Dynamic creep behavior of acrylic bone cement

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Recent studies concerning the fixation of cemented total hip arthroplasty (THA) have led to new hypotheses about the dynamic, long-term failure mechanisms leading to prosthetic loosening. As a result, the long-term mechanical behavior of acrylic bone cement has gained more interest since little is known about these properties. In this study, the dynamic, compressive creep deformation of acrylic bone cement was examined. An amount of creep was found, with creep strains exceeding the elastic strain during $14 \times 10^6$ loading cycles. There was a linear relationship between the logarithmic values of the number of loading cycles and the creep strain. The effect of stress level on the amount of creep was different from that in results of static experiments reported in the literature. Comparing the results with tensile creep experiments revealed that bone cement under a tensile load creeps much quicker than under a compressive one. Young's modulus was significantly higher when the material was loaded at higher strain rates. The bone cement became stiffer with an increasing number of loading cycles. The creep behavior of bone cement is important for the long-term behavior of cemented THA. It enables subsidence of the stem and attenuation of stress peaks in the cement mantle.

INTRODUCTION

The clinical success rate of total hip arthroplasty (THA) exceeds 90% at 10 years postoperatively. However, because of the increasing number of THAs performed each year, the number of revisions is still increasing. One important aspect in the failure of cemented THAs is the mechanical performance of the bone cement. Static and dynamic mechanical properties of bone cement have been determined by many investigators. When compared to the stress levels expected in the cement mantle, the strength values found indicate that the bone cement is prone to fatigue fracture due to dynamic loading. For this reason, subsidence of a prosthesis is often associated with the occurrence of cement fractures. However, radiologic observations of THA show subsidence of the stem within the cement mantle without visible cement fractures. This phenomenon has led to the hypothesis that bone cement creeps under physiologic loads, giving the stem the opportunity to subside without the occurrence of cement fractures. To validate this hypothesis, the amount of creep occurring in the bone cement has to be determined. Several investigators have studied the creep and relaxation behavior of bone cement. These studies revealed that creep strains could exceed the elastic ones.

However, these studies investigated the performance of bone cement under static loading conditions, while bone cement under in vivo conditions is loaded dynamically. Using a four-point bending test, Lee et al. demonstrated that bone cement does creep when exposed to dynamic forces. However, their experiments were relatively short and the effect of stress level on the amount of creep was not determined. Verdonschot and Huiskes tested bone cement under tension and showed that a creep strain of about 50% of the elastic strain could be expected after 250,000 loading cycles. Specimens loaded at stress levels of 7 and 11 MPa showed the common primary, secondary, and tertiary creep phases. The latter phase involves crack initiation and propagation leading to fracture of the specimens. This phase was not present during the 250,000 loading cycles at a stress level of 3 MPa.

Considering the creep mechanism of bone cement, it is likely to give different results in tension and compression. The bone cement in vivo can be exposed to either one of these components. The purpose of this study was to test this hypothesis and determine the creep parameters in tension and compression. The creep behavior under dynamic tensile loads was already determined. In this study, we determined the
MATERIAL AND METHODS

Surgical simplex P bone cement was hand mixed for 2 min and hand packed in a polytetrafluoroethylene (PTFE) mould. The molds were sealed and the cement was allowed to cure for 15 min. In this way, standardized cylindrical compressive specimens (32 mm in length, 17 mm in diameter) were fabricated. To ensure that the end-faces were perpendicular to the longitudinal axis of the specimens, they were ground and polished using a metal mold. The specimens were radiographed and stored in saline solution at a temperature of 37°C for a period of 3–6 months.

To investigate the time-dependent behavior of bone cement, 20 specimens were exposed to a sinusoidal load from 0 to a particular compressive amplitude with a frequency of 1 Hz. To investigate the effects of loading, four physiologic load levels with a maximum of 7, 11, 15, and 20 MPa, respectively, were used. In this way four test groups, each composed of five specimens, were obtained. The dynamic compressive creep tests were performed under load control using an MTS servohydraulic system (MTS, Berlin, Germany). The experimental configuration is shown in Figure 1. Specimens were kept in saline solution at a temperature of 38.5°C during the whole testing period. This temperature was chosen to simulate the actual in vivo temperature rise in a THA reconstruction as a result of hip-joint motions, as measured by Bergmann et al.\textsuperscript{14}

The displacement were measured using an Instron extensometer with a resolution of 0.58 \( \mu \text{m} \). The displacement and force signals were recorded and stored in a computer. The duration of the tests was 250,000 cycles in all cases. After testing, the relationships between the amounts of creep, stress-levels, and number of loading cycles were determined. The elastic properties of the specimens were analyzed as well.

An important reference of the amount of creep strain is the elastic strain at a particular load level. Using the established relation between creep strain, number of loading cycles, and stress level, the number of loading cycles was calculated, which led to a creep strain which equaled the elastic strain. The elastic strain was determined by the ratio of the stress level and Young’s modulus. The results were compared with data from the literature concerning static and dynamic creep behavior of bone cement.\textsuperscript{8,13}

RESULTS

The viscoelastic behavior of bone cement under a compressive dynamic load becomes clear when the immediate strain response to the dynamic force is considered (Fig. 2). A small phase shift was found in the strain signal relative to the stress signal. As a result of bone cement creep, deformation of the specimens progressed with the number of loading cycles. The creep-strain amplitudes as functions of the number of loading cycles are depicted separately for each group in Figure 3. The total creep strain after 250,000 loading cycles was significantly different (\( P = 0.01 \), Student \( t \) test) among the four test groups. Higher creep strains were found in groups with higher load levels. Conventional creep theories suggest that the creep curves exhibit a linear relationship between time (\( t \)) and creep strain (\( \epsilon_c \)) when considered on a double-logarithmic scale. This model was also used

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{figure1.png}
\caption{Schematic of the experimental configuration.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{figure2.png}
\caption{The strain response of a sinusoidal load.}
\end{figure}
by Chwirut, who performed static compressive creep tests on bone cement specimens. We applied this model to our experimental data with time (t) being replaced by the number of loading cycles (N):

$$\log \varepsilon_c = b_0 \log N + b_1$$

where $b_0$ and $b_1$ (depending on the stress level $\sigma$) are the parameters to be determined.

Because of relatively large variations during the first 600 loading cycles, we decided to discard this period in the model-fitting procedure. Applying Equation (1) to the creep data revealed that parameter $b_0$, representing the inclination of the log-log creep curves, was not statistically different ($P = .01$) among the four groups (Table I), although it must be appreciated that $b_0$ tended to be higher in the group with 20 MPa. For this reason we chose a constant value $b_0 = 0.314$ (SD 0.036) as the average of all groups.

Using this value for $b_0$, the values for $b_1$ were determined (Tables II–V). The tables also give the standard errors of estimate (SEOE) which represent the average error between the creep values predicted by the model with respect to the experimental data. This error is $<5\%$ of the total creep strain at the end of the tests. It appeared that $b_1$ was statistically different ($P = .01$) in all groups. A higher value was found when

<table>
<thead>
<tr>
<th>Spec</th>
<th>7 MPa</th>
<th>11 MPa</th>
<th>15 MPa</th>
<th>20 MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.3540</td>
<td>0.3595</td>
<td>0.3069</td>
<td>0.3329</td>
</tr>
<tr>
<td>2</td>
<td>0.3654</td>
<td>0.2640</td>
<td>0.3091</td>
<td>0.3318</td>
</tr>
<tr>
<td>3</td>
<td>0.3676</td>
<td>0.3161</td>
<td>0.3115</td>
<td>0.3329</td>
</tr>
<tr>
<td>4</td>
<td>0.2186</td>
<td>0.2805</td>
<td>0.3066</td>
<td>0.3709</td>
</tr>
<tr>
<td>5</td>
<td>0.2795</td>
<td>0.2976</td>
<td>0.3140</td>
<td>0.3191</td>
</tr>
<tr>
<td>Mean (SD)</td>
<td>0.3050 (0.0601)</td>
<td>0.3035 (0.0368)</td>
<td>0.3096 (0.0031)</td>
<td>0.3375 (0.0196)</td>
</tr>
</tbody>
</table>
a higher maximal stress level was used. The dependency of \( b_1 \) on the maximal stress level was virtually linear (Fig. 4). The best-fit relationship was:

\[
b_1(\sigma) = 0.033 \sigma - 4.9117
\]

with \( \sigma \) (MPa) the maximal stress level generated by the dynamic load.

Combining Equations (1) and (2) leads to:

\[
\log \epsilon_c = 0.314 \log N + 0.033 \sigma - 4.9117
\]

which can be written in a more convenient way as:

\[
\epsilon_c = C N^{b_0} 10^{S\sigma}
\]

where \( C = 1.225 \times 10^{-5} \); \( b_0 = 0.314 \); \( S = 0.033 \); and \( \sigma \) is the total stress amplitude in MPa.

The creep strains found with this model for the four stress levels are depicted in Figure 5, together with the average experimental strain amplitudes in the four groups.

Using Equation (4), the number of loading cycles until the creep strain had reached the level of the elastic strain could be calculated. Obviously, this number of loading cycles depended on stress level, as is depicted in Figure 6. One should realize that both the creep and the elastic strains depend on stress level. The latter has a linear relationship, while the relationship of the creep strain on stress level can be described using Equation (4). At a stress level of 15 MPa it takes about 4000 h before the creep strain exceeds the elastic strain. Using other stress levels, this time period can be considerably shorter.

The tests were performed under load-control. This means that the strain rate became higher when a higher load amplitude was used. We defined the elastic modulus as the ratio between the amplitudes of the stresses and the strains. Figure 7 shows the average effect of the number of loading cycles on the elastic moduli for each group, plotted on a double-logarithmic scale. Statistical evaluation of the data showed that the logarithmic values of the elastic moduli increased almost linearly with the logarithmic values of the numbers of loading cycles:

\[
\log E = A \log N + B
\]

where \( A \) and \( B \) are the parameters to be determined. Parameter \( A \) represents the increase of the elastic modulus, while \( B \) indicates the logarithmic value of the initial \( (N = 1) \) elastic modulus in MPa. The best-fit relationships are listed in Tables II–V for each specimen. The elastic modulus increased for all specimens with the number of loading cycles (\( A \) is positive for all specimens). A comparison of the elastic moduli of the four groups during the first 3600 loading cycles revealed that higher-stressed specimens had significantly higher moduli \( (P = 0.01) \). A tendency was found of higher elastic moduli with higher densities (Table II–V).

**DISCUSSION**

Specimens were made by using hand-mixing techniques and hand packing in molds. This will cause
DYNAMIC CREEP BEHAVIOR OF BONE CEMENT

TABLE IV
Parameters of Group 3: Maximum Stress Level 15 MPa

<table>
<thead>
<tr>
<th>Spec</th>
<th>Density (g/cm³)</th>
<th>loge, = 0.134 · logN + b₁</th>
<th>SEOE</th>
<th>Total logE = AlogN + B</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.176</td>
<td>-4.429</td>
<td>17.94</td>
<td>1823</td>
</tr>
<tr>
<td>2</td>
<td>1.180</td>
<td>-4.412</td>
<td>18.99</td>
<td>1938</td>
</tr>
<tr>
<td>3</td>
<td>1.169</td>
<td>-4.421</td>
<td>39.67</td>
<td>1804</td>
</tr>
<tr>
<td>4</td>
<td>1.169</td>
<td>-4.341</td>
<td>58.50</td>
<td>2164</td>
</tr>
<tr>
<td>5</td>
<td>1.174</td>
<td>-4.415</td>
<td>27.45</td>
<td>1931</td>
</tr>
<tr>
<td>Mean (SD)</td>
<td>1.174 (0.005)</td>
<td>-4.404 (0.036)</td>
<td>1932 (143)</td>
<td>6.388 (0.001)</td>
</tr>
</tbody>
</table>

variations in the specimens such as polymer chain orientations, molecular weight, internal stresses, and porosity. For small creep strains, the creep behavior is very sensitive for these variations. This explains the variations found in the creep curves for low stress levels, and in the initial creep phase (Fig. 3).

Using different stress levels on bone cement with a constant frequency results in different strain rates. It appeared that Young’s modulus of bone cement was significantly affected by the strain rate. As Lee et al. and Saha and Pal also demonstrated, higher strain rates resulted in higher moduli. Not only the stress level had an effect on the elastic properties, but also the number of loading cycles. For all specimens it was found that Young’s modulus increased with the number of loading cycles. This stiffening effect can be explained by polymer chain reorientation, decreasing length, and the compression of pores in the specimen.

In the dynamic tensile experiments specimens were divided over three groups tested with maximal loads of 3, 7, and 11 MPa. They also found an increase of Young’s moduli for specimens of group 1. However, the moduli of the group 2 specimens were hardly affected by the duration of the tests, while group 3 showed a decrease in moduli when loading proceeded. This was explained by accumulation of internal damage in the higher-loaded specimens, leading to lower elastic moduli.

Compressive static creep tests have been reported by Chwirut. He defined the relationship between the creep strain (ε), loading time (t), and stress level (σ) as:

$$\varepsilon = C \cdot t^p \cdot \sigma^2$$  \hspace{1cm} (6)

where C = 1.798 × 10⁻⁶; b = 0.283; S = 1.858; and σ is the stress level in MPa. Comparing Equation (4) to Equation (6) reveals that the dependency of the amount of creep on the stress level under static conditions is different from that of dynamic ones. An explanation for this phenomenon is very difficult to find, but one can speculate that a cyclically loaded material, having the possibility of relaxing every loading cycle, may act different from a statistically loaded one. The dependency of the creep strain on loading time is about the same under dynamic and static conditions. The parameter representing the slope of the creep curves equals 0.314 in our study [Eq. (4)], while Chwirut reported a similar value of 0.283 [Eq. (6)].

The results of Chwirut are also included in Figure 6. In a large stress interval, Chwirut found creep strain rates which were considerably higher than found in our tests. Obviously, this is partly caused by the fact that bone cement is loaded continuously in static experiments, while it is unloaded every loading cycle in a dynamic experiment. On an average basis, statically loaded specimens are loaded with a load which is twice the amount of dynamically loaded ones. Hence, a higher creep rate can be expected. Besides this effect, it should be remembered that Chwirut tested the specimens already after 4 days.

TABLE V
Parameters of Group 4: Maximum Stress Level 20 MPa

<table>
<thead>
<tr>
<th>Spec</th>
<th>Density (g/cm³)</th>
<th>loge, = 0.134 · logN + b₁</th>
<th>SEOE</th>
<th>Total logE = AlogN + B</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.176</td>
<td>-4.257</td>
<td>36.09</td>
<td>2793</td>
</tr>
<tr>
<td>2</td>
<td>1.153</td>
<td>-4.246</td>
<td>65.24</td>
<td>2964</td>
</tr>
<tr>
<td>3</td>
<td>1.177</td>
<td>-4.227</td>
<td>64.97</td>
<td>3098</td>
</tr>
<tr>
<td>4</td>
<td>1.178</td>
<td>-4.296</td>
<td>97.26</td>
<td>2721</td>
</tr>
<tr>
<td>5</td>
<td>1.180</td>
<td>-4.250</td>
<td>36.84</td>
<td>2901</td>
</tr>
<tr>
<td>Mean (SD)</td>
<td>1.173 (0.011)</td>
<td>-4.255 (0.025)</td>
<td>2895 (147)</td>
<td>6.009 (2.187)</td>
</tr>
</tbody>
</table>
Figure 4. The effect of stress amplitude on the parameter $b_1$ obtained from the experiments and fitted by the creep model.

Lee et al. demonstrated that the storage period has a marked effect on the creep rate, with considerably higher strain rates with shorter storage periods. This is mainly caused by the polymerization process, which is incomplete early after mixing, which results in a lower creep resistance.

Verdonschot and Huiskes established the relationship between creep strain ($\varepsilon_r$), number of loading ($N$), and stress level ($\sigma$) under cyclic tensile loads as:

$$\varepsilon_r = C N^b \sigma^{5/2} N^{5/2 \log \sigma}$$  \hspace{1cm} (7)

where $C = 7.985 \times 10^{-7}; b = 0.4113; S_a = 1.9063; S_m = -0.116$; and $\sigma$ is the total stress amplitude in MPa.

The number of loading cycles required until the creep strain equals the elastic strain under these circumstances is included in Figure 6. It appears that bone cement creeps considerably quicker when it is loaded under tension. In the physiologic stress range of 5-15 MPa, bone cement creeps five to 10 times quicker under tension than under compression. However, it should be recognized that the elastic strain may not always be reached under a tensile load because the material may have failed before the elastic strain level is reached, because of fatigue.

Lee et al. measured the creep of bone cement under dynamic loads using a four-point bending test. To be able to compare our results with theirs, we simulated this experiment using finite element techniques and implemented the creep laws as obtained from our experiments [Eqs. (3) and (7)]. In our simulation the deflection of the specimen was about 20% smaller after 3 h of loading. This difference can be explained by the storage period of our specimens, which was about twice as long as that used by Lee et al. As explained earlier, longer storage periods can have a decelerating effect on the creep rates. However, apart from this difference, the results of Lee et al. can be approximated nicely with the relationships presented here.

This study demonstrates that cement does creep under physiologic conditions. Conceptually, it is possible to have a prosthesis subside without fractures in the bone cement. However, the amount of creep oc-
occurring in the in vivo situation depends on many factors, such as prosthetic shape and prosthesis–cement interface conditions, loading patterns and history, cement mantle thickness, porosity, and contaminations. Therefore, it is uncertain whether the prosthetic subsidence which is detectable on a radiogram can occur under in vivo conditions, and more research is required to give a definite answer. After implantation, the cement mantle is exposed to a certain stress distribution with high- and low-stressed regions. The amount of creep depends on the stress level. A higher stress level will result in a higher creep rate. Hence, high-stressed areas in the cement mantle are exposed to high amounts of creep. Therefore, it is likely that stress peaks will be attenuated. For this reason creep would also reduce stress peaks occurring in the acrylic material around implants. Again, the extent of this stress attenuating process is uncertain.

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References


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