The ART of GIC proximal restorations in primary teeth

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Chapter 9

Flexural strength of a two-layer glass ionomer: a Finite Element Analysis

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Submitted
Abstract

Objective: A high-viscosity consistency of the glass-ionomer cement (GIC) may lead to poor adaptation into the cavity. The use of a flowable GIC layer seemed to improve its adaptation in approximal restorations in vitro. In this study we assessed the flexural strength of a two-layered GIC, using a flowable GIC as a liner (two-layer technique). Additionally, Finite Element Analysis (FEA) on standardized bar-shaped models and on a representative tooth model were performed to rationalize the obtained results.

Methods: The flexural strength and Young’s modulus were calculated from the results of a three-point-bending test. Bar-shaped specimens were prepared either with a conventional GIC, with a flowable GIC (powder/liquid ratio 1:2), and with two-layers. Three dimensional FEA models of the bar-shaped specimens and a model of tooth 46 provided information on the stress distribution of each component of the specimen and on the restoration.

Results: The apparent flexural strength and Young’s modulus of both two-layered groups were significantly lower than that of the conventional group. FEA showed that the layers of the two-layer specimens with the flowable GIC down detached from each other under load. The tooth model showed better stress distribution for the two-layer restorations.

Significance: The two-layer GIC showed inferior flexural strength, which might be explained by the detachment of the layers under load. Nevertheless the tooth model showed that the two-layer GIC provides a lower stress concentration on the occlusal surface of the material.
Introduction

Glass ionomer cements (GICs) are the most used filling material for minimal invasive restorations done by Atraumatic Restorative Treatment (ART) (1). Essentially, this is due to the combination of its adhesive properties with a relatively slow chemical setting reaction, and a possible therapeutic effect on demineralized enamel and dentin provided by the fluoride released from the GICs (2).

Specially developed for ART, high-viscosity GICs have better mechanical properties than their predecessors (3-5), but because of their brittleness and difficult handling, their performance on multi-surface cavities is far from optimal (6-8).

With regard to the adaptation of any restorative material in a posterior proximal cavity, the cervical margin is the weakest point. A high-viscosity material may lead to difficult insertion and cervical gaps, both of which contribute to restoration failure (9-11). Aiming to improve cervical adaptation and reduce secondary caries occurrence, GICs were often used as liners before the insertion of a resin composite or amalgam restoration (12). Laboratory studies suggested that a flowable GIC layer as a liner within proximal cavities before the insertion of a regular high-viscosity GIC (two-layer technique) improved the adaptation of the material to teeth structures, reduced microleakage (13) and allowed a better adhesion in sound dentin than in carious dentin (14).

However, a flowable GIC contains less reinforcing glass filler particles, thereby reducing the fracture resistance. We, therefore, assessed the flexural strength, the ability to withstand an applied stress, of a two-layered GIC, using a flowable GIC as a liner (two-layer technique). Additionally, Finite Element Analysis (FEA) on standardized bar-shaped specimens model and on a representative tooth model were performed to rationalize the obtained results.

Material and Methods

The flexure strength and Young’s modulus were determined for conventional GIC, flowable GIC, and layered specimens where the flowable GIC was under tension (flowable GIC down) and compression (flowable GIC up). Bar-shaped specimens (25 x 2 x 2 mm; n = 20 per group) were made according to the ISO Standard 9917-2. The flexural strength and the Young’s modulus were determined using a three-point-bending test. Hand mixed Fuji IX GP (GC Europe, Leuven, BE; batch nr 1105131) was used as material for all specimens.

Group 1 (conventional GIC only - C): specimens were prepared with an uniform layer of the GIC mixed according to the manufacturer’s instructions (conventional GIC, powder/liquid ratio 1:1).

Group 2 (two-layer flowable GIC down - FD): specimens were prepared using a two-layer technique. In the first layer one powder portion was mixed with two liquid drops (powder/liquid ratio 1:2). A flowable consistency mixture was achieved and the first layer inserted in the mold. Immediately thereafter, a second layer was mixed according to the manufacturer’s instructions (powder/liquid ratio 1:1) and applied before the setting of the first layer.

Group 3 (two-layer flowable GIC up - FU): specimens were prepared as in group 2, but were tested up-side-down, to allow tensile stress to occur in the conventional layer.
Group 4 (flowable GIC only - F): specimens were prepared with a uniform flowable GIC layer mixing one powder portion with two liquid drops (powder liquid ratio 1:2).

Acetate strips covered with microscope slides were placed on the top and the bottom of the filled mold and the mold assembly was clamped and left to set for 15 min. All groups were stored at 37°C in liquid paraffin. After 24 hour the height and width of the specimens were measured using a digital caliper. The specimens were subjected to a three-point-bending test on a universal testing machine (Hounsfield Ltd, Redhill, Surrey, UK) at a crosshead speed of 1.0 mm/min. The flexural strength (FS) was calculated with the following equation:

\[ FS = \frac{3Fl}{2wh^2} \]

where \( F \) is the load at failure, \( l \) the distance between the supports \( (l = 20.0 \text{ mm}) \), \( w \) the specimen width, and \( h \) the specimen height. The apparent flexure strength was calculated for the two-layer specimens.

The Young’s modulus \( (E_M) \) was calculated using the following equation:

\[ E_M = \frac{\Delta Fl^3}{\Delta z 4wh^3} \]

where \( \Delta F \) is the increase of applied force, \( l \) the distance between the supports \( (l = 20.0 \text{ mm}) \), \( \Delta z \) the increase in deflection at the increase of force, \( w \) the specimen width, and \( h \) the specimen height. The apparent Young’s modulus was calculated for the two-layer specimens.

Finite Element Analysis (FEA)

The Finite Element modeling was carried out using FEMAP software (FEMAP 10.1.1; Siemens PLM software, Plano, Texas, USA) and the analysis was done with NX Nastran software (NX Nastran; Siemens PLM Software, Plano, Texas, USA). Three dimensional FEA models of the three-point-bending test set-up and of a proximal cavity in a permanent molar were created. For the Young’s modulus the following data were used: conventional GIC 12.6 GPa (Table 1), flowable GIC 7.2 GPa (Table 1), dentine 18.6 GPa, and a Poisson ratio of 0.3 was used for all materials. The tested models of the two-layer specimens were analyzed with the two layers attached and detached from each other (groups 2a and 3a). For the models with the two layers detached, the interface between the two layers was designed as a contact surface. The bar-shaped models \((25 \times 2 \times 2 \text{ mm})\) were composed of 46,353 parabolic tetrahedron solid elements. The models were loaded with the experimental determined values of the load at failure (Table 1). The nodes at the bottom of the model at the points of support were not allowed to move vertically. The nodes in the centre of the models were only allowed to move in the vertical plane.

In a model of tooth 46, a occluso-mesial cavity of 2.0 mm high and 2.0 mm deep with a width of 2.5 mm was created. Two types of fillings were made: one of conventional GIC only and another of conventional GIC with a liner of 1 mm of a flowable GIC. The models were composed of 52,365 parabolic tetrahedron solid elements. The cavity was loaded with a load perpendicular on the surface, where the vertical component was made 50 N. A load perpendicular to the cavity surface is most likely the load direction in clinical situations. The nodes at the bottom of the tooth were fixed.
**Statistical analysis**

One-way ANOVA and Tukey post-hoc were used to test differences for the flexural strength and the Young’s modulus. The data were analysed with SPSS 12.0.1 software (SPSS Inc., Chicago, IL USA) using a 95% confidence interval.

**Results**

The flexural strength and the Young’s modulus obtained by the three-point-bending test are summarized in Table 1. The flexural strength of the conventional GIC and the flowable GIC were not significantly different, but the Young’s modulus of the flowable GIC was significantly lower. The apparent flexural strength of both two-layered groups were significant weaker than that of the conventional GIC, and the apparent Young’s modulus of the two-layered groups was also lower than that of the conventional GIC and the flowable GIC groups alone.

<table>
<thead>
<tr>
<th>Group</th>
<th>Load at failure (N)</th>
<th>FS (MPa)</th>
<th>E (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (C)</td>
<td>6.7 (2.6)</td>
<td>24.5 (10.7)</td>
<td>12.6 (5.1)</td>
</tr>
<tr>
<td>2 (FD)</td>
<td>2.8 (0.6)</td>
<td>9.9 (2.3)</td>
<td>4.2 (2.2)</td>
</tr>
<tr>
<td>3 (FU)</td>
<td>4.4 (2.1)</td>
<td>15.1 (6.9)</td>
<td>5.5 (3.5)</td>
</tr>
<tr>
<td>4 (F)</td>
<td>5.1 (1.9)</td>
<td>18.7 (6.8)</td>
<td>7.2 (4.6)</td>
</tr>
</tbody>
</table>

Note: Different superscripts represent significant differences at the 95% level when the one-way ANOVA and Tukey’s test were employed.

Figure 1a shows the stresses in the length direction of the bars in the two-layer FD specimen with the layers attached to each other compared with the stresses in the flowable GIC only specimen. Figure 1b shows the stresses in the two-layer FD specimen with the layers detached from each other compared with the stresses in the conventional GIC only specimen. The highest tensile stresses in the flowable GIC in both specimens in Figure 1a are different, while the highest tensile stresses in the conventional GIC in both specimens in Figure 1b are comparable. Figure 2 shows the stresses in the length direction of the bars on the interface for the two layers attached, with the flowable layer down and with the flowable layer up. The stresses in the interface are tensile stresses in the FD specimen and compressive stresses in the FU specimen. Table 2 shows the highest tensile stress (MPa) in the length direction of the bars calculated with FEA.

Figure 3 shows the maximum solid principle stresses in a model of tooth 46 with an occluso-mesial cavity. The cavity is filled either with a conventional GIC only or with the two-layer GIC. The maximum solid principle stress in the conventional GIC is 16.5 MPa for the cavity of conventional GIC only and 11.0 MPa for the cavity with the two-layers of GIC. For this load direction, the stresses between the cavity of the conventional and the flowable GIC are compressive stresses. When submitted to the same load, the conventional and the two-layer GIC differ in amount of absorbed stress, with lower stress values for the two-layer GIC.
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Figure 1: (a) The stresses in the length direction of the bar for group 2 with the two layers attached compared with the tensile stresses in the flowable GIC only, and (b) for group 2a with the two layers detached compared with the tensile stresses in the conventional GIC only.

Figure 2: The stresses in the length direction of the bar for the two-layers (attached) flowable GIC down and for the two-layers (attached) flowable GIC up.
Table 2: The highest tensile stress (MPa) in the length direction of the bars calculated with FEA.

<table>
<thead>
<tr>
<th>Group</th>
<th>in the conventional GIC</th>
<th>in the flowable GIC</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (C)</td>
<td>23.7</td>
<td></td>
</tr>
<tr>
<td>2 (FD)</td>
<td>1.2</td>
<td>7.8</td>
</tr>
<tr>
<td>3 (FU)</td>
<td>17.5</td>
<td>0</td>
</tr>
<tr>
<td>4 (F)</td>
<td></td>
<td>17.3</td>
</tr>
<tr>
<td>2a (FD) layers detached</td>
<td>20.9</td>
<td>11.3</td>
</tr>
<tr>
<td>3a (FU) layers detached</td>
<td>34.5</td>
<td>18.0</td>
</tr>
</tbody>
</table>

Figure 3: The solid maximum principle stress in tooth model 46 with a occluso-mesial cavity filled with conventional GIC only and with the two-layer GIC.

Discussion

In this study we assessed the apparent flexural strength of a two-layer GIC specimen using a three-point-bending test set-up, and rationalized the results with a Finite Element Analysis (FEA). The FEA simulation provided information with regard to the stress distribution of each component of the restoration and allowed a better understanding of the values found in the three-point-bending test. The flexure stress obtained from the test (Table 1) showed significantly lower values for the two-layer groups. These values were
considered only as the apparent flexure stress because the formula to calculate the flexure stress based on a three-point-bending test is intended for a single-layer specimen.

The reduction of the powder content by 50% in the flowable GIC group (F) did not result in a flexural strength that was statistically significantly different from that of a conventional GIC (C). These findings are consistent with Fonseca et al. (15), who reported no difference in diametral strength between the GIC specimens with 100% or 50% powder content. However, Darvell showed that the validity of the diametral strength methodology for brittle materials like GIC is low (16). Fleming et al. (17), though, observed a significantly lower compressive strength when the powder content was reduced to 50% of the manufacturer’s recommended consistency. The difference between the results obtained in these studies may be attributed to the designs of the strength tests.

Different methods are available for testing the strength of a material. The ISO standard for water-based cement, such as the GIC, describes only the compressive strength test (ISO standard 9917-1). As this test has been shown to be an invalid measure of strength, it may not be the ideal test to predict a failure mechanism as it is more representative of a combination of tension and shear (16, 18). Nonetheless, the ISO standard was formulated at a time when GIC were not considered for use in Class II cavities. Recently, Dowling et al. (18) investigated an alternative to the compressive fracture strength test for GIC and concluded that the International Organization for Standardisation should replace the compressive strength test by flexural strength tests. The authors recommended both three- and four-point-bending tests as valid strength measures for GIC (18).

The obtained flexural strength for the conventional group (C) were consistent with those previously published (19-21). Although the two-layer flowable GIC down (FD) specimens contained more glass-filler particles than the flowable GIC only (F) specimens, FD showed significantly lower flexural strength than the flowable GIC only (F). This result was the trigger for investigating the stress distribution in the different specimens with FEA.

Wang and Darvell (22) stated that the difference in mechanical properties of a two-layered material may also affect its failure behavior as the elastic modulus mismatch between the layers can produce new stresses at the interface between the two layers. We hypothesized that when submitted to a load until fracture, the stresses in the interface might become higher than the bond strength between the two GIC layers. To investigate this hypothesis, we performed the FEA on the two layers attached to and detached from each other. The FD values from the three-point-bending experiment are correspondent to the FEA values of the FD with detached layers. During loading, the tensile stresses in the interface may have indeed became higher than the bond strength between the two layers, detaching them. The FEA demonstrated that the highest flexural stresses of FD with the two layers detached are concentrated in the lower side of the conventional layer (Figure 1b). On the other hand, the specimens with two layers and the flowable GIC up (FU) seems to remain with both layers attached to each other when submitted to flexural stress. This can be explained by the fact that the stresses in the interface of the FU specimens are mainly compressive, while the stresses on the interface of the FD are mainly tensile stresses (Figure 2).

FEA demonstrates that the low flexural strength values from the FD specimens are due to a lack of relevant adhesion between the two layers. One should realise that this results cannot be extrapolated to resin based materials. In resin-based materials the
inhibition layer formed by the contact with oxygen allows a good chemical adhesion between the layers of the material (23), even if they have different consistencies (24).

The Young’s modulus or modulus of elasticity of a material is a measure of the resistance to deformation under load. Bulk, chip, and marginal fractures have been observed to be more frequent in restorations using materials with a low Young’s modulus (25). The use of a high Young’s modulus material in the second layer of the two-layer GIC is intended to avoid these type of failures in occluso-proximal-ART restorations and, at the same time, the low Young’s modulus flowable layer provides a better material adaptation in the margins of the cavity (13).

The tooth model shows that the stresses in the restoration at a minimum load (50 N) may already put the restoration at risk. In particular with the conventional GIC, in which a tensile stress of 17.5 MPa is observed, while the strength of the material is only 24.5 (10.7) MPa. This may explain the great number of failure reported in approximal GIC restorations (11, 26, 27). The flowable layer, although, might be beneficial, as it dissipates the stress from the occlusal load and could, consequently, improve the lifetime of these restorations. The survival of the restoration might be also dependent on the design of the preparation and the presence of lateral walls in the cavity. If the cavity is too large or lateral walls to support the material are absent, tension in the interface might occur, resulting in detachment of the layers similar to the three-point-bending test.

It should be considered that the flowable GIC, by having less glass-filler particles, is more sensitive to solubility. By being located in the cervical region, this layer might be more often in contact with dental plaque and with a acidic environment, which can lead to the dissolution of the material and the absence of support, exposing the restoration to a risky situation that will probably lead to failure.

In conclusion, the two-layer glass ionomer showed inferior performance on the three-point-bending test, which might be explained by the fact that the layers may be detached from each other under load. The FEA tooth model showed that the two-layer GIC might be beneficial when used in an occluso-proximal cavity, as it provides a lower stress concentration in the occlusal surface of the material.
References


