters in each thickness of the self- and dual-cured group indicate significant differences (p<0.05, one-way analysis of variance and Tukey’s test).

Table 4  Shear strengths (MPa) of SARCs

|                  | Self-cured       | Dual-cured       |
|------------------|------------------|------------------|
|                  | 0.05 mm  | 0.20 mm  | 0.40 mm  | 0.05 mm  | 0.20 mm  | 0.40 mm  |
| PANAVIA SA Cement Plus Automix (PC) | 5.7aA (0.4) | 12.2aA (1.4) | 50.5aA (2.9) | 11.5aA (1.4) | 30.9aA (2.3) | 51.1aA (2.5) |
| iCEM Self Adhesive (IC)   | 6.6b (0.3) | 10.5b (0.9) | 19.5b (1.0) | 10.6b (1.3) | 26.1b (1.6) | 54.6b (2.6) |
| BisCem (BC)   | 2.9c (0.4) | 9.2c (0.8) | 30.5c (1.4) | 5.0c (0.5) | 15.2c (1.7) | 32.8c (1.1) |

( ): SD. Different upper case letters in each resin cement indicate significant differences, and different lower case letters in each thickness of the self- and dual-cured group indicate significant differences (p<0.05, one-way analysis of variance and Tukey’s test).

Table 5  Flexural strengths (MPa) of SARCs

|                  | Self-cured       | Dual-cured       |
|------------------|------------------|------------------|
| PANAVIA SA Cement Plus Automix (PC) | 87.8aA (6.1) | 100.7aA (10.9) |
| iCEM Self Adhesive (IC)   | 41.6b (3.2) | 87.8b (6.3) |
| BisCem (BC)   | 51.3c (4.6) | 48.5c (7.2) |

( ): SD. Different upper case letters in each resin cement indicate significant differences (p<0.05, one-way analysis of variance and Tukey’s test), and different lower case letters in each thickness of the self- and dual-cured group indicate significant differences (p<0.05, Student’s t-test).

With respect to PC, in 0.05-mm and 0.2-mm thick specimens, the shear strength in the dual-cured group was significantly higher than that in the self-cured group (0.05 mm: p<0.0001, 0.20 mm: p<0.0001); however, the shear strength in the two groups was not significantly different with a specimen thickness of 0.40 mm (p=0.9893). Moreover, for IC, in specimens with all thicknesses, the shear strength in the dual-cured group was significantly greater than that in the self-cured group (0.05 mm: p<0.0001, 0.20 mm: p<0.0001, 0.40 mm: p<0.0001). For BC, in specimens with the same thickness, the shear strength was significantly greater in the dual-cured group than in the self-cured group (0.05 mm: p<0.0001, 0.20 mm: p<0.0001, 0.40 mm: p<0.0003).

**Flexural strength**
In the self-cured group, PC showed the highest flexural strength, followed by BC (p<0.0001) and IC (p<0.0001, Table 5). In the dual-cured group, PC showed the highest flexural strength, followed by IC (p=0.005749) and BC (p<0.0001).

**Stress distribution and fracture pattern**
For the tensile models, positive maximum principal stress values (tensile stress) were gradually increased...
on the top surface of the specimen and homogeneously concentrated at the boundary between the corner edge of each jig and specimen (indicated by yellow arrows in Fig. 5). For the shear models, the maximum principal stress value was gradually increased and cylindrically and homogeneously concentrated on the surface of specimens with 0.2-mm and 0.4-mm thickness, while the stress was locally concentrated on the top surface of specimen with 0.05-mm thickness (indicated by yellow arrows in Fig. 6).

For the tensile models, fracture was initiated from the corner edge of each jig based on the tensile stress concentration. Initial crack was immediately propagated along the corner edge of each jig (indicated by green arrows in Fig. 6).

Fig. 5  Maximum principal stress distribution (left) and fracture initiation (right) in specimens of microtensile tests.

Fig. 6  Maximum principal stress distribution and sectioned close-up image (left) and fracture initiation (right) in specimens of shear tests.
arrows in Fig. 5). With respect to the shear models, fracture was cylindrically initiated from the top surface of the specimens with 0.2-mm and 0.4-mm thickness, and there was no separation from the disk while fracture was initiated as per local stress concentration for the specimen with 0.05-mm thickness (indicated by green arrows in Fig. 6); the specimen was finally pushed out with the cylindrical rod.

**DISCUSSION**

We assessed the mechanical strengths of the film-formed SARCs while reflecting cement layer thickness. Owitayakul et al. investigated setting zirconia crown models fabricated using CAD/CAM system on model abutment teeth (maxillary premolar) with two different types of resin cements under a load of 50 N. The cement layer thicknesses were measured to obtain mean values in the range of 0.028 to 0.208 mm\(^{19}\). May et al. showed that failure loads of feldspathic ceramic crowns bonded to dentin analog dies, with occlusal resin cement thicknesses of 0.05 mm and 0.5 mm\(^{16}\). The specimen thicknesses selected in this study (0.05, 0.2, and 0.4 mm) were within the range of cement layer thicknesses reported by Owitayakul et al. and May et al. and could be fabricated by molding.

In the present study, the specimen was rectangular; the width was 3 mm and the length was 13.2 mm. The width and length were determined by following the dimensions of the specimen in “dumbbell method” described in “ISO/TS11405: 2015 Dentistry — Testing of adhesion to tooth structure”\(^{15}\) as a method for tensile test. As per the “dumbbell method,” a tensile bond strength test, a dumbbell shape is adopted to maximize the tensile stress at the bonded site to induce fracture\(^{19}\). In this study, the tensile test did not require the adjustment of the specimen width because the aim is not to increase the tensile stress at a specific site in the specimen. Thus, the shape of the specimen was set to rectangular.

The jigs used for the tensile test were the same as that used in the “microtensile test method”\(^{20}\) described in ISO/TS 11405: 2015 as a method of tensile bond strength test\(^{15}\). The specimens were glued on the jigs with cyanoacrylate adhesives, following the “microtensile test method”\(^{20}\). Specimens of dual-cure type SARC: PC, IC and BC, were prepared in the self-cure mode or the dual-cure mode, and the tensile test was conducted at a crosshead speed of 1 mm/min by following the conditions used for the “microtensile test method”\(^{20}\). There were no significant differences in the tensile strengths of the three materials in either group as per the specimen thickness. The results suggest that tensile strength was not affected by the specimen thickness.

The standard test method for shear strength of plastics is performed by punching out the center of the disk-shaped specimen\(^{13}\) and has been used in the evaluation of the mechanical strength of luting cements\(^{2, 21, 22}\). In this study, the shear strength of SARCs was evaluated for film-formed specimens with thicknesses of 0.05, 0.2, and 0.4 mm, similar to the thicknesses used in the tensile test. The shear strengths of the SARCs were affected by the thickness of the specimens in all three materials that were tested. In both the “self-cured” and “dual-cured” groups, the shear strength decreased significantly as the specimen thickness decreased.

The tensile strength of SARCs was unaffected by the specimen thickness, while the shear strength decreased with a reduction in the specimen thickness, which indicates that the tensile test and the shear test exhibited different fracture mechanisms in the film-formed SARCs. FEA of the specimen under tensile and shear loadings was conducted to determine the effect of different specimen thickness on stress distribution and fracture patterns.

The in silico nonlinear dynamic FEA used in this study demonstrated that the maximum principal stress distribution was homogeneous on the surface of specimens even with different thicknesses, while the specimen with 0.05-mm thickness had different maximum principal stress and varying fracture patterns than specimens with other thicknesses. For the shear models of 0.2-mm and 0.4-mm thickness, clear boundaries of positive and negative values of maximum principal stress (tensile and compressive stress) were confirmed at the surface of specimens, as depicted in the close-up image (Fig. 6), which suggests that fractures of these two models were initiated from shear stress concentration. However, the shear model of 0.05-mm thickness only has tensile stress concentration at the boundary because of large deformation due to thinner than others, which suggests that fracture mode might be different. These results indicate that the tensile test is more appropriate than the shear test to evaluate film-formed specimens (0.05-mm thickness).

Compared with the flexural strength tested using the conventional method, the mechanical strength of SARCs obtained in this study based on the tensile test showed the same order. That is, in the “self-cured” group, PC had the highest tensile strength, followed by BC and IC, and in the “dual-cured” group, PC had the highest tensile strength, followed by IC and BC. These results and the above-mentioned comparison with the shear test indicate that the tensile test using film-formed SARCs with cement thickness (0.05, 0.2, and 0.4 mm) is a more suitable test method that accurately shows the clinical situation and helps evaluate the mechanical strength of SARCs than the three-point bending or shear test.

The curing system of the SARCs used in this study was the dual-cure type, which includes both the redox- and photo-polymerization systems. The mechanical strength of both the specimens without light irradiation (the self-cure mode) and with light irradiation (the dual-cure mode) was measured. The compressive strength, diametral tensile strength, and Vickers hardness of dual-cure type SARCs were dependent on the product. These results were related to the curing system, such as the type of redox- and/or photo-polymerization initiators and their ratios\(^{16}\). The difference in the mechanical strength between the “self-cure” and “dual-cure” groups of SARCs tested in this study might be related to the
difference in the design of polymerization reaction of the SARC, whether emphasized mainly on redox- or photo-polymerization. The results of tensile and flexural strengths suggest that for IC, there was a large difference in the mechanical strength with and without light irradiation.

CONCLUSION
The novel testing method proposed in this study showed that the tensile strength did not differ significantly with different specimen thickness; however, the shear strength decreased significantly as the specimen thickness decreased. These results were also supported by a different perspective of stress distribution and fracture patterns with in silico nonlinear dynamic FEA. These results suggest that the proposed tensile test is useful for evaluating the mechanical strength of the film-formed SARCs while reflecting the cement thickness.

ACKNOWLEDGMENTS
We thank Edanz Group (https://en-author-services.edanz.com/ac) for editing a draft of this manuscript.

REFERENCES
1) Sarr M, Mine A, De Munck J, Cardoso MV, Kane AW, Vreven J, et al. Immediate bonding effectiveness of contemporary composite cements to dentin. Clin Oral Investig 2010; 14: 569-577.
2) Roydhouse RH. Punch-shear test for dental purposes. J Dent Res 1970; 49: 131-136.
3) De Munck J, Vargias M, Van Landuyt K, Hikita K, Lambrechts P, Van Meerbeek B. Bonding of an auto-adhesive luting material to enamel and dentin. Dent Mater 2004; 20: 963-971.
4) Lin J, Shinya A, Gomi H, Shinya A. Bonding of self-adhesive resin cements to enamel using different surface treatments: bond strength and etching pattern evaluations. Dent Mater J 2010; 29: 425-432.
5) Pwowarczyk A, Lauer HC. Mechanical properties of luting cements after water storage. Oper Dent 2003; 28: 535-542.
6) Kim AR, Jeon YC, Jeong CM, Yun MJ, Choi JW, Kwon YH, et al. Effect of activation modes on the compressive strength, diametral tensile strength and microhardness of dual-cured self-adhesive resin cements. Dent Mater J 2016; 35: 298-308.
7) Schittly E, Le Goff S, Besnault C, Sadoun M, Ruse N. Effect of water storage on the flexural strength of four self-etching adhesive resin cements and on the dentin-titanium shear bond strength mediated by them. Oper Dent 2014; 39: E171-177.
8) Costa LA, Carneiro KK, Tanaka A, Lima DM, Bauer J. Evaluation of pH, ultimate tensile strength, and micro-shear bond strength of two self-adhesive resin cements. Braz Oral Res 2014; 28: 1-7.
9) ISO/TS16506:2017. Dentistry —Polymer-based luting materials containing adhesive components. Geneva: The International Organization for Standardization; 2017.
10) ISO4049:2019. Dentistry —Polymer-based restorative materials. Geneva: The International Organization for Standardization; 2019.
11) Fujishima A, Ikeda K, Aoyama M, Miyazaki T, Sasa R, Ferracane JL. Durability of resin-modified glass ionomer cements after long term water immersion. J Showa Univ Dent Soc 2001; 21: 178-185.
12) Yamazaki A, Hibino Y, Honda M, Nagasawa Y, Hasegawa Y, Omatsu J, et al. Effect of water on shear strength of glass ionomer cements for luting. Dent Mater J 2007; 26: 708-712.
13) ASTM International. Standard Test Method for Shear Strength of Plastics by Punch Tool. West Conshohocken, Pittsburgh, 2017.
14) Yamaguchi S, Katsumoto Y, Hayashi K, Aoki M, Kunikata M, Nakase Y, et al. Fracture origin and crack propagation of CAD/CAM composite crowns by combining of in vitro and in silico approaches. J Mech Behav Biomed Mater 2020; 112: 104083.
15) Owitayakul D, Lertrid W, Anamatama C, Pittayachawan P. The comparison of the marginal gaps of zirconia framework luted with different types of phosphate based-resin cements. Mahidol Dent J 2015; 35: 237-251.
16) Gressler May L, Kelly JR, Bottino MA, Hill T. Influence of the resin cement thickness on the fatigue failure loads of CAD/CAM feldspathic crowns. Dent Mater 2015; 31: 895-900.
17) Nakabayashi N. Importance of mini-dumbbell specimen to access tensile strength of restored dentine: historical background and the future perspective in dentistry. J Dent 2004; 32: 437-442.
18) ISO/TS11405:2015. Dentistry —Testing of adhesion to tooth structure. Geneva: The International Organization for Standardization; 2015.
19) Nakabayashi N, Watanabe A, Arai T. A tensile test to facilitate identification of defects in dentine bonded specimens. J Dent 1998; 26: 379-385.
20) Sano H, Shono T, Sonoda H, Takatsu T, Ciucchi B, Carvalho R, et al. Relationship between surface-area for adhesion and tensile bond strength. Dent Mater 1994; 10: 236-240.
21) Nomoto R, Carrick TE, McCabe JF. Suitability of a shear punch test for dental restorative materials. Dent Mater 2001; 17: 415-421.
22) Bagheri R, Mese A, Burrow MF, Tyas MJ. Comparison of the effect of storage media on shear punch strength of resin luting cements. J Dent 2010; 38: 820-827.