

## Is the assumption of linear elasticity within prosthodontics valid for polymers? —An exemplary study of possible problems

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As shown in previous studies within other scientific fields, the material behavior of polymethyl methacrylate (PMMA) is viscoelastic-viscoplastic. However, in dental biomaterial science it is mostly considered as linear elastic or elastic-plastic. The aim of the present study was to evaluate, whether the assumption of elastic or elastic-plastic material behavior for PMMA is a practicable simplification or a potential source of error, especially considering clinical loading conditions. Telio-CAD was tested in three-point bending tests with different test velocities to examine the material behavior at different initial loading rates. Additionally, a dynamic-mechanical-thermal-analysis at different frequencies and temperatures was used. Here, a significant influence of loading rate and temperature as well as stress relaxation and creep were observed. To describe the rate-dependency of the elastic modulus, a new model was created, from which the elastic modulus can be calculated with a given strain rate. This model was validated using linear elastic finite element analysis.

**Keywords:** polymethyl methacrylate, Dynamic mechanical thermal analysis, Finite element analysis, Three-point bending, Digital image correlation

### INTRODUCTION

Temporary restorations consisting of polymethyl methacrylate (PMMA) fulfill a wide range of applications within prosthodontic dentistry (e.g., long- or short-term provisional treatments, restorations of the vertical dimension, trial wearing previous to the final restoration). Alongside the primary protection of the prepared tooth structure, saving the pulp from external noxae like hotness, coldness or acids, provisional treatments are often necessary to maintain oral functions like phonetics, mastication and esthetics<sup>1-4</sup>. Frequently occurring problems with temporary treatments are fractures; thus, they could become partially or complete lost<sup>5,6</sup>. Pain, change of tooth position, or caries could be possible consequences. Because of these possible consequences of fractures, a full investigation of the material behavior of temporary dental materials consisting of PMMA is required<sup>1-4</sup>. Most of the previous studies within dental biomaterial science and current standards within prosthodontics assume linear elastic or elastic-plastic material characteristics<sup>7-11</sup>, neglecting the influence of loading rate in clinical application in particular. However, it was shown in numerous studies within other fields of research (mechanical engineering, etc.), that the material behavior of PMMA is viscoelastic-viscoplastic, which means that dependencies on loading rate and temperatures have major influences on the overall material behavior<sup>12-14</sup>. Therefore, the aim of the present study was to evaluate, whether the assumption

of elastic or elastic-plastic material behavior for PMMA is a practicable simplification or a potential source of error in clinical application. This includes an investigation on whether the given status-quo within prosthodontics holds validity over different test velocities (i.e. considering masticatory velocities) and temperatures that are common in clinical conditions<sup>15-17</sup>. Therefore, one common PMMA for long-time temporary crown and bridge treatments (Telio Cad, Ivoclar Vivadent, Schaan, Lichtenstein), as was used in previous investigations<sup>5,7,9,18</sup>, was investigated exemplarily for precise material characterization. Regardless of the necessary mechanical properties, within the manufacturer's specifications for the material, the exact material behavior was neither referred to nor investigated, which further indicates that the rather complex behavior of polymeric materials is not yet sufficiently considered in dental applications.

At the current time, three-point bending tests (3PBTs) are a common testing procedure in dental biomaterial science<sup>10,19</sup>, for which reason these are also carried out within this study. The test velocity of 1 mm/min was selected as it was used in several other studies and as described in the ISO 10477. Since chewing velocities will exceed this standardized test velocity, in addition, test velocities of 10 and 100 mm/min as well as 0.5, 1 and 1.5 m/s were chosen to simulate possible influences of loading rates, corresponding to different chewing velocities. Further, a modified 3PBT with a superposed relaxation test was developed to examine the material's time dependency at quasi-static loading. Dynamic mechanical thermal analysis (DMTA) was also conducted to investigate temperature dependencies

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and simulate clinical conditions. Furthermore, in order to investigate more precisely whether the assumption of linear elasticity remains valid in clinical practice, finite element simulations were also performed on 3PBT specimens with the boundary conditions given by the prior experiments.

## MATERIALS AND METHODS

Due to the complex issue and for a clear overview, the entire procedure of the study is shown in Fig. 1.

### 3PBTs

Telio CAD blocks (shape A3, Ivoclar Vivadent, Schaan, Lichtenstein) were cut water-cooled with a high-precision saw (IsoMet 1000, Buehler, Esslingen, Germany) into  $2 \times 2 \times 55$  mm and  $2 \times 2 \times 40$  mm specimens. Overall, 60 of the shorter specimens were examined, each with test velocities of 1, 10 and 100 mm/min (20 per group) with a support distance of 17 mm. The 3PBTs were performed with a servo electric universal testing machine Inspect 5 (Hegewald & Peschke, Nossen, Germany). High-speed tests with velocities of 0.5, 1.0 and 2.5 m/s were carried out with the longer specimens (30 pieces, 10 per group) on an Impetus Pendulum System (4a technology, Traboch, Austria) with a support distance of 35 mm (Fig. 2). A longer geometry was chosen for the high velocity tests to fit the specimens into the Impetus Pendulum System properly. All the experiments within this study were conducted under laboratory conditions ( $23 \pm 1^\circ\text{C}$ ,  $50 \pm 10\%$  rel. humidity) by the same examiner (P.S.).

### Modified 3PBT

To further examine the material behavior, a modified 3PBT setup was developed. During the tests runtime, the local true strain of the specimen was measured using digital image correlation (DIC). An ARAMIS 3D Motion and Deformation Sensor (GOM, Braunschweig,

Germany) was used. During the test, a  $6 \times 2 \times 55$  mm specimen was placed on a support with a 17 mm distance and was loaded with a test velocity of 1 mm/min until a displacement of 1.5 mm was reached, since it was found during pretests that most specimens failed shortly after such deformation. This position was upheld for one minute to examine, whether stress relaxation and creep are present in the material's behavior. After that, the specimen was rapidly unloaded until it was no longer in contact with the bending fin. Within the next 300 s, the local strain of the unloaded specimen was continuously captured by the DIC system. This test was also performed on the servo electric universal testing machine Inspect 5 under laboratory conditions ( $23 \pm 1^\circ\text{C}$ ,  $50 \pm 10\%$  rel. humidity).

### DMTA

To investigate the time dependent thermomechanical properties of the given material, a specimen ( $2 \times 2 \times 55$  mm) was prepared similarly as in the 3PBT procedure. The viscoelastic material parameters were determined using a DMA/SDTA 861 (Mettler Toledo, Giessen, Germany). During the test, the specimen was subjected to a sinusoidal load in a frequency range between 1 and 100 Hz at temperatures of 0, 35 and  $55^\circ\text{C}$  to simulate

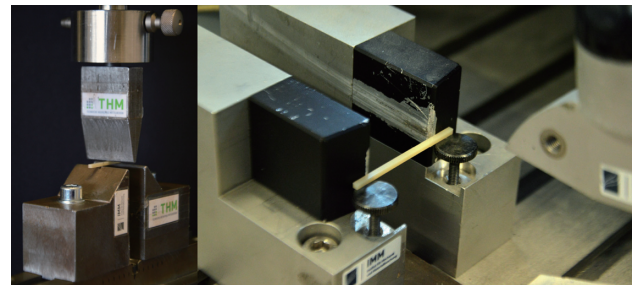


Fig. 2 3PBT setup for low (left) and high velocities (right).

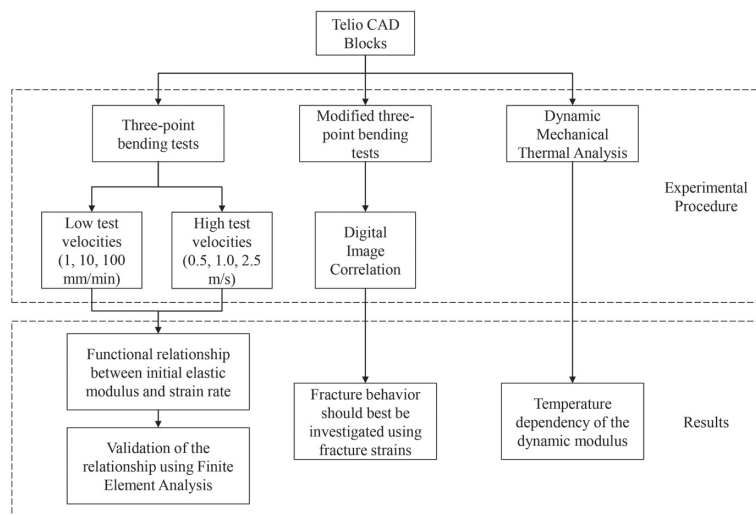


Fig. 1 Overview of the entire study procedure.

different chewing velocities and intraoral temperatures while corresponding forces were measured. From this, the dynamic modulus can be calculated, which is comparable to the initial elastic modulus (IEM) that was determined from the 3PBT. To cool the specimen during the test at 0°C, liquid nitrogen was used.

#### Finite element analysis (FEA)

The computational study was conducted with FEA using the pre- and postprocessor LS-PrePost and the implicit finite element solver LS-DYNA (LSTC, Livermore, CA, USA). As shown in Fig. 3 the 3PB specimens were modelled using fully integrated solid elements with a mesh size of 0.2 mm. Both the bending fin and the bearing are considered as rigid shell elements and were meshed with a size of 0.1 mm and a radius of 1 mm. The distance of the bearing as well as the loading velocity were input into the model according to the 3PBT setups discussed prior. Within this study, a linear elastic material model with the independent material constants elastic modulus, Poisson's ratio and density is used and examined on its suitability for recreating the observed material behavior.

#### Statistical procedure

All statistical analyses were performed using MATLAB 2017b (MathWorks, Natick, MA, USA). The IEM obtained from the 3PBT was investigated on normal distribution (Levene and Shapiro-Wilk tests) and

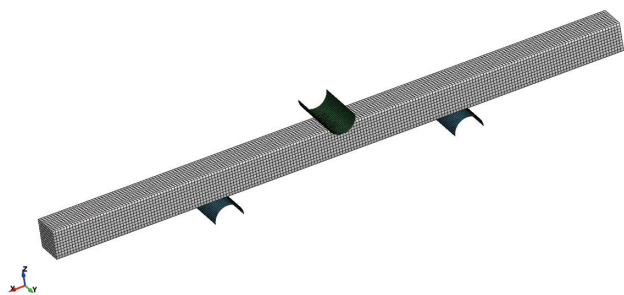


Fig. 3 Finite Element Simulation setup of 3PBTs.

standard deviation homogeneity for the data from each test group. The results between the different test velocities were analyzed using the means of the pairwise comparisons ( $p < 0.05$ ).

## RESULTS

#### 3PBTs

The force-displacement curves resulting from the 3PBTs under differing loading velocities are depicted in Figs. 4a and b.

To obtain the IEM, the linear elastic stress  $\sigma$  and strain  $\varepsilon$  are calculated *via*

$$\sigma = \frac{3FL}{2wt^2} \quad (1)$$

and

$$\varepsilon = \frac{6st}{L^2} \quad (2)$$

for small strain and stress with  $F$  as the measured force,  $s$  as the measured displacement,  $L$  as the support distance and  $w$  and  $t$  as the width and thickness of the specimen (see schematic 3PB setup in Fig. 5).

The IEM for each tested specimen is then calculated with a linear regression through the initial stress-strain values. At low-velocity tests, the first 100 values were selected for regression (50 Hz sampling rate); at high velocities, the regression was performed on the first 75 values (150 Hz sampling rate) after filtering the

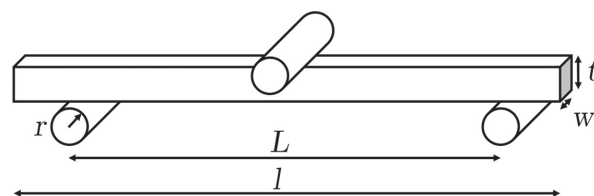


Fig. 5 Schematic 3PBT setup.

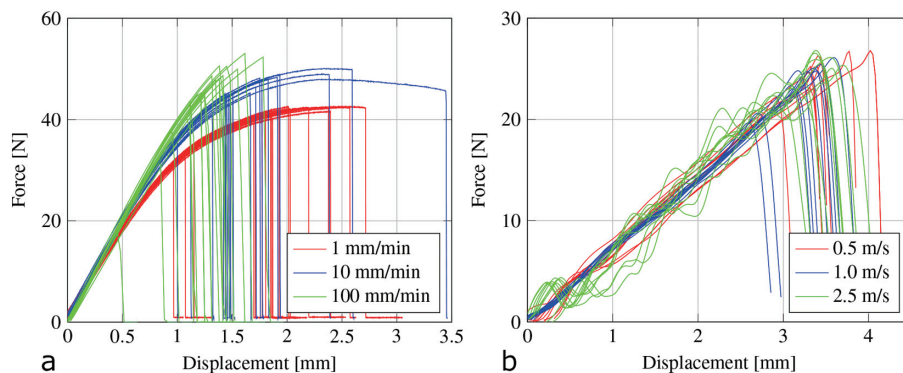


Fig. 4 a: Results for the test velocities of 1, 10 and 100 mm/min.  
b: Results for the test velocities of 0.5, 1.0 and 2.5 m/s.

measurements with the corresponding SAE filters. The determined mean IEM values and the displacement at fracture are depicted in Table 1 with their corresponding standard deviations for the different loading velocities. The results for the  $p$ -values between the investigated test velocities are depicted in Table 2. The initial strain rate  $\dot{\epsilon}$  is computed with the loading velocity  $v_T$  according to

$$\dot{\epsilon} = \frac{6t}{L^2} v_T \quad (3)$$

to estimate the rate-dependency of the material. This rate-dependency is displayed in Fig. 6, in which both the determined IEM at its corresponding strain rate and an interpolation function in the form of

$$E(\dot{\epsilon}) = [E_{qs} - E_{dyn}] \exp(\lambda_E \dot{\epsilon}) + E_{dyn} \quad (4)$$

are shown. By using this function, one can determine the IEM of a polymeric material at arbitrary loading rates after fitting the growth rate  $\lambda_E$  under the assumption, that the IEM can neither fall below the determined quasi-static IEM  $E_{qs}$  nor exceed the mean IEM  $E_{dyn}$  from the dynamic tests. The calculated parameters of the

above equation for Telio Cad are given in Table 3.

As it was already pointed out by Sweeney *et al.* as early as in 1954, it is advisable to specify the strain rate for rate-dependent materials for comparability between the different experiments and experimental setups<sup>20,21</sup>. However, the authors of this present study believe that most of today's studies within dental biomaterial research

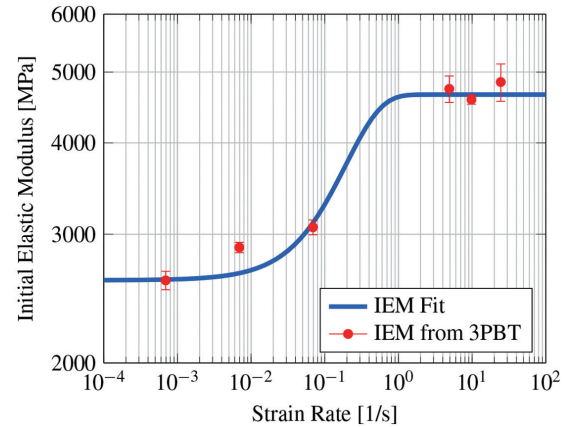


Fig. 6 Rate-dependency of the IEM.

Table 1 Flexure modulus and displacement at fracture sorted by different test velocities

Loading velocity $v_T$	Initial strain rate $\dot{\epsilon}$ [1/s]	Sample size	Initial elastic modulus (IEM) [MPa]	Displacement at fracture [mm]
1 mm/min	$6.920 \cdot 10^{-4}$	20	$2,594.19 \pm 75.04$	$1.86 \pm 0.45$
10 mm/min	$6.920 \cdot 10^{-3}$	20	$2,877.67 \pm 47.08$	$1.65 \pm 0.37$
100 mm/min	$6.920 \cdot 10^{-2}$	20	$3,066.33 \pm 71.17$	$1.23 \pm 0.29$
0.5 m/s	4.898	10	$4,741.29 \pm 197.59$	$3.57 \pm 0.36$
1.0 m/s	9.796	10	$4,585.61 \pm 67.24$	$3.41 \pm 0.29$
2.5 m/s	24.490	10	$4,845.07 \pm 284.37$	$3.34 \pm 0.43$

Table 2  $p$ -Values for the flexure modulus based on the different test velocities

	1 mm/min	10 mm/min	100 mm/min	0.5 m/s	1.0 m/s	2.5 m/s
1 mm/min	—	0.000	0.000	0.000	0.000	0.000
10 mm/min	—	—	0.000	0.000	0.000	0.000
100 mm/min	—	—	—	0.000	0.000	0.000
0.5 m/s	—	—	—	—	0.028	<b>0.340</b>
1.0 m/s	—	—	—	—	—	0.012

No significant differences are printed in bold type.

Table 3 Determined parameters of IEM interpolation for Telio Cad

Quasistatic IEM $E_{qs}$	Dynamic IEM $E_{dyn}$	Fitted growth rate $\lambda_E$
2,594.19	4,656.90	-4.1494

lack the important specification of the experimental initial strain rate.

### Modified 3PBT

First, before the results of the local strain measurements are examined precisely, the results of the force and displacement measurements received by the testing machine shall be discussed, since these can also be gained from a conventional test setup without utilizing DIC. These measurements are displayed in Fig. 7a. As seen in the graph after loading, the force is decreasing at a constant displacement, which is a clear indicator of stress relaxation. Furthermore, it can be observed that a hysteresis loop is formed during loading and unloading, further suggesting viscoelastic behavior. The relaxation process can be observed more clearly in the force-time curve (Fig. 7b): During the 60 s of constant displacement, the force decreases from a peak of approximately 115 N to approximately 100 N. Unfortunately, since stress may not be calculated accurately from the 3PBT if the material's elastic limit is exceeded, the stress relaxation behavior cannot be examined more accurately with this setup. The presence of stress relaxation leads to the conclusion that the fracture stress of PMMA must not

be calculated analytically with the beam theory formula (1).

The results of the strain measurements using DIC can be seen in Fig. 8. The global maximum strain, local maximum strain near the bending fin and strain averaged over a line in the region of strongest deformation are captured over time and are displayed in Fig. 9, along with the strain following an analytic calculation with the machine path according to formula (2). The local displacement of the specimen in the load direction is also measured with DIC and is compared with the machine path for validation purposes.

### DMTA

The results of the DMTA measurements are displayed in Fig. 10. It can be observed clearly that the dynamic modulus increases with frequency (chewing velocity) and decreases with temperature.

### FEA

For the simulation of the 3PBT with FEA, material cards with the prior determined interpolation function between IEM and strain rate and a density of  $1.19 \text{ g/cm}^3$  were created to investigate the deviations that follow

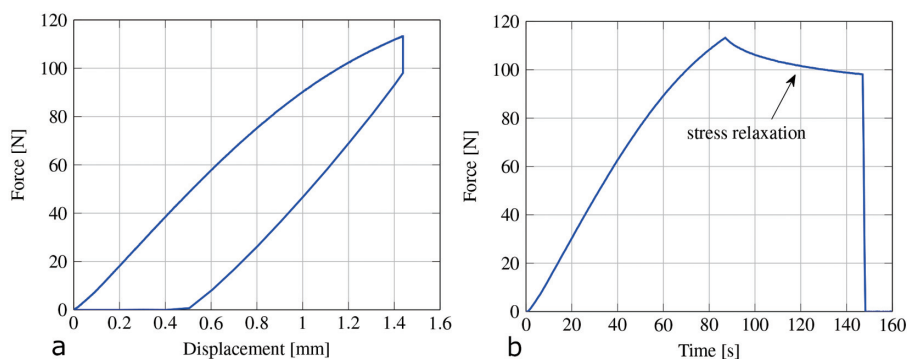


Fig. 7 a: Force displacement curve showing loading and unloading behavior. b: Force measurement over time.

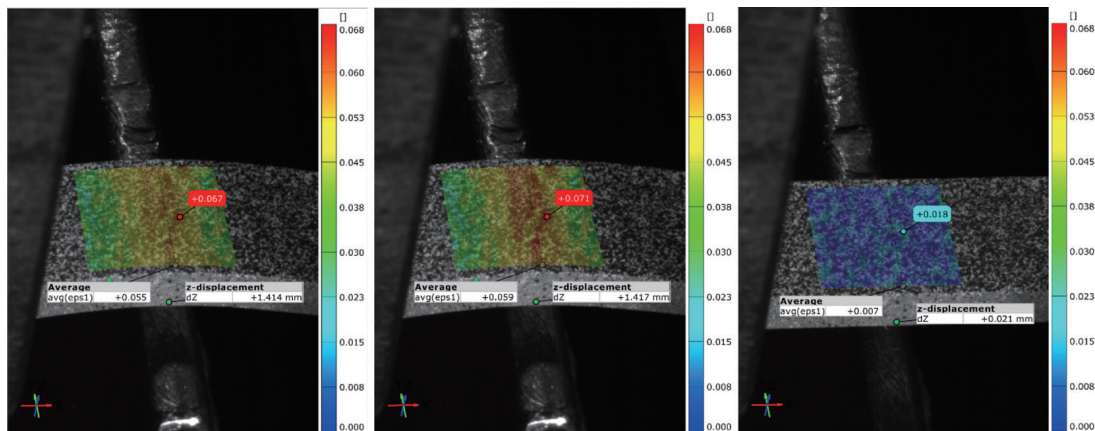


Fig. 8 Local true strain fields after initially reaching maximum displacement (left), 60 s of constant maximum displacement (middle) and 300 s after complete unloading (right).

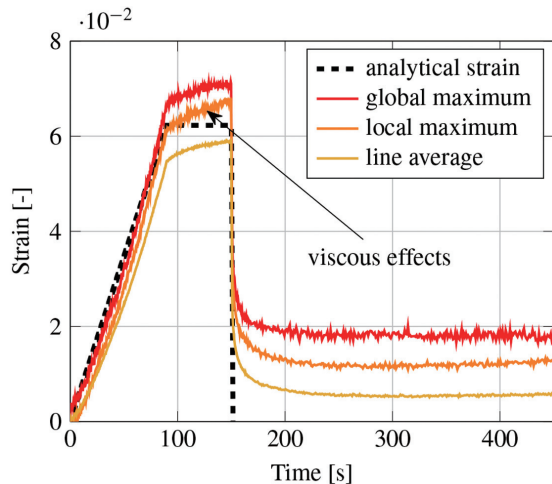


Fig. 9 DIC strain measurements over time.

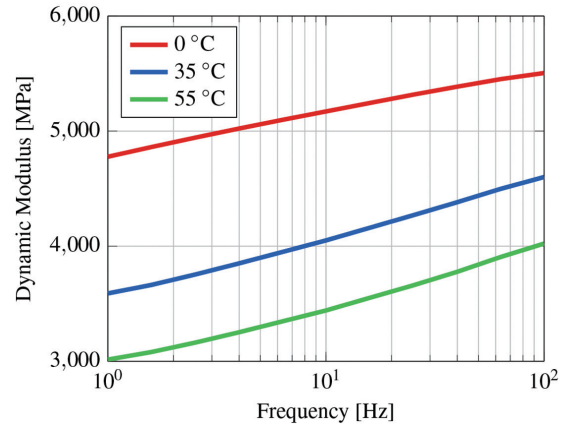
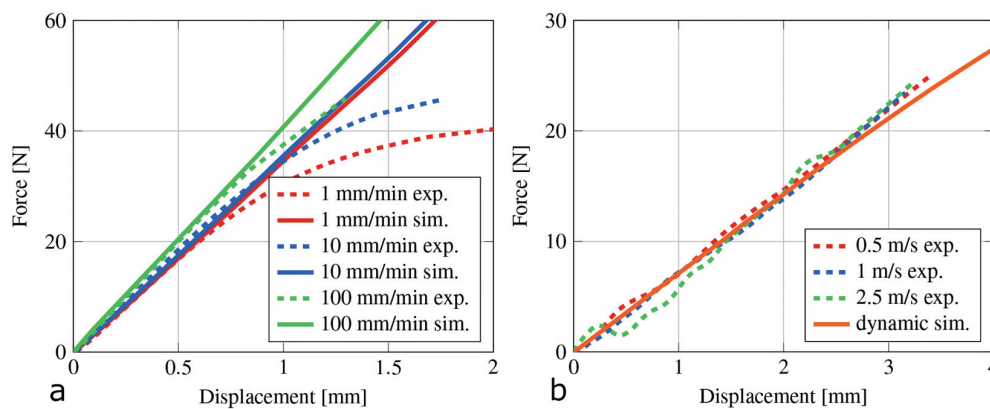


Fig. 10 DMTA results at different temperatures and frequencies.

Fig. 11 a: FEA of low velocity 3PBTs.  
b: FEA of high velocity 3PBT.

from the assumption of linear elasticity for PMMA. At the quasi-static test, a constant Poisson's ratio of 0.36 was assumed, whereas the value was selected as 0.3 following the findings of Rühl in the other tests<sup>12</sup>. The results of these simulations are shown in Figs. 11a and b in the form of force-displacement curves with the mean measured values displayed as dashed lines and the simulation results displayed as bold lines. Here it can be observed that a linear elastic material model heavily overestimates the forces that arise from the experiments conducted on the Telio CAD specimens at lower rates. However, the initial stiffness of the material is captured quite well by the simulations.

## DISCUSSION

Currently, temporary restorations fulfill a wide range of applications within the prosthodontic dentistry (*e.g.*, long- or short-term provisional treatments, restorations of the vertical dimension, trial wearing before the final restoration). Along with primary protection of the prepared tooth structure, the pulp should be protected

from external noxae, such as hotness, coldness or acidic, provisional treatments, and the oral functions including phonetics, mastication and esthetics should be maintained<sup>1-4</sup>. In the present study, one common PMMA for long-time temporary crown and bridge treatments (PMMA; Telio Cad, Ivoclar Vivadent), as was used in previous investigations, was investigated to simulate common clinical situations regarding to different chewing velocities and intraoral temperatures<sup>5,7,9,18</sup>. Telio CAD is a cross-linked PMMA with a percentage by weight of 99.5% to which pigments (less than 1% by weight) have been added. As described in other studies, no further fillers are added<sup>18,22,23</sup>.

The form as an industrial blank warrants a homogeneity structure that is comparable to a mixed dispensing temporization material<sup>1,24-28</sup>. In addition, this form can be used in current CAD/CAM procedures within digital dentistry.

For the 3PBTs, it should be noted in advance that the specimen lengths of the tested 3PB specimens were longer than specified in ISO 4049. Within this study, the specimen lengths of 40 and 55 mm were selected

to minimize possible shear forces within the beam, leading to a failure solely dependent on the yielded bending moment. Further, with longer specimens, greater support distances can be achieved, which lead to a greater deflection of the specimen. Consequentially, plastic deformations, if present, can be provoked more easily.

In the present study, the IEM was calculated with a linear regression through the initial stress strain values. Other authors suggested that the elastic modulus should be calculated from one point of the force-displacement curves<sup>11,29</sup>. This approach, however, forces a zero-intercept of the force-displacement curves, which is not necessarily the case within the experiments. For example, in the dynamic 3PBT at 2.5 m/s shown in Fig. 4b, the initial takeoff often deviates from the zero-intercept, which is due to the pendulum system's measurement procedure (contact angle as start of measurement). If one measured value was used here, deviations between calculated and true IEM would have occurred. This would also be the case, if a zero-intercept was present but the single used value was not selected accordingly. Therefore, the chosen approach of linear regression is to be regarded as recommendable in general, since the inclusion of several measured values will achieve a higher degree of precision in the obtained results. Furthermore, it is important point out again that formula (1) should (per definition) only give accurate information about stresses within the linear elastic range of the force-displacement curves. This can be derived from beam theory in which linear elasticity is assumed, since Hooke's law is inserted in the derivation of the stress-strain relationship<sup>30</sup>. This means that, for a polymeric material showing nonlinear stress-strain relationships, fracture toughness must not be calculated from 3PBT. While using beam theory may be a pragmatic approach to calculate stresses within the material, deviations of unpredictable magnitude must be put up with after the materials elastic limit is exceeded, which might invalidate the results in the worst case.

The 3PBTs conducted in this study hint at a viscoelastic material behavior which is strongly indicated by an increase of the IEM with increasing loading rate. For this reason, slightly differing test speeds might lead to a substantial change in the stress-strain behavior (e.g. changing the IEM) and material failure (e.g. fracture stress and strain). This is undermined by Fig. 6, in which the IEM derived from the 3PBT is displayed over logarithmic strain rate with the interpolation function (4). The made assumptions for the definition of relationship (4) with a minimum quasi-static IEM and a maximum dynamic IEM are considered as reasonable for viscoelastic materials. These results heavily imply that the rate-dependency of polymeric materials should be incorporated into dental biomaterial testing, especially since minor changes in loading rate can lead to a substantial change of the IEM.

Furthermore, as can be seen in Figs. 4 and 5, force and deflection at fracture scatter statistically. This indicates differing fracture stresses and strains, which has not been investigated further at this point. However,

the mean displacements at fracture from Table 1 show a declining trend. In future works, the fracture behavior of the given PMMA should be examined more thoroughly, especially to enable a statistically safe design of prosthodontic treatments.

With the presented modified 3PBTs, a novel test setup was proposed to determine quasi-static material behavior of a material using DIC measurements in a 3PBT setup. Within the test, stress relaxation, creep and a hysteresis loop during loading and unloading were observed which clearly indicate a viscoelastic-viscoplastic material behavior of the investigated PMMA<sup>31-33</sup>.

A very strong agreement between machine path and DIC position measurement was found during the measurements, which suggests a high DIC measurement accuracy. It can clearly be observed from the strain fields that the strain further increases after reaching the maximum displacement until the specimen is unloaded, indicating creep and plastic deformation. In the last DIC image (Fig. 8) it can be observed, that the plastic deformations mostly occur locally. A maximum plastic strain of 1.8% and an average plastic strain of about 0.7% was found.

When comparing the analytically calculated, maximum and averaged strain as seen in Fig. 9, it can be concluded that local peaks of strain form during the measurements which may not be accounted for accurately with beam theory calculations. However, the analytically calculated strain during loading correlates quite well with the local maximum strain measured with DIC near the bending fin although the initial elastic range of the material behavior is exceeded. Further, the analytically calculated strain only underestimates the maximum strain about 0.005% at a comparatively large displacement of about 1.5 mm after loading, which means that the fracture strain of the given PMMA may be calculated approximately using beam theory. It should also be noted that the actual strain rate within the test only deviates slightly from the analytically determined initial strain rate during loading, leading to the important conclusion that the initial strain rate calculated from formula (3) is a pleasing comparative benchmark.

The presence of stress relaxation further substantiates the conclusion that the stress at fracture (and hence fracture toughness) must not be calculated with beam theory equations. In contrast, it was shown with the DIC measurements that the strain at fracture may approximately be calculated by beam theory formula (2). This further allows the conclusion that the scattering fracture behavior of the given PMMA observed within the 3PBT could be examined statistically with the usage of fracture strains acquired from the measured machine path in future research.

DMTA within dental biomaterial science are often used to determine the influence of additives on the thermomechanical behavior of a material in an intraoral situation. Within the present study, DMTA was used to substantiate the rate- and temperature-dependency of the given material within clinically

relevant dimensions. Although it is rather complex to compare the frequencies from the DMTA measurements with the IEM determined from the 3PBT, it is further shown in the DMTA measurements that the material's rate-dependency is of significant extent. Further it can be observed that the stiffness deviates greatly within the clinically relevant range of temperatures. In future research one should further investigate how these DMTA measurements could be incorporated in the standardization and material testing of dental PMMA, since the influence of temperature seems to be of rather large magnitude.

As for the FEA, the linear elastic approach is based only on three independent material parameters (elastic modulus; Poisson's ratio; density). It could already be seen from the performed tests that the material evidently does not behave in a linear elastic manner, since rate-effects, temperature-dependencies, energy dissipation during loading and unloading and plastic deformations have already been observed. However, since the linear elastic material model is commonly used during FEA in dental biomaterial science<sup>3,34-36</sup>, it shall be investigated whether the linear elastic material model provides sufficiently accurate results for the respective rates. Furthermore, these simulations are used to validate the determined IEM interpolation function from formula (4).

Although the initial slope of the force displacement curves is in good agreement with the linear elastic model at each loading velocity, indicating that the determined interpolation function is indeed applicable, the results are unsatisfactory at low rates, since the force (and stress, correspondingly) is greatly overestimated by the linear elastic material model. Nevertheless, the mean curves are captured excellently at high rates. Hence it can be concluded from these simulations that viscous effects or plastic deformations seem to play a negligible role in the high velocity 3PBT. This allows the assumption that the material behavior at chewing velocities is dominated by viscoelasticity and less affected by viscoplastic effects. It shall be noted that the usage of non-linear FEA is mandatory to investigate whether geometric nonlinearities could arise within the performed 3PBT, since geometric nonlinearities could falsely be interpreted as (visco-)plastic deformations. Linear FEA would not be able to account for effects due to large displacements within the simulation.

As a consequence, future studies should investigate the rate-dependent material failure to improve the design and safety of prosthodontic treatments consisting of PMMA.

## CONCLUSIONS

As it was shown in this study, the material behavior of PMMA deviates with different loading velocities and temperatures within a clinically relevant range. The results of this study indicate that a wider range of chewing velocities should be considered in dental biomaterial testing. It is therefore advised to

compare different polymeric dental biomaterials with standardized test conditions under various strain rates and temperatures.

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

- (1) The investigated PMMA shows rate and temperature dependent material behavior within a clinically significant range. To reduce possible fractures within temporary prosthodontic treatments with PMMA, biomechanical testing conditions should be considered and standardized.
- (2) PMMA should not simply be considered as linear elastic or elastic-plastic within dental biomaterial testing. This may lead to elusive sources of error, especially considering the calculation of fracture stresses with formulae derived from linear elastic beam theory.
- (3) For a better comparability between future studies, a linear regression instead of a determination with only one measuring point should be used to determine the modulus of elasticity. Further, a function, which enables modeling the rate-dependency of the IEM, was presented and validated by finite element simulations.
- (4) Although one should not use the beam theory equations to determine the stresses, it was shown that the strain could be calculated from beam theory with a reasonable accuracy for the given material.

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