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Dynamic and Static Flexural Appraisal of Resin-based Composites: Comparison of the ISO and Mini-flexural Tests

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Clinical Relevance

The mini-flexural test holds promise as a replacement for the ISO flexural test for the dynamic and static appraisal of dental resin-based composites.

SUMMARY

The objective of this study was to determine the influence of specimen dimension and conditioning medium on the dynamic and static flexural properties of resin-based composites (RBCs). One conventional (Filtek Z350) and two bulk-fill RBCs (Filtek Bulk-fill and Beautifil-Bulk Restorative) were evaluated. Bar-shaped specimens with dimensions 25 × 2 × 2 mm (ISO flexural [IFT]) or 12 × 2 × 2 mm (mini-flexural [MFT]) were fabricated using customized stainless-steel molds, finished, measured, randomly divided into two groups, and conditioned in air or artificial saliva (SAGF) for seven days at 37°C. The specimens (n=10) were then subjected to dynamic and static three-point flexural testing. Data for storage modulus, loss modulus, loss tangent, flexural strength, and modulus were computed and subjected to *t*-test, analysis of variance/Tukey test, and Pearson correlation at a significance level of $\alpha = 0.05$. For both IFT and MFT, significant differences in dynamic and static flexural properties were more prevalent between materials after storage in saliva. For both conditioning mediums, the strongest correlation between IFT and MFT was observed for flexural strength. While significant positive correlations were observed for all flexural properties with saliva, no significant correlations were detected for loss tangent and flexural modulus with air. For both IFT and MFT, storage in saliva appeared to be more discriminative than storage in air. As moderate to strong positive relationships exist between IFT and MFT for dynamic and static flexural

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properties, the mini-flexural test holds promise as a replacement for the ISO 4049 in view of its clinical relevance and greater efficiency.

INTRODUCTION

The use of light-polymerized, resin-based composites (RBCs) in clinical dentistry has increased substantially over the past decade as a result of heightened patient esthetic demands, advancement in formulations, and simplification of clinical techniques. New RBCs are constantly being introduced to the dental market as manufacturers continue to improve upon their products.[1] RBCs are subjected to considerable flexural forces and need to withstand repetitive flexing and bending when used in anterior and posterior teeth.[2] The flexural properties of RBCs are usually assessed using destructive static tests that apply an escalating load until material failure.[3] As RBCs are visco-elastic in nature, static tests, which emphasize the elastic component, offer limited information on material structure.[4] Conversely, dynamic tests such as dynamic mechanical analysis (DMA), can define both elastic and viscous components of RBCs. These nondestructive tests have greater sensitivity to both macroscopic and molecular relaxation processes than do static techniques.[4,5] In addition, dynamic tests better simulate the cyclic masticatory and parafunctional loading to which RBCs are clinically subjected. The visco-elastic properties of RBCs have been studied[4,6,7] using DMA and were reported to be valuable in terms of predicting clinical performance.

DMA utilizes a range of frequencies and preset displacements that are within the elastic limits of the RBCs. Small oscillating "sinusoidal" stresses are applied isothermally or over a temperature range, and the resultant strains are measured as a function of time. Stress and strain of visco-elastic materials can be represented as follows:[8]

Stress:

$$\sigma = \sigma_0 \times \sin(\omega t + \delta);$$

Strain:

$$\varepsilon = \varepsilon \times \sin(\omega t)$$

where $\omega = 2\pi f$, where f is the frequency of strain oscillation; t is the time; and δ is the phase lag between stress and strain.

Parameters that can be derived from DMA include storage (elastic) modulus (E'), loss (viscous) modulus (E'',) and loss tangent (tan δ). Storage modulus embodies the stiffness of the material and indicates its ability to store elastic energy during a loading cycle. Loss modulus relates to the amount of energy loss by the material through viscous flow via conversion into heat.[9] Loss tangent is a dimensionless property that quantifies the material's ability to damp mechanical energy and is defined by the ratio of E'' to E'. When a sinusoidal stress is applied to a completely elastic or viscous material, deformation occurs precisely in phase or lags 90° behind the stress applied, respectively. For visco-elastic materials, the ensuing strain will lag behind the stress by an angle s, where s is $<90°$.

Bar-shaped specimens used in dynamic and static flexural tests[4,10-12] are often based on dimensions (25×2×2 mm) specified by the ISO 4049 standard.[13] Specimens measuring up to 50 mm long have also been employed in dynamic testing.[14] When flexural load is applied to the bar specimens, compressive, tensile, and shear stresses are evoked. Compressive stress occurs in the upper portion of the cross section, while tensile stress occurs in the lower. To simplify stress states, support spans (L) are planned long relative to specimen height (H) as shear stress and bending moments are independent and directly proportional to specimen length, correspondingly. In addition to changing support span at constant thickness, L/H ratios can also be modified by altering specimen height.[15] The large ISO bar-shaped specimens are, however, technically arduous to prepare without flaws. Several overlapping light irradiations are necessary as the exit windows of commercial curing lights are typically less than 25 mm. This leads to specimens that are not homogeneously cured with enduring stresses that may compromise flexural data reliability.[16,17] In addition to material and time wastage, these large specimens are also clinically irrelevant, as the mesio-distal diameter of molars is only about 11 mm and the cervico-incisal length of central incisors is around 13 mm.[18] Flexural tests involving smaller and more clinically relevant specimens are hence desirable.

Several studies have investigated the influence of specimen dimensions on the flexural strength of RBCs. While some reported similar flexural strength values, others observed higher strengths with shorter specimens.[16,17,19,20] Flexural strength correlation between the ISO and shorter mini-flexural specimens (12×2×2 mm) was found to be significant, positive, and very strong (r=0.95). Correlation for flexural modulus was also significant and positive, but strength of association was just moderate (r=0.53).[16] All preceding studies only focused on

Table 1: *Technical Profiles and Manufacturers of the Materials Evaluated*

Material (Abbreviation)	Manufacturer	Type	Resin	Filler	Filler Content, % by Weight/% by Volume	Lot No.
Filtek Z350 (FZ) A2 shade	3M ESPE, St Paul, MN, USA	Nanohybrid restorative	Bis-GMA Bis-EMA UDMA TEGDMA	Zirconia/silica cluster and silica nanoparticle	78.5/63.3	N771467
Filtek Bulk-Fill (FB) A2 shade	3M ESPE, St Paul, MN, USA	Bulk-fill restorative	AUDMA AFM DDDMA UDMA	Zirconia/silica cluster, ytterbium trifluoride	76.5/58.4	N789842
Beautifil-Bulk Restorative (BB) A2 shade	SHOFU Inc, Kyoto, Japan	Bulk-fill giomer restorative	Bis-GMA UDMA Bis-MPEPP TEGDMA	S-PRG based on F-Br-Al-Si glass	87/74.5	051623

Abbreviations: AFM, addition-fragmentation monomers; AUDMA, aromatic urethane dimethacrylate; Bis-EMA, ethoxylated bisphenol-A glycidyl methacrylate; Bis-GMA, bisphenol-A glycidyl methacrylate; Bis-MPEPP, bisphenol-A polyethoxy-dimethacrylate; DDDMA, 1,12-dodecanediol dimethacrylate; F-Br-Al-Si, fluoroboroaluminosilicate; S-PRG, surface-modified pre-reacted glass; TEGDMA, triethylene glycol dimethacrylate; UDMA, urethane dimethacrylate.

static flexural testing, and none investigated the influence of specimen dimension on dynamic appraisal of RBCs. The objective of this study was to determine the influence of specimen dimension (specifically the ISO and mini-flexural test) on the dynamic and static flexural properties of RBCs. As the static flexural properties of RBCs had been shown to be dependent on storage medium,[20,21] the effect of conditioning in air and artificial saliva as confounding variables was also explored. Furthermore, correlations between the ISO and mini-flexural test results were performed for the various flexural properties. The null hypotheses were as follows: 1) there are no significant differences in dynamic and static flexural test values between the ISO and mini-flexural test; 2) there are no significant differences between conditioning in air and artificial saliva for the various flexural properties; and 3) there are no correlations between the ISO and mini-flexural tests for dynamic and static testing.

METHODS AND MATERIALS

Specimen Preparation and Conditioning

The materials evaluated and their technical profiles are shown in Table 1. They included a conventional composite (Filtek Z350 [FZ]) and two bulk-fill materials (Filtek Bulk-fill [FB] and Beautifil-Bulk Restorative [BB]). ISO flexural test (IFT) specimens of the various RBCs were fabricated according to ISO 4049 specifications (25×2×2 mm) using customized stainless-steel molds. The RBCs were placed in one increment and excess material was removed by compressing the molds between two polyester strips with glass slides. The top surface of the specimens was light polymerized with four overlapping 10 second irradiations using an LED curing light (Demi Plus, Kerr, CA, USA) with an output irradiance of 1330 mW/cm^2, a wavelength of 450-470 nm, and a light exit window of 8 mm. The glass slides and polyester strips were removed and the specimens were light-cured with another four overlapping 10 second irradiations. The specimens were detached from their molds, and any minor material excess was gently removed with fine polishing discs (Sof-Lex, 3M ESPE, St Paul, MN, USA). The final dimension of the specimens and their parallelism were verified with a digital caliper (Mitutoyo Corporation, Kawaski, Japan). Procedures for fabricating the mini-flexural test (MFT) specimens (12×2×2 mm) were similar, with the exception that light polymerization was accomplished with two overlapping irradiations arising from their smaller specimen size, as compared to MFT specimens. Twenty IFT and MFT specimens were produced, randomly divided into two groups of 10 (n=10), and conditioned in air or artificial saliva (SAGF)[22] for seven days at 37°C in sealed containers. The pH of the artificial saliva was adjusted to 6.8 to resemble the pH of natural saliva and verified with a digital pH meter (Eutech ph2700, Singapore).

Dynamic Flexural Testing

After conditioning, the test specimens were subjected to dynamic flexural testing (DMA RSAG2, TA Instruments, New Castle, DE, USA) in their air or artificial saliva at 37°C. Specimens were loaded using a three-point bending configuration with span lengths of 20 mm for IFT and 10 mm for MFT inside an immersion container enclosed in an environmental chamber.

Loading frequency was set to 0.1 to 10 Hz to represent the range from "close to static" to the upper limit of normal chewing frequency.[7,23] Storage modulus, loss modulus, and loss tangent data were recorded throughout the experiment and were computed as follows:[24]

Storage modulus:

$$E' = (\sigma^\circ/\varepsilon^\circ)\text{cosd} = (f_o/b\text{k})\text{cosd};$$

Loss modulus:

$$E'' = (\sigma^\circ/\varepsilon^\circ)\text{sind} = (f_o/b\text{k})\text{sind};$$

Loss tangent:

$$\text{Tan}\delta = E''/E',$$

where σ° is the maximum stress at the peak of the sine wave, ε° is the strain at the maximum stress, f is the force applied at the peak of the sine wave, b is the sample geometry term, and k is the sample displacement at the peak.

The sample geometry b for a three-point bending bar was calculated as follows:

$$4BH^3/L^3,$$

where B is the width of the specimen (in millimeters), H is the height of the specimen (in millimeters), and L is the distance between the supports (in millimeters).

Static Flexural Testing

After dynamic testing, the MFT and IFT specimens were loaded until fracture in a universal testing machine (Shimadzu Corporation, Kyoto, Japan) with a load cell of 5 KN and a crosshead speed of 0.5 mm/min until fracture occurred. Flexural strength, σ, in megapascals (MPa), was calculated using the following equation:

$$\sigma = \frac{3PL}{2BH^2},$$

where P is the maximum load exerted on the specimen (in Newtons), L is the distance between the supports (in millimeters: 20 mm for IFT and 10 mm for MFT), B is the width of the specimen (in millimeters), and H is the height of the specimen (in millimeters).

Flexural modulus, E', in megapascals (MPa), was calculated using the following equation:

$$E' = \left(\frac{F}{D}\right)\left(\frac{L^3}{4BH^3}\right),$$

where F/D is the slope (in Newtons per millimeter), measured in the straight-line portion of the load-deflection graph. L, B, and H were defined in the flexural strength equation. Flexural modulus was subsequently converted to Gigapascal (GPa).

Statistical Analysis

The SPSS statistical program (Version 12.0.1, SPSS Inc, Chicago, IL, USA) was used to analyze the flexural data obtained. Normality testing was done using the Shapiro-Wilk test. As data were found to be normally distributed, parametric analysis was permissible. The interaction effects between the independent variables (specimen dimension, conditioning medium, and material) and each of the dependent variables (storage modulus, loss modulus, loss tangent, flexural strength, and flexural modulus) were evaluated using factorial analysis of variance (ANOVA). One-way ANOVA/Tukey post hoc test and *t*-tests were used to compare material, specimen dimension, and storage medium differences. Correlations between IFT and MFT for dynamic and static testing results were done with Pearson correlation. All statistical analyses were carried out at significance level of $\alpha = 0.05$.

RESULTS

The mean storage modulus, loss modulus, loss tangent, flexural strength, and modulus values for the various RBCs, flexural tests, and conditioning mediums are reflected in Tables 2 and 3. Although interaction effects among material, specimen dimension, and conditioning medium were not significant, the influence on storage modulus and loss tangent of RBCs was medium- and specimen dimension–dependent.

Table 4 shows the intermaterial comparison of dynamic and static flexural properties when materials were conditioned in air and artificial saliva for IFT and MFT. When conditioned in air, no significant differences in flexural properties were observed between materials, with the exception of loss modulus and loss tangent for IFT and flexural strength for MFT. BB had significantly lower loss modulus, loss tangent, and flexural strength values than the other RBCs. When conditioned in artificial saliva, no significant differences in flexural proper-

Table 2: *Mean Dynamic and Static Flexural Values (Standard Deviations in Parentheses) for the Various Materials, IFT and MFT, When Conditioned in Air*

Materials	Air									
	ISO 4049 Flexural Test (IFT)					Mini-Flexural Test (MFT)				
	Storage Modulus, GPa	Loss Modulus, GPa	Loss Tangent, 10^{-3}	Flexural Strength, MPa	Flexural Modulus, GPa	Storage Modulus, GPa	Loss Modulus, GPa	Loss Tangent, 10^{-3}	Flexural Strength, MPa	Flexural Modulus, GPa
Filtek Z350 (FZ)	6.79	0.46	68	99.49	10.95	6.29	0.42	68	135.20	8.23
	(0.41)	(0.02)	(3)	(13.83)	(0.76)	(0.29)	(0.04)	(5)	(17.08)	(0.89)
Filtek Bulk-Fill (FB)	6.35	0.47	73	110.13	12	6.20	0.43	69	144	8.04
	(0.33)	(0.05)	(5)	(15.01)	(1)	(0.72)	(0.06)	(4)	(19.32)	(1.11)
Beautifil-Bulk Restorative (BB)	6.46	0.40	62	98.90	11.58	5.79	0.38	66	117.53	8.19
	(0.58)	(0.05)	(4)	(11.14)	(0.55)	(0.36)	(0.05)	(7)	(10.22)	(1.12)

ties between materials were observed only for storage modulus with IFT and loss modulus with MFT.

Significant differences in dynamic and static flexural values between the two flexural tests and conditioning mediums are indicated in Table 5 and Figures 1 and 2. Differences between IFT and MFT as well as air and artificial saliva were material-dependent. For all RBCs, MFT resulted in higher flexural strength than did IFT, regardless of the conditioning medium. Flexural modulus with IFT was greater than with MFT. For both IFT and MFT, exposure to artificial saliva resulted in higher loss tangent values, while conditioning in air led to greater flexural strength. In addition, conditioning in air gave rise to greater flexural modulus with IFT.

The results of correlation analysis are displayed in Tables 6 and 7. For both conditioning mediums, the strongest correlation between IFT and MFT was observed for flexural strength (r=0.85 and 0.97, respectively). While significant positive correlations were observed for all flexural properties with saliva, no significant correlations were detected for loss tangent and flexural modulus with air.

DISCUSSION

This study compared the static and dynamic flexural properties of RBCs between IFT and MFT with conditioning medium as a confounding variable. Based on the findings of this study, all three null hypotheses were rejected. Storage modulus, loss tangent, and flexural strength of the RBCs were found to be reliant on conditioning medium. For both IFT and MFT, storage modulus, flexural strength, and modulus when stored in air were significantly greater than when stored in artificial saliva, in which case significant differences in flexural properties exist. In contrast, loss modulus and loss tangent values were higher with artificial saliva. Conditioning in aqueous solutions has been reported[21] to decrease the flexural properties of RBCs, and this finding was supported by this study as well. The RBCs evaluated contain silica or silicate glass fillers that have irregularly distributed Si-O-Si bonds. When exposed to artificial saliva, the resin matrices

Table 3: *Mean Dynamic and Static Flexural Values (Standard Deviations in Parentheses) for the Various Materials, IFT and MFT, When Conditioned in Artificial Saliva*

Materials	Artificial Saliva									
	ISO 4049 Flexural Test (IFT)					Mini-Flexural Test (MFT)				
	Storage Modulus, GPa	Loss Modulus, GPa	Loss Tangent, 10^{-3}	Flexural Strength, MPa	Flexural Modulus, GPa	Storage Modulus, GPa	Loss Modulus, GPa	Loss Tangent, 10^{-3}	Flexural Strength, MPa	Flexural Modulus, GPa
Filtek Z350 (FZ)	5.97	0.50	83	64.82	9.44	5.48	0.47	88	91.71	6.58
	(0.31)	(0.07)	(9)	(5.39)	(0.67)	(0.56)	(0.06)	(9)	(10.10)	(0.76)
Filtek Bulk-Fill (FB)	6.19	0.54	88	90.34	10.36	6.09	0.46	84	122.39	7.64
	(0.20)	(0.03)	(5)	(9.54)	(0.46)	(0.49)	(0.06)	(10)	(16.63)	(1.07)
Beautifil-Bulk Restorative (BB)	6.17	0.42	68	64.10	10.35	5.51	0.43	73	86.6	7.34
	(0.52)	(0.06)	(7)	(5.33)	(0.64)	(0.53)	(0.06)	(5)	(3.57)	(0.92)

Table 4: *Results of Intermaterial Comparison of Dynamic and Static Flexural Properties When Conditioned in Air and Artificial Saliva for IFT and MFT*[a]

Test	Properties	Differences	
		Air	Artificial Saliva
IFT	Storage modulus	NS	NS
	Loss modulus	FB, FZ > BB	FB, FZ > BB
	Loss tangent	FB > FZ > BB	FB, FZ > BB
	Flexural strength	NS	FB > FZ, BB
	Flexural modulus	NS	FB, BB > FZ
MFT	Storage modulus	NS	FB > FZ
	Loss modulus	NS	NS
	Loss tangent	NS	FZ, FB > BB
	Flexural strength	FB > BB	FB > FZ, BB
	Flexural modulus	NS	FB > FZ

Abbreviations: BB, Beautifil-Bulk; FB, Filtek Bulk-Fill; FZ, Filtek Z350; IFT, ISO 4049 flexural test; MFT, mini-flexural test.
[a] *> Indicates statistical significance, while NS indicates no statistical significance. Results of one-way analysis of variance and post hoc Tukey test (*$p<0.05$*).*

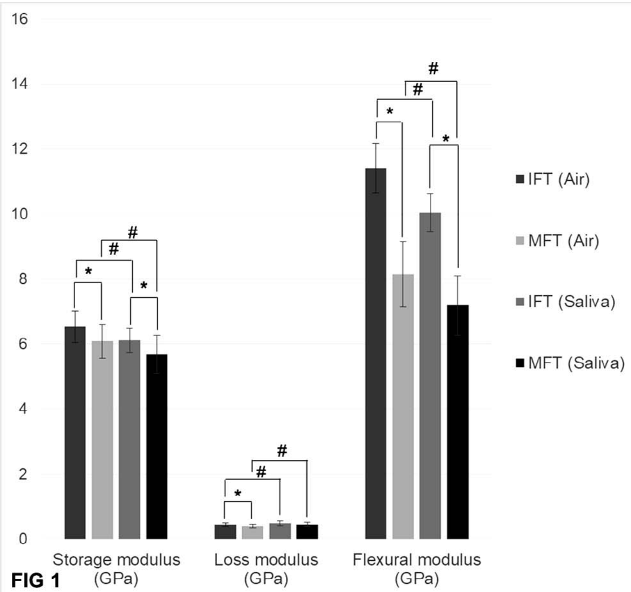
absorb water, swell, and radial stresses develop at the filler interfaces, thus straining the Si-O-Si bonds present. The high energy levels arising from the strained Si-O-Si bonds render the fillers more susceptible to stress corrosion attack ($Si_2O+H_2O=2\ SiOH$).[25] Complete or partial filler debonding occurs and results in the decreased storage modulus, flexural strength, and modulus observed. The plasticizing effect of water on the resin matrices also explains the significantly greater loss tangent values (which are inversely proportional to storage modulus) when the RBCs were stored in artificial saliva.

For both IFT and MFT, storage in artificial saliva appeared to be more discriminative than storage in air. When conditioned in air, few significant differences in dynamic and flexural properties were observed between materials for both tests. For IFT, FB and FZ had significantly greater loss modulus and tangent than did BB. For MFT, the flexural strength of FB was significantly greater than that of BB. When conditioned in artificial saliva, significant differences between materials were observed for almost all flexural properties, with the exception of storage modulus for IFT and loss modulus for MFT. BB generally had lower loss tangent and flexural strength than did FZ and FB. BB, a bulk-fill giomer material, is based on pre-reacted glass ionomer (PRG) technology in which acid-reactive fluorosilicate glass is reacted with polyacids in the presence of water, freeze-dried, milled, silanized, ground, and utilized as fillers. Despite its higher filler content (74.5% as compared to 58.4% and 63.3% volume for FB and FZ, respectively), the lower flexural strength of BB may be attributed to the use of irregularly shaped PRG fillers that may serve as foci of stress concentrations.[26] Moreover, the degree of conversion of BB has been found[27] to be relatively lower than that of other bulk-fill RBCs.

Table 5: *Comparison of Static and Dynamic Flexural Properties Between IFT and MFT as Well as Air and Artificial Saliva for the Various Materials*[a]

Material	Properties	IFT vs MFT		Air vs Artificial Saliva	
		Air	Artificial Saliva	IFT	MFT
Filtek Z350 (FZ) [control]	Storage modulus	IFT > MFT	IFT > MFT	Air > saliva	Air > saliva
	Loss modulus	IFT > MFT	NS	NS	NS
	Loss tangent	NS	NS	Saliva > air	Saliva > air
	Flexural strength	MFT > IFT	MFT > IFT	Air > saliva	Air > saliva
	Flexural modulus	IFT > MFT	IFT > MFT	Air > saliva	Air > saliva
Filtek Bulk-Fill (FB)	Storage modulus	NS	NS	NS	NS
	Loss modulus	NS	IFT > MFT	Saliva > air	NS
	Loss tangent	NS	NS	Saliva > air	Saliva > air
	Flexural strength	MFT > IFT	MFT > IFT	Air > saliva	Air > saliva
	Flexural modulus	IFT > MFT	IFT > MFT	Air > saliva	NS
Beautifil-Bulk Restorative (BB)	Storage modulus	IFT > MFT	IFT > MFT	NS	NS
	Loss modulus	NS	NS	NS	NS
	Loss tangent	NS	MFT > IFT	Saliva > air	Saliva > air
	Flexural strength	MFT > IFT	MFT > IFT	Air > saliva	Air > saliva
	Flexural modulus	IFT > MFT	IFT > MFT	Air > saliva	NS

[a] *> Indicates statistical significance, while NS indicates no statistical significance. Results of* t*-test (*$p<0.05$*).*



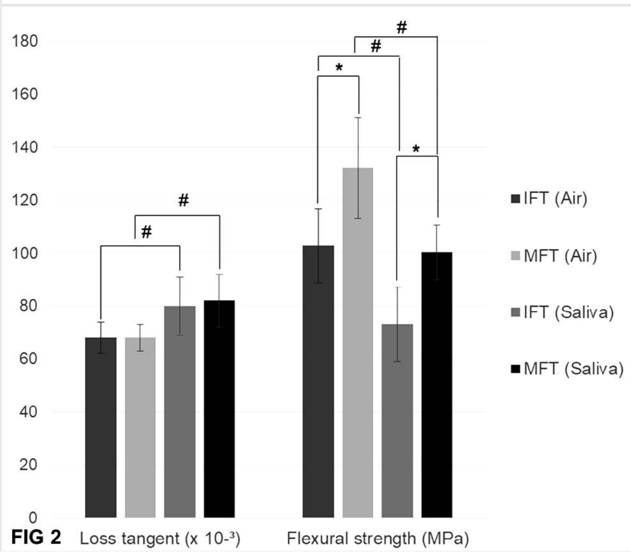


Figure 1. *Comparison of mean storage, loss, and flexural modulus between IFT and MFT as well as air and artificial saliva (pooled data for all materials). Results of* t*-test (*$p<0.05$*).*

Figure 2. *Comparison of mean loss tangent and flexural strength between IFT and MFT as well as air and artificial saliva (pooled data for all materials). Results of* t*-test (*$p<0.05$*).*

Storage modulus and loss tangent of the RBCs were also predisposed to specimen dimension variations. For both conditioning mediums, storage, loss, and flexural modulus obtained with IFT were higher than for MFT. In contrast, loss tangent and flexural strength associated with MFT were greater than for IFT. The difference in storage, loss, and flexural modulus between IFT and MFT, though statistically significant, was only marginal when compared to flexural strength (Figures 1 and 2). Among the aforementioned dynamic and static flexural properties, flexural strength was the most widely reported by other authors. The higher flexural strength observed with MFT corroborated the findings of earlier studies[16,20] and had been attributed to shear deformation with reduction of support distance. Calabrese and others,[17] however, reported significantly higher flexural strength with IFT. The incongruity in findings is attributable to variances in the RBCs evaluated.[15] Moreover, Muench and others[19] found that flexural strength was not influenced by length when specimens were light-cured on both surfaces. For stress-bearing restorations, RBCs with high flexural strength and modulus of elasticity are desirable to resist occlusal loads and sustain the tooth-restoration interface.[16]

All RBCs fulfilled the ISO flexural strength (IFT) requirement of 80 MPa when conditioned in air, but only FB achieved this value when conditioned in artificial saliva. As flexural strength values observed with MFT were higher than those observed with IFT, new minimum flexural strength values must be established for MFT, and conditioning should be carried out in artificial saliva or distilled water.

The modulus of elasticity quantifies a material's resistance to elastic (nonpermanent) deformation when a force is applied. It is defined by the slope of the stress-strain curve in the elastic region. Values for modulus of elasticity (elastic modulus) obtained with both dynamic and static testing should theoretically be similar. The dynamic and static

Table 6: *Correlations Between Dynamic and Static Flexural Properties When Conditioned in Air*

Properties	MFT Storage Modulus	MFT Loss Modulus	MFT Loss Tangent	MFT Flexural Strength	MFT Flexural Modulus
IFT storage modulus	**0.72****	0.59**	NS	0.59**	NS
IFT loss modulus	0.77**	**0.67****	NS	0.76**	NS
IFT loss tangent	0.44*	0.44*	**NS**	0.52**	NS
IFT flexural strength	0.81**	0.68**	NS	**0.85****	NS
IFT flexural modulus	NS	NS	NS	NS	**NS**

Abbreviations: IFT, ISO 4049 flexural test; MFT, mini-flexural test; NS, not significant.
** Correlation is significant at the 0.05 level,* $p<0.05$*; ** Correlation is significant at the 0.01 level,* $p<0.01$*. Results of Pearson correlation. Bold numbers indicate correlation between IFT and MFT for the same flexural properties.*

Table 7: *Correlations Between Dynamic and Static Flexural Properties When Conditioned in Artificial Saliva*

Properties	MFT Storage Modulus	MFT Loss Modulus	MFT Loss Tangent	MFT Flexural Strength	MFT Flexural Modulus
IFT storage modulus	**0.82****	0.50**	NS	0.42*	0.53**
IFT loss modulus	0.62**	**0.38***	0.44*	0.68**	NS
IFT loss tangent	NS	NS	**0.46***	0.57**	NS
IFT flexural strength	0.80**	NS	NS	**0.97****	0.47**
IFT flexural modulus	NS	NS	NS	NS	**0.45***

Abbreviations: IFT, ISO 4049 flexural test; MFT, mini-flexural test; NS, not significant.
** Correlation is significant at the 0.05 level,* $p<0.05$*; ** Correlation is significant at the 0.01 level,* $p<0.01$*. Results of Pearson correlation. Bold numbers indicate correlation between IFT and MFT for the same flexural properties.*

modulus of elasticity for RBCs for both IFT and MFT had not been compared in prior studies. The MFT geometry still permitted adequate deflection of the RBCs within the small load capacity of the DMA instrument employed. For both flexural tests, modulus of elasticity obtained with dynamic testing (storage modulus) was lower than that obtained with static testing (flexural modulus), regardless of conditioning medium. Sabbagh and others,[28] however, reported higher elastic modulus with dynamic testing for IFT. In their study, dynamic modulus of elasticity was determined through signal analysis with the Grindosonic instrument (Lemmens Elektronics, Haasrode, Belgium) and not DMA. The findings of the current study also contradicted those on other industrial materials in which dynamic modulus of elasticity was about 20% to 40% higher than static modulus.[29] The ratio of dynamic to static modulus of elasticity was relatively constant and ranged between 53% and 63% for IFT and between 70% and 83% for MFT for both conditioning mediums. As the ratios for MFT were more favorable (closer to 100%), flexural test specimens based on MFT dimensions are advocated. If possible, the modulus of elasticity of the RBCs should be similar to or higher than that of dentin, which is approximately 19 GPa.[30] None of the RBCs evaluated achieved this value for both IFT and MFT.

Correlations between IFT and MFT varied somewhat between conditioning in air and artificial saliva. To better simulate the wet oral environment, conditioning and testing in artificial saliva or distilled water is recommended. When conditioned in artificial saliva, significant positive correlations were observed for all dynamic and static flexural properties between IFT and MFT. Strength of the relationships ranged from moderate for loss modulus, loss tangent, and flexural modulus to strong for storage modulus and flexural strength. As MFT allows for the prediction of mechanical performance of RBCs under more clinically realistic conditions and is more efficient than IFT, it is a promising replacement for the ISO 4049 for both dynamic and static flexural testing.

CONCLUSIONS

Within the limitations of this study, the following conclusions can be made:

1. Significant differences between IFT and MFT flexural test values were observed. With the exception of flexural strength, values for dynamic and static flexural properties were generally higher with IFT.
2. For both IFT and MFT, significant differences in dynamic and static flexural properties were observed between conditioning in air and conditioning in artificial saliva. As conditioning in artificial saliva was more discriminative and clinically relevant, it is the conditioning medium of choice.
3. Moderate to strong positive correlations were observed between IFT and MFT for all dynamic and static flexural properties when RBCs were conditioned in artificial saliva.
4. MFT holds promise as a replacement for IFT in view of its significant correlation to IFT, clinical relevance, and greater efficiency.

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Conflict of Interest

The authors have no proprietary, financial, or other personal interest of any nature or kind in any product, service, and/or company that is presented in this article.

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