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Characterization of the quasi-static and viscoelastic properties of orthopaedic bone cement at the macro and nanoscale

Josh Slane,[1,2] Juan F. Vivanco,[3,4] Matthew Squire,[2] Heidi-Lynn Ploeg[2,3]

[1]Institute for Orthopaedic Research and Training, KU Leuven/University Hospitals Leuven, Pellenberg, Belgium
[2]Department of Orthopedics and Rehabilitation, University of Wisconsin-Madison, Madison, Wisconsin
[3]Department of Mechanical Engineering, University of Wisconsin-Madison, Madison, Wisconsin
[4]Facultad de Ingeniería y Ciencias, Universidad Adolfo Ibañez, Viña del Mar, Chile

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Abstract: Acrylic bone cement is often used in total joint replacement procedures to anchor an orthopaedic implant to bone. Bone cement is a viscoelastic material that exhibits creep and stress relaxation properties, which have been previously characterized using a variety of techniques such as flexural testing. Nanoindentation has become a popular method to characterize polymer mechanical properties at the nanoscale due to the technique's high sensitivity and the small sample volume required for testing. The purpose of the present work therefore was to determine the mechanical properties of bone cement using traditional macroscale techniques and compare the results to those obtained from nanoindentation. To this end, the quasi-static and viscoelastic properties of two commercially available cements, Palacos and Simplex, were assessed using a combination of three-point bending and nanoindentation. Quasi-static properties obtained from nanoindentation tended to be higher relative to three-point bending. The general displacement and creep compliance trends were similar for the two methods. These findings suggest that nanoindentation is an attractive characterization technique for bone cement, due to the small sample volumes required for testing. This may prove particularly useful in testing failed/retrieved cement samples from patients where material availability is typically limited. © 2016 Wiley Periodicals, Inc. J Biomed Mater Res Part B: Appl Biomater, 105B: 1461–1468, 2017.

Key Words: bone cement, nanoindentation, mechanical testing, creep, orthopaedics

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INTRODUCTION

Acrylic bone cement is widely used in total joint replacement procedures to anchor an orthopedic implant by creating a mechanical interlock between the implant surface and the patient's bone. Component loosening (loss of rigid fixation at the bone-implant or bone-cement interface) is one of the most common mechanisms responsible for failure of hip and knee replacement devices. Loosening can be caused by mechanical failure of the bone cement layer surrounding an implant, among other factors,[1,2] thus making the mechanical properties of bone cement vital to the survival of a cemented implant. The *in vivo* loading of bone cement is complex and difficult to recreate experimentally; it is a combination of compression, bending, tension, shear, and torsion loading modes that are both static and dynamic in nature.[3]

Bone cement is a viscoelastic material that exhibits creep and stress relaxation, factors which can be exploited by some orthopaedic implant designs. For example, loaded-taper femoral stems (also known as force-closed designs) are intended to subside (e.g. creep) within the cement mantle over time to reach a stable position with an optimal stress distribution.[4] Conversely, excessive cement creep can be detrimental,[5,6] although there is still disagreement on the amount of creep that can be safely tolerated and if cement creep alone is responsible for levels of clinically observed implant subsidence.[7] A variety of methods have been previously used to characterize the creep properties of bone cement including three-point bending,[6] tension,[8,9] and confined compression.[10]

Recently, the utilization of nanoindentation has increased for the mechanical characterization of polymers as it has been shown to have excellent sensitivity[11] and can be successfully used with limited material volumes. In this testing method, a rigid indenter tip with a well-described geometry is driven into a material's surface while high-resolution load and displacement data are simultaneously recorded.[12] In addition to characterizing the static properties of polymers (modulus, hardness), nanoindentation can be used to measure creep, stress relaxation, and various viscoelastic parameters (storage modulus, loss factor), making it a versatile tool. Furthermore, one of the primary advantages of nanoindentation is that only small sample volumes are required to perform a multitude of tests. With respect to bone cement, this is particularly advantageous since it enables the mechanical

Correspondence to: J. Slane; e-mail: joshua.slane@kuleuven.be

TABLE I. Chemical Compositions of the Bone Cements Used in this Study, as Reported by the Manufacturers

Cement	Component	Amount	
Palacos	Powder	Poly(methyl acrylate, methyl methacrylate)	33.8 g
		Zirconium dioxide	5.9 g
		Benzoyl peroxide	0.3 g
	Monomer	Methyl methacrylate	19.57 mL
		N, N-dimethyl-p-toluidine	0.43 mL
Simplex	Powder	Polymethyl methacrylate	6.0 g
		Methyl methacrylate-styrene	30.0 g
		Barium Sulfate	4.0 g
	Monomer	Methyl methacrylate	19.5 mL
		N, N-dimethyl-p-toluidine	0.5 mL

Please note, for Simplex the methyl methacrylate-styrene copolymer contains 1.7% benzoyl peroxide.

characterization of samples retrieved from failed cemented arthroplasties where only small, irregular samples are typically available. Thus the use of nanoindentation could provide insight into the *in vivo* failure mechanisms associated with bone cement. For example, Lewis et al.[13] utilized nanoindentation to measure the quasi-static and dynamic properties of bone cement retrieved from failed hip implants. Despite this, there has not been a direct comparison (to our current knowledge) of the creep properties of bone cement obtained from macro scale techniques to those from nanoindentation.

The purpose of this study was to investigate the quasi-static mechanical properties and creep behavior of two commercially available bone cements at the macro and nano scale. At the macro scale, flexural (to failure and creep) testing was conducted since it has been suggested that bending is the most realistic loading mode of bone cement.[3] A combination of static, creep, and dynamic nanoindentation tests were utilized for nanoscale characterization of the cements. These data are important to understand the underlying properties of a class of widely used biomaterials and furthermore can be used as input parameters into various computational techniques such as finite element analysis.

MATERIALS AND METHODS

Sample preparation

Two commercially-available bone cement were used in this study: Palacos R (Heraeus Medical GmbH, Wehrheim, Germany) and Simplex P (Howmedica Osteonics, Mahwah, NJ). The relative composition of these cements is shown in Table I. The monomer and powder components were mixed according to the manufacturers' instructions by hand at ambient conditions (~22°C, 22% humidity) using a 2:1 powder to monomer ratio. Once combined, the mixture was transferred to aluminum molds and allowed to cure for 20 min. Samples used for flexural testing (static and creep) were wet ground on all sides with 400-grit silicon carbide article. For nanoindentation experiments, samples were embedded in a slow-cure epoxy and wet ground with progressively finer silicon carbide article (240, 400, 600, 800, and 1200 grit) followed by polishing with diamond slurries (6, 1, and 0.25 μm). Regardless of the testing performed, all samples were stored at ambient conditions and used within 7–14 days following initial polymerization to mitigate aging effects.[14]

Three point flexural testing

Quasi-static three-point flexural testing was conducted using flat beam samples with a width, thickness, and length of 9.94 ± 0.01 mm, 3.28 ± 0.04 mm, and 75.03 ± 0.01 mm, respectively. A materials testing frame (Criterion C43.104, MTS Systems, Eden Prairie, MN) equipped with a 250 N load cell was used. Testing was performed until failure at a displacement rate of 5 mm/min with an outer support span of 60 mm. In total, 21 samples per cement group were tested. The flexural strength (σ_F), flexural modulus (E_F), and peak outer fiber strain (ε) were calculated[15]:

$$\sigma_F = \frac{3FL}{2bd^2} \quad (1)$$

$$E_F = \frac{L^3 s}{4bd^3} \quad (2)$$

$$\varepsilon = \frac{6\delta d}{L^2} \quad (3)$$

where F is the load at failure, L is the outer span, b is the width, d is the thickness, s is the slope of the linear portion of the force-displacement curve, and δ is the peak deflection of the sample.

An electrodynamic materials testing frame (Acumen 3, MTS Systems) was used to perform flexural creep testing in a three-point configuration with an outer span of 60 mm. Sample dimensions were the same as those used quasi-static testing. Creep tests were performed at flexural stress (σ_F) of 10 with a hold time of 1 hr. Testing was conducted at ambient conditions (~22°C) and three samples from each cement variety were tested for all conditions. The creep behavior of the cements was described with a Burgers model, which is a combination of a Maxwell and Kelvin unit connected in series:

$$\varepsilon(t) = \frac{\sigma}{E_1} + \frac{\sigma}{E_2}\left(1 - e^{-t/\tau}\right) + \frac{\sigma}{\eta} t \quad (4)$$

where ε is the total strain, σ is the applied stress, t is the creep time, E_1 and η are the modulus and viscosity of the Maxwell unit, E_2 is the modulus of the Kelvin spring, and τ

is the time constant (equivalent to the time necessary for 63.2% of the deformation in the Kelvin unit to occur).[16] Model parameters were estimated by performing nonlinear least-squares curve fitting of the experimentally obtained displacement versus time data (MATLAB R2011a, Mathworks, Natick, MA). Additionally, the creep compliance, $J(t)$, of the cements was determined ($J(t) = \varepsilon(t)/\sigma$).

Nanoindentation

Quasi-static and creep nanoindentation experiments were performed at ambient conditions using a nanoindenter (TI Premier, Hysitron, Eden Prairie, MN) equipped with a calibrated diamond Berkovich tip. For quasi-static tests, a trapezoidal loading function with a peak load of 2.5 mN, a load/unload rate of 1.25 mN/s, and a dwell time of 5 s was used. For creep testing the same peak load was used while the loading rate was 5 mN/s and dwell time was 120 s. Force and tip displacement data were collected at 200 Hz and 20 Hz for quasi-static and creep testing, respectively. Indents were spaced 250 μm apart to avoid adjacent interactions and all testing was conducted within the interbead matrix to ensure consistency (bone cement is a multiphase material with polymer beads, radiopacifier particles, and interbead matrix). In total, 18 and 5 indents were performed per cement for quasi-static and creep testing, respectively.

The Oliver-Pharr (OP) method, with slight modifications, was used to analyze the collected quasi-static data to determine the elastic modulus and hardness of the cements.[17] This technique utilizes the unloading portion of the load/displacement curve to determine the contact stiffness, which is subsequently used in the calculation of various material properties. However, since time-dependency is not accounted for in the OP method, a technique introduced by Feng and Ngan, which accounts for viscoelasticity, was used to correct the contact stiffness[18]:

$$\frac{1}{S_c} = \frac{1}{S} + \frac{\dot{h}_h}{\dot{P}} \quad (5)$$

where S_c is the corrected stiffness, S is the apparent stiffness (from the OP method), $\dot{h}_h$ is the tip displacement rate at the end of the dwell period, and $\dot{P}$ is the unloading rate. Once known, S_c was used in place of the apparent stiffness for calculating hardness and modulus. Additionally, the plasticity index, ψ, and recovery resistance index, R_s, of the cements were determined[19]:

$$\psi = \frac{A_1 - A_2}{A_1} \quad (6)$$

$$R_s = 2.263\frac{{E_r}^2}{H} \quad (7)$$

where A_1 is the area under the loading portion of the load/displacement curve, A_2 is the area under the unloading portion of the curve, E_r is the reduced modulus, and H is the hardness.

TABLE II. Results (Mean ± SD) Obtained From Quasi-Static Three-Point Bend Testing

Cement	Modulus (GPa)	Flexural Strength (MPa)	Peak Flexural Strain
Palacos	2.88 ± 0.13	86.14 ± 4.33	0.046 ± 0.007
Simplex	2.87 ± 0.07	76.95 ± 7.80[a]	0.032 ± 0.006[a]

[a] $p < 0.001$, relative to Palacos.

The nano creep properties of the cements were fit to a Burgers model[20] using nonlinear least-squares curve fitting of the indenter displacement data:

$$h^2(t) = \frac{\pi}{2} P_o \cot\alpha \left(1-\upsilon^2\right)\left(\frac{1}{E_1} + \frac{1}{E_2}\left(1-e^{-t/\tau}\right) + \frac{t}{\eta(1-\upsilon^2)}\right) \quad (8)$$

where h is the indenter displacement, t is the creep time, P_o is the peak load, α is the equivalent cone semi-angle for a Berkovich tip (70.3°), υ is Poisson's ratio (0.3), E_1 and E_2 are moduli, τ is the time constant, and η is the long-term creep viscosity. To account for the trapezoidal loading function, the moduli values were corrected using the method introduced by Oyen.[21] Finally, the creep compliance, $J(t)$, was determined[22]:

$$J(t) = \left(1-\upsilon^2\right)\left(\frac{1}{E_1} + \frac{1}{E_2}\right) - \left(\left(1-\upsilon^2\right)\frac{1}{E_2} e^{-t/\tau}\right) + \frac{t}{\eta(1-\upsilon^2)} \quad (9)$$

Dynamic nanoindentation tests were performed using frequency sweeps from 1 to 100 Hz to determine the storage modulus and loss factor. Once contact between the indenter tip and cement surface was established, a small oscillatory load with an amplitude of 100 μN was superimposed on a quasi-static force of 2.5 mN. The resulting changes in phase and amplitude of the force/displacement signal were monitored by the nanoindentation system and specialized software (nanoDMA III, Hysitron).

Statistical analysis

All statistical analyses were performed with Minitab 15 (Minitab Inc., State College, PA) and the significance level was set to 5% for all tests. The Anderson-Darling test was used to check data for normality, which was confirmed for quasi-static nanoindentation testing but not quasi-static three-point bending data. Therefore, a mixture of parametric (analysis of variance with Tukey HSD post-hoc test) and non-parametric (Kruskal–Wallis with Mann-Whitney *post hoc* test) analyses were used. Where applicable, all data are presented as the mean ± standard deviation.

RESULTS

Flexural modulus was not significantly different between Palacos and Simplex cements (Table II). Conversely, both flexural strength and peak flexural strain were significantly ($p < 0.001$) lower for Simplex with a difference relative to Palacos of 11.3% and 35.9%, respectively. Maximum outer-fiber strain in the cements was always below 5% during

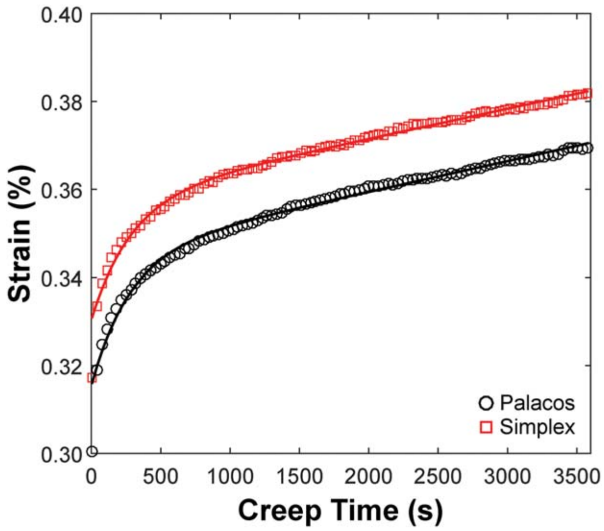

FIGURE 1. Representative force-t curve obtained from three-point bending. Symbols represent experimentally measured data while solid lines are the Burgers model fit.

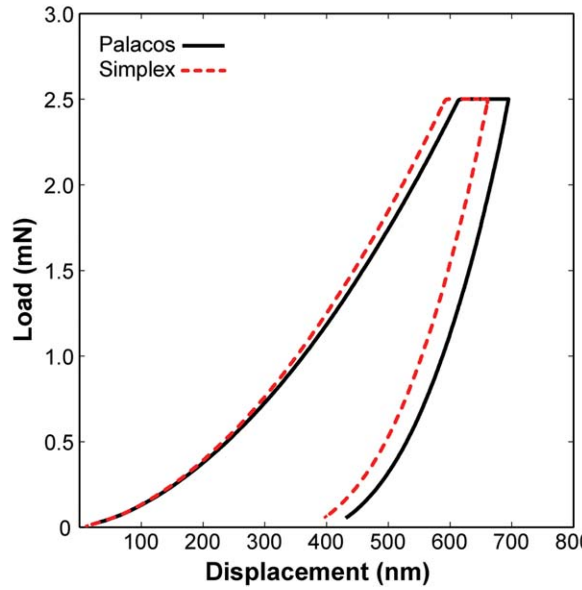

FIGURE 3. Representative force-displacement curves obtained from quasi-static nanoindentation.

testing, indicating strain calculations from Eq. (3) were valid.[15]

The experimentally obtained creep data were found to be well described by the Burgers model [Eq. (4)], with adjusted R^2 values of the nonlinear regression fit exceeding 0.990 for both Palacos and Simplex cements (Fig. 1). For a σ_F of 10 MPa and holding time of 1 hr, the creep compliance of Simplex reached a peak value of 0.382 GPa^{-1}, which was higher relative to the peak of Palacos at 0.370 GPa^{-1} (Fig. 2). The general trend in creep compliance was similar between both cements.

Representative force-displacement curves obtained from quasi-static nanoindentation are shown in Figure 3 while topographical images of the residual idents are given in Figure 4. To generate these images, the Berkovich probe raster scanned the surface of the cement (acting as a scanning probe microscope) following the completion of an indent. Results from quasi-static nanoindentation testing are given in Table III. It was found that both elastic modulus and hardness were significantly higher for Simplex cement, with relative differences of 6.0 and 6.5%, respectively, compared to Palacos. No significant differences in plasticity index were found, however, the recovery resistance of Simplex was significantly higher.

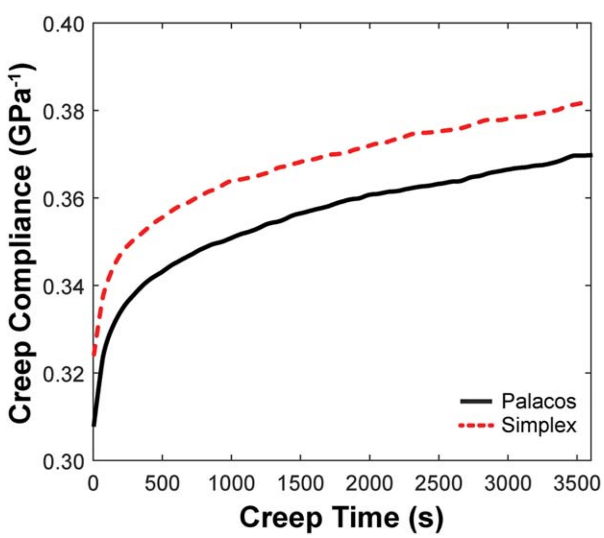

FIGURE 2. Average creep compliance (ϵ_t/σ_o) of Palacos and Simplex bone cements in three-point bending for a holding time of 1 hr at an applied stress of 10 MPa.

Nanoindentation creep data were well described by the Burgers model, as shown by representative force-displacement curves in Figure 5. The calculated creep compliance values were generally higher than those obtained from flexural testing, yet the same general trend in curve shape was similar between the two methods. In contrast to flexural testing, creep compliance of Palacos was found to be higher than Simplex using nanoindentation (Fig. 6). During creep tests, displacement of the indenter tip (under the same load) was greater for Palacos cement indicating reduced stiffness relative to Simplex, which correlates well with results from quasi-static indentation.

Figure 7 provides a comparison of the Burgers model parameters calculated for each cement using flexural testing and nanoindentation. For Palacos and Simplex, both moduli values (E1 and E2) were found to be significantly lower ($p < 0.01$) for nanoindentation relative to flexural testing. Similarly, the time constants obtained using nanoindentation were significantly ($p < 0.001$) lower relative to flexural testing. In contrast, creep viscosity values were significantly higher for both cements using nanoindentation ($p < 0.05$), yet this is expected due to the differences in loading times between the two methods. Regardless of the testing method used, no significant differences were found between Palacos and Simplex for any of the model parameters.

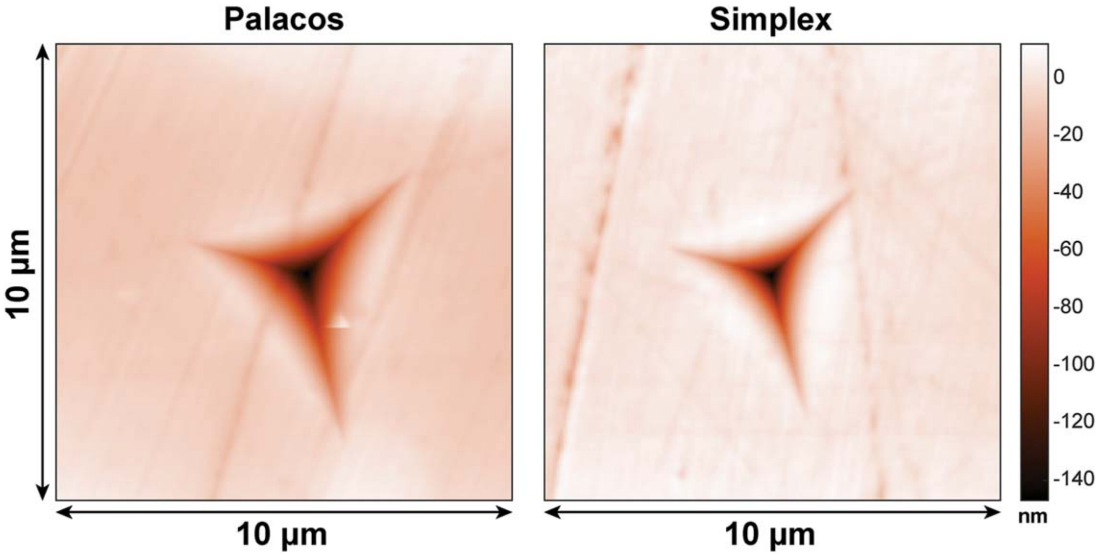

FIGURE 4. Topographical in-situ images were taken of the cement surfaces immediately following an indentation. The Berkovich probe was used as a scanning probe microscope to obtain indentation images.

The storage modulus (i.e. stored elastic energy) and loss factor (i.e. dampening factor) of the cements found using dynamic nanoindentation are shown in Figure 8. Storage modulus increased with increased frequency, while the converse occurred for loss the actor. Interestingly, the storage modulus for Palacos was higher than Simplex at 1 Hz, but lower for all other tested frequencies.

DISCUSSION

Commercially available bone cements are generally packaged in a two-component form with a liquid monomer and a pre-polymerized polymer powder that are mixed together at the time of surgery. Virtually all commercial cements are based on polymethylmethacrylate (PMMA) or similar acrylics, however, their specific chemical compositions vary which can have a substantial impact on the cement's final mechanical and material properties. For example, the monomers used to produce the powder component can range from a PMMA homopolymer to copolymers containing methyl acrylate, ethyl acrylate, or styrene, among others.[23] The cements studied in this work, Palacos and Simplex, were chosen since they are the two most widely used acrylic cements in the European and North American markets. Despite differences in their chemical composition (Table I), molecular weight, hydrophobicity, and sterilization techniques (Palacos – ethylene oxide, Simplex – irradiation), all of which can influence the properties of a cement,[24,25] both demonstrate high clinical success rates according to joint implant registry databases.[26]

Bone cements containing methyl acrylate co-polymers, such as Palacos, tend to exhibit more ductile behavior than cements made with stiffer co-polymers like styrene, such as Simplex.[27] This is one of the primary factors resulting in the different static flexural properties observed in this study. Additionally, the radiopacifier particles within the cement are known to influence the mechanical properties. Barium sulfate particles tend to form agglomerates (e.g. stress concentration sites) within the cement whereas zirconium dioxide is more readily dispersed within the polymer matrix. The morphology of the radiopacifier particles also lay a contributing role: the cauliflower shape of zirconium dioxide provides slight reinforcement resulting from mechanical anchorage within the polymer matrix, whereas the smoother shape of barium sulfate particles do not allow this.[28]

Flexural creep testing was conducted using a stress level of 10 MPa, which represents a 'worst-case' scenario of the expected *in vivo* loading within the bone cement mantle surrounding a typical femoral stem implant.[29] The Burgers model used to describe the creep behavior provides physical descriptions of the elastic moduli, viscosities, and relaxation times of the tested cements, parameters which can be used as inputs into various computational modeling techniques.

TABLE III. Results (Mean ± SD) Obtained From Quasi-Static Nanoindentation Testing

Cement	Modulus (GPa)[a]	Hardness (MPa)	Plasticity Index	Recovery Resistance (GPa)
Palacos	3.72 ± 0.08	256.02 ± 17.30	0.58 ± 0.04	146.87 ± 8.52
Simplex	3.95 ± 0.13[b]	273.33 ± 21.19[c]	0.57 ± 0.07	155.74 ± 11.76[c]

[a] Note, this is the true modulus not the reduced modulus.
[b] $p < 0.001$, relative to Palacos.
[c] $p < 0.02$, relative to Palacos.

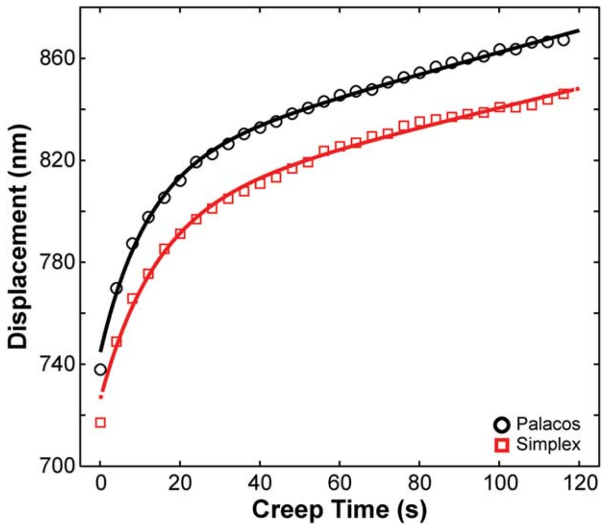

FIGURE 5. Representative experimentally measured indenter tip displacements (symbols) during the dwell phase of nanoindentation testing were fit to a Burgers Model [Eq. (8)], represented by the solid lines.

This is in contrast to phenomenological models that have been used to model the creep behavior of acrylic cements.[6] Previous work conducted by Kuzmychov et al.[6] investigated the creep properties of Palacos bone cement in a three-point bending configuration and fit the measured data to a modified Burgers model. Values for creep compliance obtained in their study (~0.28 – 0.4 GPa^{-1}) are similar in magnitude and trend to those found in the current work.

Quasi-static nanoindentation revealed that Simplex cement exhibited modulus and hardness values significantly greater than Palacos. This finding is contrary to those observed in flexural testing and can be explained by the type of co-polymers used within the cements. The styrene contained within Simplex is a stiffer material than the methyl acrylate used in Palacos, however, at the macroscale this difference was not observed. Flaws within Simplex,

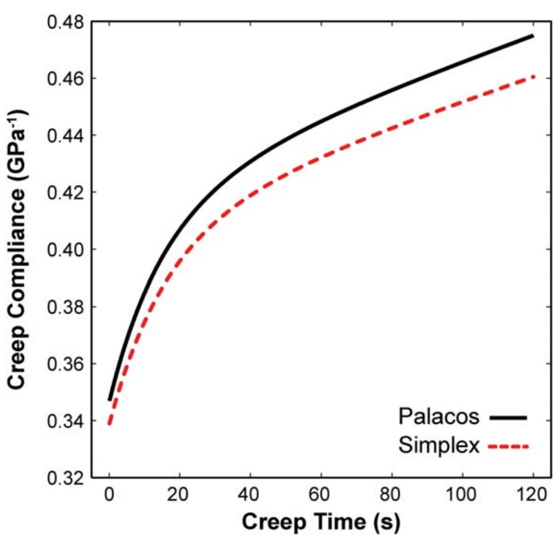

FIGURE 6. Creep compliance curves obtained from nanoindentation testing.

such as those caused by radiopacifier agglomerations, could potentially obscure the influence of the styrene copolymer. Nanoindentation is performed at a length scale able to avoid these factors and hence probe the underlying mechanical properties of the polymer. Additionally, relative differences in mechanical properties between the two methods can result from variations in loading modes. Macro-scale three-point flexural testing applies a normal stress and transverse shear stress in the bending plane of the beam sample, while nanoindentation results in a transverse loading scenario[30]; the stress distribution in nanoindentation is more complex relative to a bending loading mode.

While nanoindentation has been widely applied to characterize the mechanical properties of polymers, there have been relatively few studies utilizing the technique to characterize acrylic bone cement. Arun et al.[31] reported a hardness of 140 MPa for Simplex cement, which is substantially lower than the value of 273 MPa determined in this work, likely caused by differences in the loading profile and peak force (hardness is generally positively correlated with indenter tip penetration). Lewis et al.[32] used nanoindentation to measure the mechanical properties of Palacos samples retrieved from hip implants after 0.9–21 years of *in vivo* service. They reported elastic modulus and hardness values ranging from 2.82 to 3.78 GPa and 94 to 169 MPa, respectively, which agrees well with the value of 3.72 GPa for Palacos measured in this study. Differences in measured hardness can again be attributed to variations in loading profiles, among others. Finally, a recent study from Prokopovich et al.[33] used an atomic force microscope to perform nanoindentation on cement samples (brand name not provided) and reported modulus values ranging from ~4 to 24 MPa, a discrepancy potentially caused by difficulties in using atomic force microscopy to perform nanoindentation on hard polymers.[34]

The plasticity index is a measure of the elastic-plastic response of a material, where 0 indicates fully elastic behavior and 1 indicates fully plastic[35] while the recovery resistance describes the energy dissipated during an indentation loading cycle.[36] The plasticity index of Palacos and Simplex was not significantly different from each other and the calculated values indicate that both cements exhibit viscoelastic-plastic behavior, as expected. The recovery resistance of Simplex was significantly higher, thus demonstrating enhanced elastic work and recovery of the surface post-indentation.[19] Compared to a study conducted by Karimzadeh and Ayatollahi[19], who reported values of 0.78 and 241 for plasticity index and recovery resistance, respectively, values calculated in the current work are significantly lower.

Creep testing performed with nanoindentation was found to be well described using a Burgers model, similar to results from flexural testing. The model parameters given in Figure 7 demonstrate differences between flexural testing and nanoindentation, and while the magnitudes between the parameters vary, the same general trends are consistent. The calculated creep compliance from nanoindentation for both cements was generally higher than those obtained from flexural testing. Interestingly, the creep compliance of Palacos was found to be higher using nanoindentation

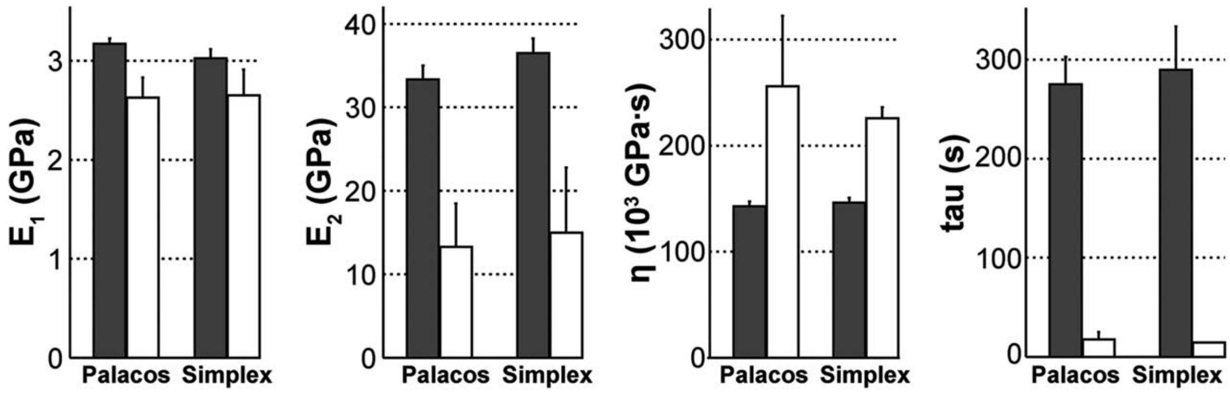

FIGURE 7. Comparison between the Burgers model parameters (mean ± SD) obtained from flexural testing (grey bar) and nanoindentation (white bar) for Palacos and Simplex cements.

(Fig. 7). Again, a potential explanation for this finding is the difference in the chemical compositions of the cements.

The frequency range used for dynamic nanoindentation testing was chosen to replicate loading frequencies seen in human gait and traumatic impact.[37] Values for storage modulus increased with increased testing frequency and ranged from 5.4 to 6.3 GPa and 5.2 to 6.4 GPa for Palacos and Simplex, respectively. In contrast the loss factor decreased with increasing frequency, as expected, with values for Palacos and Simplex of 0.05–0.08. To our knowledge, only one other study has used nanoindentation to characterize dynamic mechanical behavior of bone cement. In their study, Lewis et al.[13] reported storage modulus values of ∼4 to 6 GPa at loading frequencies of 2 to 200 Hz for Palacos bone cement retrieved from hip implants.

Several limitations of this study should be noted. First, all nanoindentation testing was conducted in dry conditions at ambient temperature, which was done for practical considerations since the ability to perform nanoindentation testing in a wet environment was unavailable. Likewise, to ensure consistency between testing methods, flexural creep testing was also conducted in dry conditions at ambient temperature. It is widely known that temperature and hydration have a substantial impact on the mechanical behavior of acrylic bone cement and while it would be preferable to conduct testing in conditions that mimic the *in vivo* scenario, all specimens were conditioned and tested in the same settings to minimize confounding factors. Additionally, prior work has demonstrated that submersion of bone cement in fluid generally results in a reduction of the mechanical properties while preserving the relative trends across cement groups.[38,39] Second, a hand-mixing technique was used to prepare cement samples even though vacuum mixing devices are sometimes used clinically. Since vacuum mixing can influence the porosity of bone cement, among other factors, it could potentially elicit different results. Last, a relatively short creep time was used for nanoindentation testing to mitigate the effect of drift (thermal, mechanical) that can introduce errors into nanoindentation measurements. Future work should investigate extended nanoindentation creep times while implementing newly introduced control algorithms that allow total compensation of drift effects.

CONCLUSION

In this study, the quasi-static and viscoelastic properties of two commercially available orthopaedic bone cements were determined using a combination of macro and nanoscale. It was observed that despite high similarities in bone cement

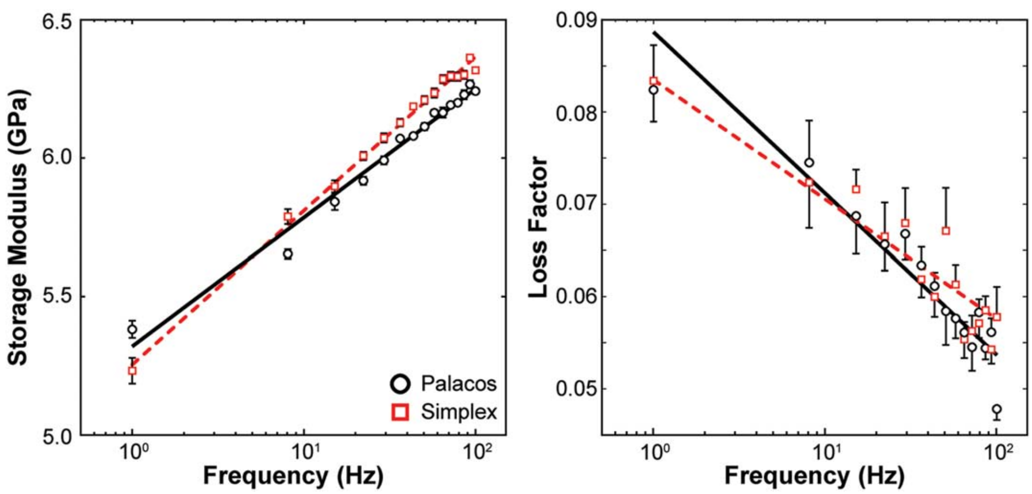

FIGURE 8. The storage modulus and loss factor of the cements (mean ± SD) obtained from dynamic nanoindentation frequency sweeps.

formulations, alterations to the chemical composition can have a large impact on the resulting mechanical properties. Creep experiments conducted using nanoindentation resulted in creep compliance values slightly higher than those found with flexural creep. Regardless, nanoindentation is an attractive technique for biomaterial characterization, due to the small sample volume required for testing. This may prove particularly useful in testing failed/retrieved materials from patients where material availability is limited and could thus provide information regarding *in vivo* failure mechanisms of bone cement. Finally, these data can be used as input parameters into various computational techniques, such as finite element analysis, to aid in the design and evaluation of orthopaedic implants.

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