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Effects of Bond Primers on Bending Strength and Bonding of Glass Fibers in Fiber-Embedded Maxillofacial Silicone Prostheses

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Keywords
Maxillofacial silicone elastomer; artificial aging; pull-out test; glass fiber; bending strength; bond primer.

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Abstract

Purpose: To evaluate the effect of three commonly used bond primers on the bending strength of glass fibers and their bond strength to maxillofacial silicone elastomer after 360 hours of accelerated daylight aging.
Materials and Methods: Eighty specimens were fabricated by embedding resin-impregnated fiber bundles (1.5-mm diameter, 20-mm long) into maxillofacial silicone elastomer M511 (Cosmesil). Twenty fiber bundles served as control and did not receive surface treatment with primers, whereas the remaining 60 fibers were treated with three primers (n = 20): G611 (Principality Medical), A-304 (Factor II), and A-330-Gold (Factor II). Forty specimens were dry stored at room temperature ($23 \pm 1°C$) for 24 hours, and the remaining specimens were aged using an environmental chamber under accelerated exposure to artificial daylight for 360 hours. The aging cycle included continuous exposure to quartz-filtered visible daylight (irradiance 760 W/m^2) under an alternating weathering cycle (wet for 18 minutes, dry for 102 minutes). Pull-out tests were performed to evaluate bond strength between fiber bundles and silicone using a universal testing machine at 1 mm/min crosshead speed. A 3-point bending test was performed to evaluate the bending strength of the fiber bundles. One-way Analysis of Variance (ANOVA), Bonferroni post hoc test, and an independent *t*-test were carried out to detect statistical significances ($p < 0.05$).
Results: Mean (SD) values of maximum pull-out forces (N) before aging for groups: no primer, G611, A-304, A-330-G were: 13.63 (7.45), 20.44 (2.99), 22.06 (6.69), and 57.91 (10.15), respectively. All primers increased bond strength in comparison to control specimens ($p < 0.05$). Primer A-330-G showed the greatest increase among all primers ($p < 0.05$); however, bonding degraded after aging ($p < 0.05$), and pull-out forces were 13.58 (2.61), 6.17 (2.89), 6.95 (2.61), and 11.72 (3.03). Maximum bending strengths of fiber bundles at baseline increased after treatment with primers and light aging in comparison with control specimens ($p < 0.05$), and were in the range of 917.72 to 1095.25 and 1124.06 to 1596.68 MPa at both baseline and after 360 hours aging ($p < 0.05$).
Conclusions: The use of A-330-G primer in conjunction with silicone Cosmesil M511 produced the greatest bond strength for silicone-glass fiber surfaces at baseline; however, bond strength was significantly degraded after accelerated daylight aging. Treatment with primer and accelerated daylight aging increased bending strength of glass fibers.

Maxillofacial prostheses are constructed to restore function and natural appearance of the face and associated structures of facially disfigured patients. Silicone elastomers have been widely used in fabricating these prostheses, as they are biocompatible, elastic, and can be pigmented to simulate skin tone.[1,2]

In maxillofacial silicone prostheses, silicone elastomers are conventionally bonded to a retentive acrylic baseplate, which holds the retentive magnets or clips,[3,4] or a cast titanium plate.[5] Alternatively, the baseplate can be attached to a polyurethane layer[6] when the prosthesis is adhesively retained.[7] Recently, a new technique was reported indicating that the silicone body can encapsulate in a retentive glass fiber-embedded framework as in fiber-embedded maxillofacial prostheses.[8,9]

The glass fiber bundles consist of unidirectional E-glass fiber filaments impregnated with a resin mixture of bisphenol a glycidyl methacrylate (bis-GMA) and bisphenol ethoxylated a glycdyl dimethacrylate (bis-EMA) and light activators to achieve a good bond with the surrounding matrix.[10] Previously, fibers had been incorporated into some dental materials to modify and improve their properties. Fiber-reinforced composites (FRC) have proved to be suitable dental and medical biomaterials.[11,12] In addition, fibers are used as reinforcement in removable prostheses, fixed partial dentures, periodontal splints, orthodontic retainers, and endodontic dowels.[13]

While in use, maxillofacial silicone prostheses often suffer deterioration in color stability and their mechanical properties, along with possible delaminating of silicone from the acrylic baseplate.[14,15] This might be related to a number of factors, such as body secretions, weathering, and growth of microorganisms. In addition, aggressive cleaning techniques may affect the bond, resulting in a decrease in the longevity of the facial prosthesis.[16] Accordingly, various artificial aging protocols have been used to investigate the interaction of silicone elastomers to simulated grading conditions, including accelerated artificial daylight aging,[17,18] immersion in simulated sebum solution,[19,20] acidic and alkaline perspiration,[20] and cleaning solutions[16,21]; however, it was reported that accelerated artificial daylight aging changed properties of silicones faster and in a greater magnitude than other aging procedures.[22] Various improvements have been made in silicone elastomer to maximize and enhance functional properties' (tensile, tear, and hardness) resistance to environmental changes.[23,24]

During clinical service, forces expected to influence the bond integrity between fibers and silicones are likely to generate when the patient holds the silicone to dislodge the prosthesis from the magnetic retentive sites or bars, or during cleaning of the prosthesis.[25] The pull-out forces required to disrupt the bond integrity between fibers and silicone elastomer have been reported previously to be in the range of 13.63 to 15.49 N without aging[26] and 10.37 to 19.67 N[8] after different light aging intervals (200, 400, 600 hours). Such forces are still greater than the retention forces provided by maxillofacial retention methods such as magnets (7.2 N),[27] Magna-CAP® attachments (3 to 10 N) (MAGNA-CAP attachments, Technovent, Leeds, UK), or bars (5 to 7 N)[28]; however, recorded pull-out forces are not reliable for long-term serviceable prostheses. Various bond primers have been reported to increase bonding of silicone to polyurethane[16,29,30] or acrylic substrate.[3,31,32]

The aim of this work was to investigate the effect of three commonly used bond primers on glass fiber bending strength and their bond strength to silicone elastomer after 360 hours of accelerated daylight aging. The null hypothesis stated that the primers have no effect on glass fiber bending strength and bonding integrity with silicone elastomers.

Materials and methods

Specimen fabrication procedure was similar to previous studies.[8,26] Eighty specimens were constructed by embedding unidirectional glass fiber-bundles (C&B Fibers, StickTech, Turku, Finland) (1.5-mm diameter, 20-mm embedded length) into a heat-polymerized silicone elastomer (Cosmesil M511, Principality Medical, Newport, UK). Specimens were constructed using a sectional flask (100 × 80 × 30 mm^3) made of two parts: lower section (100-mm long × 80-mm wide × 10-mm height) and upper section (100-mm long × 80-mm wide × 20-mm height) (Fig 1). The basal (lower) section had 20 holes (1.50 diameter, 5 mm deep) into which the fiber bundles were fixed. The upper section had 20 cylindrical molds (14.40-mm diameter, 20-mm long), where the silicone was packed. The two parts were isolated with a thin layer of sodium alginate (Hillier Dental, Kent, UK). Eighty unidirectional glass fiber bundles were light polymerized for 4 minutes in a curing unit (ESPE Visio® Beta Vario, 3M ESPE, Seefeld, Germany). Twenty fiber bundles acted as control and did not receive surface treatment with adhesive primers. The remaining 60 fibers were treated with three primers (n = 20) (Table 1). Fiber surface treatment was performed at room temperature (23 ± 1°C) and 50 ± 5% relative humidity. Surfaces of the glass fibers were degreased with acetone and allowed to air dry, and then two consecutive brushes of the primer were painted over the glass fiber. The fibers were left to bench dry for 45 minutes (according to manufacturer instructions).

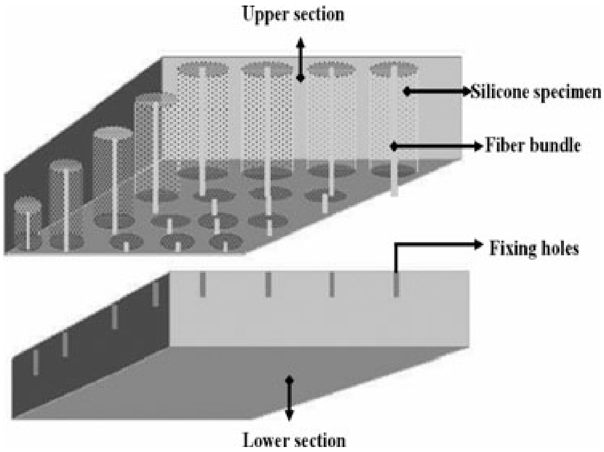

Figure 1 Two-section flask used in fabricating the specimens.[8]

Each fiber bundle was 25-mm long, corresponding to 5 mm inserted into the holes of the basal part, and 20 mm projecting above the surface, and acted as the embedded length within the silicone elastomer. The second part of the flask was assembled in place over the basal part, with the fiber bundles projecting through the center of the cylindrical molds. Maxillofacial silicone elastomer was weighted according to manufacturer's instructions (10 g to 1 g rubber-to-hardener ratio) using a microbalance. Forty grams of rubber were mixed with 4 g hardener, and this quantity was enough to fabricate ten specimens (≈4.4 g per specimen).

The silicone was mixed manually for 5 minutes, followed by mechanical mixing under vacuum for 5 minutes (Multi Vac 4, Degussa, Hanau, Germany). After completing the mixing, the silicone was poured into the molds of the flask, with the aid of vibration.

Table 1 Primers used

Primers (code)	Batch number	Composition	Manufacturer
Ancillary Materials platinum primer (G611)	Lot 07/03	Organic solvent-based primer includes components of propan-2-ol and various vinyl silanes	Principality Medical, Cardiff, UK
Platinum primer (A-304)	Lot L42587	A mixture of naptha (85%), tetra-n-propyl silicate (5%), tetrabutyltitnate (5%), and tetra (2-methoxyethoxy) silane (5%)	Factor II, Inc., Lakeside, AZ
Platinum primer (A-330-G) [Gold]	Lot I4707836	A solution of modified polyacrylates in ethylmethylketone and dichloromethane	Factor II, Inc., Lakeside, AZ

The flask contents were heat polymerized in an oven (Gallenkamp, Loughborough, UK) according to manufacturer's instructions (100°C for 1 hour), and left to bench cool for 2 hours. Then specimens were cautiously removed. Half were dry stored at room temperature (23 ± 1°C) for 24 hours; the other half were aged using an environmental chamber (Heraeus Suntest Chamber CPS, Atlas Material Testing Solutions Gmbh, Linsengericht, Germany) under accelerated exposure to artificial daylight for 360 hours. The groups tested are presented in Table 2.

Quartz-filtered radiation was generated using a Xenon lamp. The UV component of the radiation that was directed upward was reflected on the specimens by mirrors placed over the Xenon lamp. A complete weathering cycle lasted for 120 minutes, including 18 minutes of wet weathering (29 ± 2°C) by distilled water, followed by 102 minutes of dry weathering (36 ± 2°C). Relative humidity was approximately 70%, and air pressure was 700 to 1060 hPa. Specimens were stored for 24 hours at room temperature (23 ± 1°C), and then pull-out tests were conducted using a low-load cell (0.5 kN) installed on a universal testing machine (Zwick/Roell Z020, Leominster, UK) (Fig 2). Maximum pull-out force and work were obtained.[33] The maximum pull-out (debonding) force was recorded. The pull-out work (R_p) required to extract the fiber bundles was calculated according to Equation 1:[34]

$$R_p = \frac{A_2}{\pi d L}, \tag{1}$$

where A_2 stands for area 2 under pull-out curve (Fig 3); d for diameter of fiber bundle; and L for length of embedment.

Table 2 Groups tested

Groups (n = 10)	Primer used	Conditioning
1	Control—no primer	Dry storage for 24 hours at 23 ± 1°C
2	G611	
3	A-304	
4	A-330-G	
5	Control—no primer	Accelerated daylight aging for 360 hours
6	G611	
7	A-304	
8	A-330-G	

The area under the curve (A_2) was measured using SigmaPlot software (release 8, SPSS Inc., Chicago, IL).

The fiber bundles were tested using a 3-point bending test. A load was applied to the fiber bundles by a steel bar attached to a load cell (20 kN) of the Zwick testing machine, at 2 mm/min speed. Maximum deflection and bending forces (F) were recorded by the machine, and maximum bending strength (б) was calculated according to Equation 2:[35]

$$б = \frac{8FL}{\pi d^3}, \tag{2}$$

where F is the maximum force applied (N); L is the length of fiber bundle (15 mm); and d is the average diameter of the fiber bundles (~1.5 mm).

Diameter of fiber bundles was obtained by three measurements performed by a digital caliper (Mitutoyo, Tokyo, Japan) at three locations on each bundle (one at the middle, two at both ends). After performing the pull-out test, fiber surfaces were visually inspected, and bond failures were categorized as adhesive, cohesive (within the silicone), or mixed failures. Pull-out

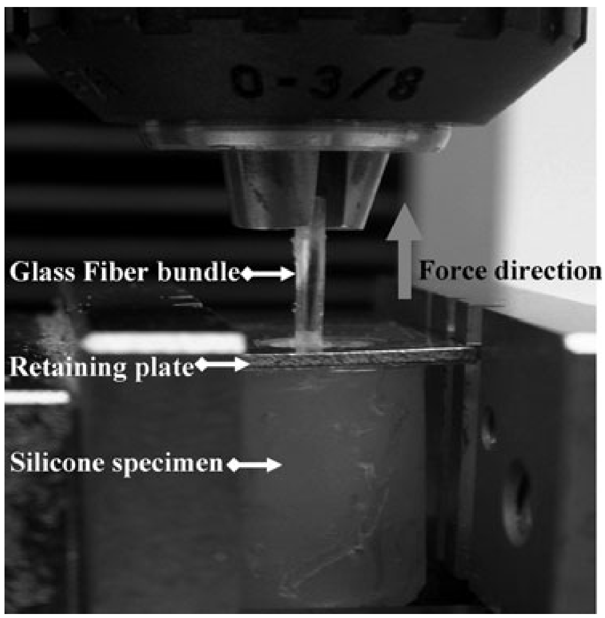

Figure 2 Close-up view of a specimen undergoing pull-out testing.

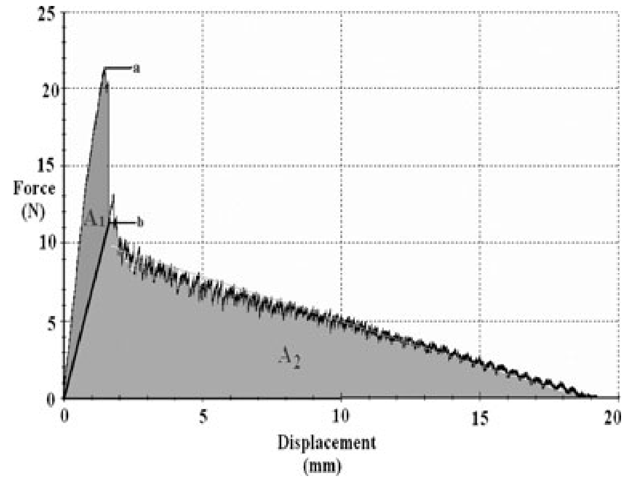

Figure 3 Typical pull-out graph of pulling 20-mm long glass fiber bundle out of a silicone matrix at 1 mm/min. Maximum pull-out force (a), arrested force (b), and area used for pull-out work calculations (A_2).

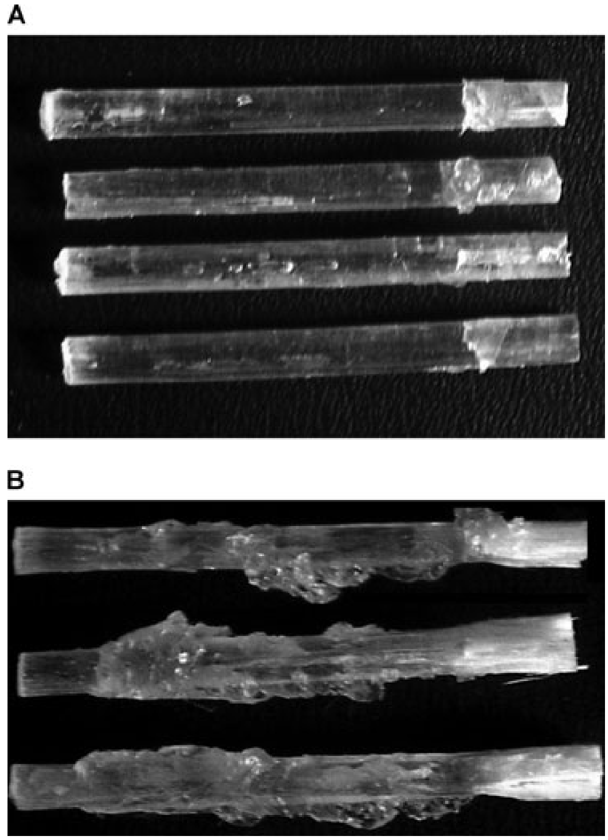

Figure 4 Adhesive (A) and mixed failures (B) presented after debonding.

parameters (forces and work) and bending values (maximum bending strength and deflection) were analyzed ($p < 0.05$) using one-way ANOVA and Bonferroni post hoc tests (release 14, SPSS Inc.). For each group, effect of aging on pull-out parameters (force and work) was analyzed using independent *t*-test ($p < 0.05$).

Results

Means of pull-out force and work are presented in Table 3. At baseline, primers increased bond strength in comparison to the control group ($p < 0.05$). Furthermore, primer 330 exhibited the greatest pull-out force and work ($p < 0.05$). After 360 hours of aging, pull-out forces and work were statistically significantly decreased for all primers in comparison to their baseline groups ($p < 0.05$); however, control specimens that received no primer treatment maintained their pull-out parameters in comparison to their nonaged specimens. Furthermore, and after 360 hours of aging, they showed greater pull-out force and work than that of primers (611 and 304) ($p < 0.05$).

Modes of failures were mainly adhesive (23), mixed (11), or cohesive (6) at baseline. After 360 hours of aging, all failures were adhesive (40) (Fig 4).

Maximum bending force, strength, and deflection are presented in Table 4. At baseline, all primers increased bending strength in comparison with the control group ($p < 0.05$). After 360 hours of aging, bending strength of glass fibers that received different primer treatments was greater than that of the control group ($p < 0.05$). In addition, and after 360 hours of aging, bending deflection of the glass fibers that received

Table 3 Mean (SD) values of pull-out force and work, and bond failures exhibited

	Pull-out data					
	At baseline			360 hours		
Groups (n = 10)	Force (N)	Work (N.mm)	Bond failures	Force (N)	Work (N.mm)	Bond failures
Control (no primer)	*$13.63^{Aa,b,c}$ (7.45)	0.94^{Aa} (0.32)	All adhesive	*$13.58^{Ba,b}$ (2.61)	$0.69^{Ba,b,c}$ (0.51)	All adhesive
Primer G611	$20.44^{Aa,d}$ (2.99)	0.21^{Bb} (0.07)	Adhesive (6) Mixed (4)	$6.17^{Aa,d}$ (2.89)	0.04^{Ba} (0.03)	All adhesive
Primer A-304	$22.06^{Ab,e}$ (6.69)	0.32^{Bc} (0.19)	Adhesive (7) Mixed (3)	$6.95^{Ab,c}$ (2.61)	0.04^{Bb} (0.02)	All adhesive
Primer A-330-G	$57.91^{Ac,d,e}$ (10.15)	$1.77^{Ba,b,c}$ (0.95)	Mixed (4) Cohesive (6)	$11.72^{Ad,c}$ (3.03)	0.10^{Bc} (0.06)	All adhesive

Within groups, similar upper case superscript letters indicate significant differences in pull-out force and work ($p < 0.05$).
Within pull-out force and work, similar lower case superscript letters indicate significant differences between groups ($p < 0.05$).
*Results adopted from previously published paper where specimens were light aged for 400 hours under the same parameters.[8]

Table 4 Mean (SD) values of maximum bending force, bending strength, and deflection

	At baseline			After 360 hours		
Groups (n = 10)	Maximum bending force (F_{max}) N	Maximum bending strength (σ_{Fmax}) MPa	Maximum deflection (S_M) mm	Maximum bending force (F_{max}) N	Maximum bending strength (σ_{Fmax}) MPa	Maximum deflection (S_M) mm
Control (no primer)	*60.84^{Aa} (4.63)	917.72^{Aa,b,c} (69.79)	2.23^{Aa} (0.45)	*74.52^{Aa} (9.49)	1124.06^{Aa,b,c} (143.15)	2.29^{Ba} (0.20)
Primer G611	66.99^{Ab} (8.42)	1010.49^{Aa} (126.99)	2.05^{Ab} (0.34)	69.70^{Bb} (15.12)	1351.73^{Aa} (164.65)	2.49^{Ab} (0.38)
Primer A-304	72.61^{Ac} (4.64)	1095.25^{Ab} (69.92)	2.04^{Ac} (0.26)	68.79^{Bc} (5.61)	1264.08^{Bb} (333.01)	2.46^{Ac} (0.28)
Primer A-330-G	61.80^{Ad} (15.25)	932.22^{Ac} (230.060	2.12^{Ad} (0.47)	63.26^{Bd} (9.16)	1596.68^{Ac} (307.88)	2.87^{Aa} (0.41)

Within groups, similar upper case superscript letters indicate significant differences in pull-out force and work ($p < 0.05$).
Within maximum bending force, strength, and deflection: similar lower case superscript letters indicate significant differences between groups ($p < 0.05$).
*Results adopted from previously published paper where specimens were light aged for 400 hours under the same parameters.[8]

primer A-330-G treatments was enhanced in comparison to the control group ($p < 0.05$).

Discussion

Fiber-embedded maxillofacial prostheses were introduced as an alternative to overcome the disadvantages associated with traditionally fabricated prostheses; namely, delaminating of the silicone of the acrylic base, poor marginal adaptation over time, and poor simulation of facial expression.[9] Bonding between glass fibers and silicones was reported to be in the range of 13.63 to 15.49 N (without aging)[26] and 10 to 19 N[8] after different amounts of accelerated artificial daylight aging. The use of different bond primers increased bond strength and affected bending strength of the glass fibers; accordingly, we rejected the null hypothesis.

To effectively discuss the effect of primers on silicone bond strength to glass fibers, we need first to consider the chemical composition of silicones, primers, and glass fibers tested. The Cosmesil M511 silicone elastomer used is a platinum-cured two-component silicone elastomer. The elastomer component consists of base polymer that has poly (dimethylsiloxane) (PDMS), reinforcing silica (i.e., surface-treated silica), and a platinum catalyst.[36] The curing component consists of a dimethylsiloxane polymer and a siloxane crosslinking agent. Polymerization of the mixture may be accomplished at room temperature or at slightly elevated temperatures. Polymerization involves the crosslinking of polysiloxanes via an addition reaction. Such reactions generally involve the addition of silyl hydride groups (–SiH) to vinyl groups (–H = CH2), which are attached to the primary polymer chain.[37]

Primer A-330-G is recommended by its manufacturer (Factor II, Inc., Lakeside, AZ) for bonding platinum-cured silicone elastomers to acrylic resin or polyurethane liners. It is made of a single component of polyacrylate in ethylmethylketone and dichloromethane to create reactive sites for the silicone (Factor II, Inc.). The hydrophilic and hydrophobic groups on the reactive sites react with the functional groups of silicone and polyurethane. Hence, primer molecules may collectively serve as chemical intermediate.[30]

A-304 primer is composed of a solution of polyacrylates in ethylmethylketone and dichloromethane (Factor II, Inc.). It is an air-drying primer designed to improve the adhesion of addition-cured silicones to various substrates, including metals, glass, ceramics, some plastics, and other silicone materials (Product Information, Factor II, Inc.).

Ancillary Material G611 is a platinum primer, composed of a dilution (in ethanol and distilled water) of vinyl-based silanes (i.e., Vinyltriethoxysilane, Vinyltrimethoxysilane) in propan-2-ol (Platinum primer G611). It is compatible with platinum-cured silicones used in this study. It enhances bond strength by swelling the surface and improving wettability of the substrate. Moreover, the vinyl silane is known to enhance bonding with its reactive groups of the silicone elastomer.[31]

Primers used in this study increased bond strength of the silicone to the glass fibers. This might be due to the dissolving effect of the primers at the fiber surfaces.[38,39]

Since the maxillofacial silicone elastomer used has different structural chemistry when compared to polymethylmethacrylate (PMMA) denture base resin or glass fibers, an adhesive is supplied to aid their bonding to the retentive substrate (i.e., acrylic resin).[40] It is likely that adhesive primers have an organic solvent and adhesive monomer that react with both silicone and resin materials.[41] They activate the surfaces via etching or promoting hydrogen bonding and covalent coupling, increasing the wettability of the substrate and by impregnating the surface layer with the polymeric ingredients.[31] Furthermore, silane coupling agents are chemically organo-functional trialkoxysilane esters, with three hydrolyzable alkoxy groups directly on the silicon atom, as they have direct –Si–C– bonds.[42]

The A-330-G primer showed the greatest bond strength (highest pull-out force) to silicone among other primers, which might be due to its unique chemical formula. This was confirmed by the high number of cohesive failures (6/10) exhibited within the silicone, as other primers exhibited adhesive and mixed failures. Cohesive failure indicates that the bond strength of silicone to fibers was greater than the tensile strength of the silicone itself; however, adhesive failure indicates that the tensile strength is greater than the bond strength.[43]

In addition, the work required to completely pull the fiber out of the silicone elastomer was greater for the same primer ($p < 0.05$), indicating greater frictional resistance of pulling the fiber out of the matrix after the debonding occurred.[44] On the other hand, and in comparison with other studies, Chang et al[29] reported that Sofreliner MS and Sofreliner T primers increased the bond strengths significantly compared to A-330-G primer; however, they bonded silicone to polyurethane and conducted a T-peel test.

After 360 hours of accelerated artificial daylight aging, primed specimens exhibited a severe reduction in pull forces in comparison to their nonaged counterparts ($p < 0.05$), and all bond failures were adhesive; however, the control group was not affected by aging. Furthermore, it exhibited greater pull-out parameters (force and work) than both primers (A-304, G611) ($p < 0.05$) after aging.

The control specimens were aged for 400 hours and compared to the other groups, which were aged for 360 hours. It is expected that such a difference in aging period (40 hours) will not significantly affect the interpretations of the current study results. It has been reported that specimens aged for 400 hours had the same results (pull-out force and work, and fiber bending strengths) of specimens aged for 600 hours.[8]

The physical interactions among silicone, glass fibers, and primers might include hydrogen bonding, dipole-to-dipole bonds, and Van der Waals forces, and are likely to increase bond strengths at baseline;[16] however, after alternate storing of specimens in water for a specific time and under continuous exposure to accelerated daylight aging, this degraded the intermediate interactions formed by the primer groups and resulted in decreased bonding among the silicone, primer, and glass fiber, as this did not affect the control group.[16] Furthermore, heat generated inside the aging chamber may have accelerated the bond degradation.[16] In dental restorations, success of fiber-reinforced restorations greatly depends on the compatibility between the glass fibers and adhesive bonding agent when applying glass fibers to an inlay bridge.[45] Furthermore, the bonding agents used should not only enhance adhesion, but also protect the fibers by facilitating stress transfer from the resin matrix to the fibers.[46]

Fracture of the acrylic body is a common problem among dental acrylic prostheses (i.e., complete dentures, partial dentures) and necessitates either increasing the thickness of the acrylic baseplate or strengthening with different types of reinforcements.[47] In fiber-embedded maxillofacial prostheses, application of primers at the fibers' surfaces significantly increased the adhesion with the silicone elastomers and enhanced the bending strength of the fibers and their resistance to fracture. This might result from the chemical formulae of the primers, as bending strength of fiber bundles varied with the resin mixtures and bonding used to impregnate the fibers.[45] Tsushima et al studied the effect of different bonding agents on the bending strength of glass fibers and reported that flurobond bonding agent exhibited the greatest value (570 MPa), whereas single bond exhibited the lowest value (224 MPa).[45]

After 360 hours of accelerated aging with artificial daylight, bending strengths of all fibers increased in comparison to their respective nonaged groups. This was mainly caused by the intensified light curing for increased durations.[8] The flexural properties of light-cured fibers were affected by the exposure time, light intensity, and polymerization temperature.[48] Hence, prolonging the polymerization time and increasing the light intensity increased the degree of conversion of the polymer matrix of FRC.[49]

Direct comparison with other studies that conducted bonding of silicone to different baseplates (i.e., acrylic, Ti) is not possible, due to variations in testing methods followed, deformation rates conducted, and materials used.[3–5] On the other hand, maximum pull-out forces exhibited at baseline were greater than the magnetic attraction forces[27] and bar retention forces;[28] however, after 360 hours of aging, which resembles a prosthesis being in service for 12 months,[50] pull-out forces were greatly reduced, highlighting the need for a more sustainable bonding system. While the accelerated artificial daylight conditioning performed in this study was considered a severe regime, as normal environmental factors are less than that generated in the aging machine, primers that survive such a regime are likely to remain in service for a longer time.

Conclusions

Within the limitations of this study, it can be concluded that:

(1) The use of A-330-G primer in combination with silicone Cosmesil M511 produced the greatest bond strength for silicone-glass fiber surfaces.
(2) Bond strength was significantly reduced after accelerated daylight aging; however, sufficient bonding between silicone and fibers still existed when A-330-G primer was used.
(3) Primers increased the bending strength of glass fibers and their resistance to fracture.

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