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Creep Behavior of Hand-Mixed Simplex P Bone Cement under Cyclic Tensile Loading

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Acrylic cement, used for the fixation of total hip replacements and other orthopedic implants, is a subject of renewed scientific interest as a result of recent hypotheses about dynamic, long-term mechanical failure mechanisms suspected to play a role in prosthetic loosening. Little is known, however, about the long-term mechanical behavior of cement. In this study, the dynamic creep deformation of hand mixed acrylic cement was examined in laboratory tests. Strain patterns found represented the familiar creep process consisting of a primary, a secondary, and a tertiary creep phase. Specimens dynamically loaded with a maximum stress of 3 MPa from 0 were subject to creep of about 50% of the elastic strain after 250 000 loading cycles. A linear relationship between the logarithmic values of the creep-strain and the number of loading cycles was found. Specimens exposed to higher loads showed significantly higher creep-strains. No relationship could be established between the strain levels and the porosity of the specimens. Specimens dynamically loaded with a maximal stress of 7 or 11 MPa from 0 failed during the tests. The number of loading cycles to failure was similar to fatigue strength data reported in earlier literature.

INTRODUCTION

The application of bone cement (polymethylmethacrylate, PMMA) in total hip arthroplasty (THA) has made this operation a successful procedure. A large number of studies concerning the mechanical properties of bone cement and the factors that affect these properties were reported in the literature.[1] However, only a few studies concerning the time dependent behavior of bone cement have been published. Certainly, little is known about dynamic creep properties. It has been hypothesized that bone cement, as a polymeric material, creeps under physiological loads, giving the stem the opportunity to subside within the cement mantle without causing fractures of the cement.[2] To validate this hypothesis, the amount of creep under *in vivo* loading conditions has to be determined. Chwirut[3] found that the static creep of bone cement depends on the type of cement and the load level. Pal and Saha[4] demonstrated a higher static creep resistance when the bone cement was carbon reinforced. Øysæed and Ruyter[5] studied the effects of cross-linking agents, monomer/polymer ratio, and the testing temperature on the static creep behavior of PMMA. Treharne and Brown,[6] after studying the effects of numerous parameters on the static creep behavior of PMMA, concluded that reducing the porosity or residual monomer, increasing the powder size, or adding an MMA-styrene copolymer increased the creep resistance of PMMA. All studies were performed using static loading conditions. However, *in vivo* bone cement is exposed to dynamic loads. Using a four-point bending test, Lee et al.[7] demonstrated that creep does occur under dynamic, physiological loads, although the testing time was relatively short and the effect of stress level was not investigated.

In this article we present the results of cyclic tensile creep tests on bone cement. For this purpose we tested radiopaque Simplex P bone cement under a range of dynamic (physiological) tensile loads while it was stored in a bath of saline solution at a physiological temperature.

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MATERIALS AND METHODS

The cement used in the experiments was hand-mixed Simplex P with barium sulfate. Using a PTFE mold, 5-mm thick slices of the cement were made, machined to dumbbell shaped specimens (measuring area: 10 mm in width and 5 mm in thickness) according to DIN 53-4555. The specimens were radiographed and stored in a saline solution at a temperature of 37°C. To allow for complete polymerization and water absorption, the storage period was between 60 and 100 days for all specimens. It can be expected that the mechanical properties will hardly be different between 60 and 100 days after mixing.[8]

Tensile tests were performed with a material testing machine (MTS; Berlin, Germany). A sinusoidal dynamic

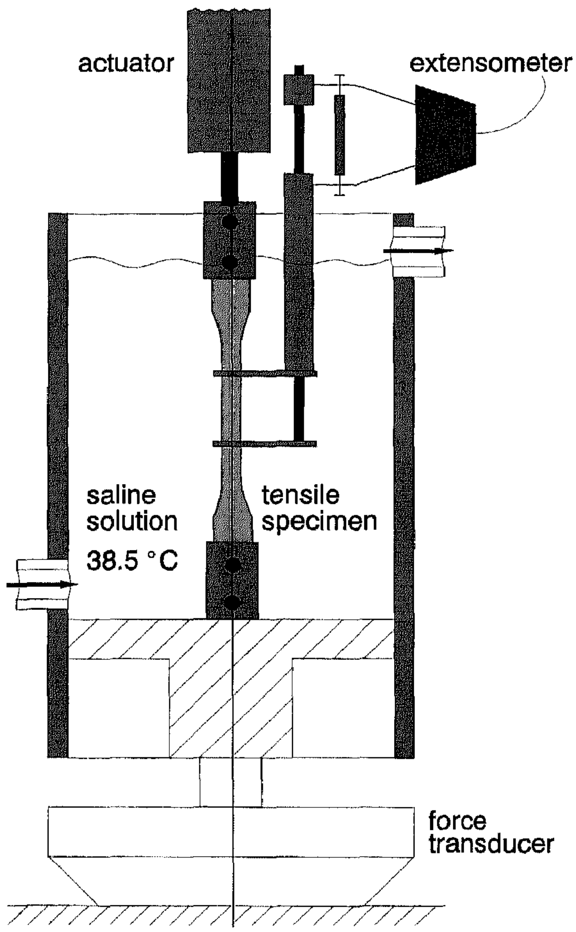

Figure 1. Schematic of the experimental configuration.

load was applied ranging from 0 to a particular tensile force amplitude with a frequency of 1 Hz. During the tests the specimens were kept in a bath of a saline solution at a temperature of 38.5 ± 0.1°C. 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 Rohlmann et al.[9] This temperature is higher than 37° because of frictional heat in the hip. The strains in the specimens were measured using a tube with a sliding rod mechanism on which an Instron extensometer was mounted. In this way a resolution of 10 microstrain was obtained. The experimental set-up is shown in Figure 1.

To analyze the influence of the amplitude of the load on the creep behavior of the cement, three load levels were used with maximal stresses of 3, 7, and 11 MPa. These levels are of the same order of magnitude as the expected stress levels in THA.[10–12] Specimens tested at stress levels of 3, 7, and 11 MPa were labeled as groups 1, 2, and 3, respectively. All specimens manufactured were included in the experiments. Fifteen specimens were equally distributed over the three testing groups, selected in such a way that the porosity distribution, judged from radiograms, was similar in each group. The tests were terminated after 250 000 cycles in group 1. In the other two groups loading was continued until the specimens fractured due to fatigue failure.

Both the loads and the displacements as functions of time were recorded, the former to check the loading of the specimens, the latter to obtain the relation between strain and time. In addition, the displacement signal of the actuator of the MTS machine was monitored to assess the overall displacement of the whole specimen. The sample frequency of the monitoring system is about 100 KHz.

To be able to accommodate the amount of data required in the limited storage area of the computer, the signals were not recorded continuously but in sample periods separated by time intervals. As the creep-strain rate was expected to decrease with time, the intervals between two sample periods increased (with a maximum of 1800 s) as the test proceeded.

After the experiments, the relation between creep-strain, number of loading cycles, and load level was determined. From the strains and the stress amplitudes, the cyclic elastic modulus could be calculated, defined as the ratio of the stress amplitude and the strain amplitude. In this way the elastic modulus could be determined in the initial stage and after the loading history.

In order to explain variations in the creep-strains as measured in the experiments, the density of the specimens was calculated and a porosity index was defined. For this purpose, the radiograms were digitized and evaluated on a quantitative video analyzer (Videk, Canandaigua, NY). The porosity index was defined by the ratio between the area containing detectable pores and the total measuring area. In this way an indication of the relative porosity among specimens was obtained. Obviously, one should recognize that this index does not signify the actual porosity, but is merely a qualitative parameter indicating the apparent porosity. In addition, the fracture surface of the specimens was digitized and the actual load carrying area at this surface was calculated.

RESULTS

The sinusoidal force resulted in a sinusoidal strain response (Fig. 2). The phase shift of the strain signal relative to the stress signal demonstrates the viscoelastic behavior of bone cement. A material with a higher creep resistance will show less of a phase shift between the stress and strain signals.

Due to repetitive loading the amplitudes of strain signal shifted, indicating that creep did occur. A typical time/displacement curve of the amplitudes of a Simplex P bone cement tensile specimen is shown in Figure 3. Three stages of creep can be identified which are hypothetically governed by three different creep mechanisms. In the first (primary creep) stage the amplitude creep-strain rate is relatively high and decreases rapidly as loading continues.

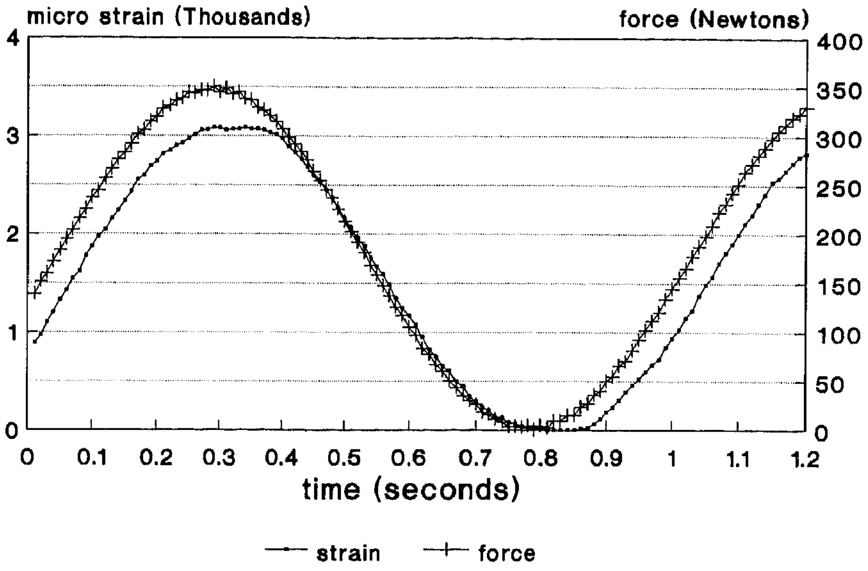

Figure 2. The strain response of a sinusoidal load.

The creep-strain rate in this phase is predominantly governed by the entanglement and stretching of the long molecules of the polymer. After the entanglement, the molecules slide along each other. The friction occurring in this process results in a fairly constant creep rate and identifies the secondary creep stage. Theoretically, these first two creep stages are recoverable, meaning that after unloading, the original shape of the specimen is restored. However, this was not verified in the experiments. The last stage (tertiary creep) is the phase in which the material undergoes a nonreversible change in material properties. Crazes and microcracks are formed, and the specimen eventually ruptures. The third stage was only seen in groups 2 and 3. This indicates that a specimen loaded at a tensile stress of 3 MPa (or lower) shows no signs of crack formation up to 250 000 loading cycles.

The discussion of the results is divided in two parts. The first part covers the primary and secondary creep stages, the second part discusses the irreversible phase (tertiary creep phase).

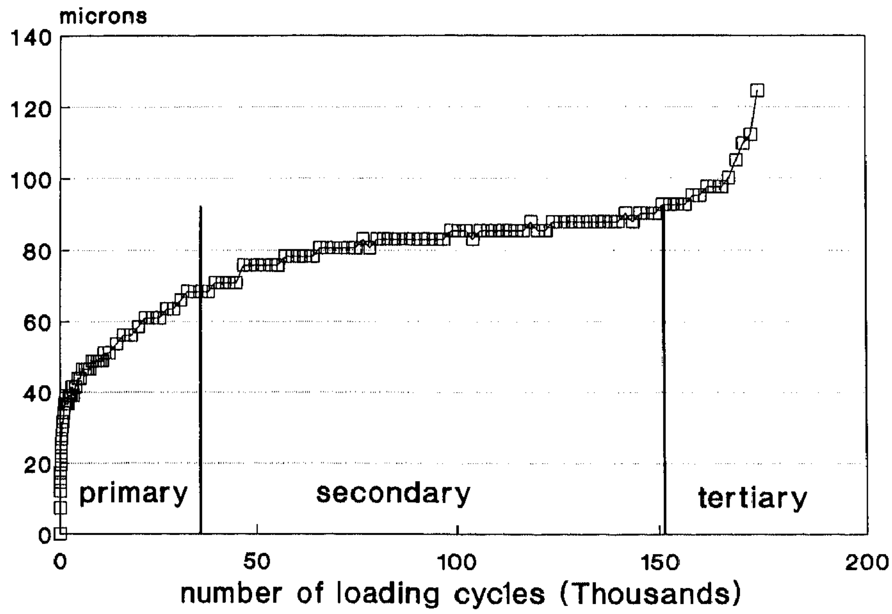

Figure 3. A typical time/amplitude-displacement curve of the actuator, showing three stages of creep of dynamically loaded Simplex P bone cement.

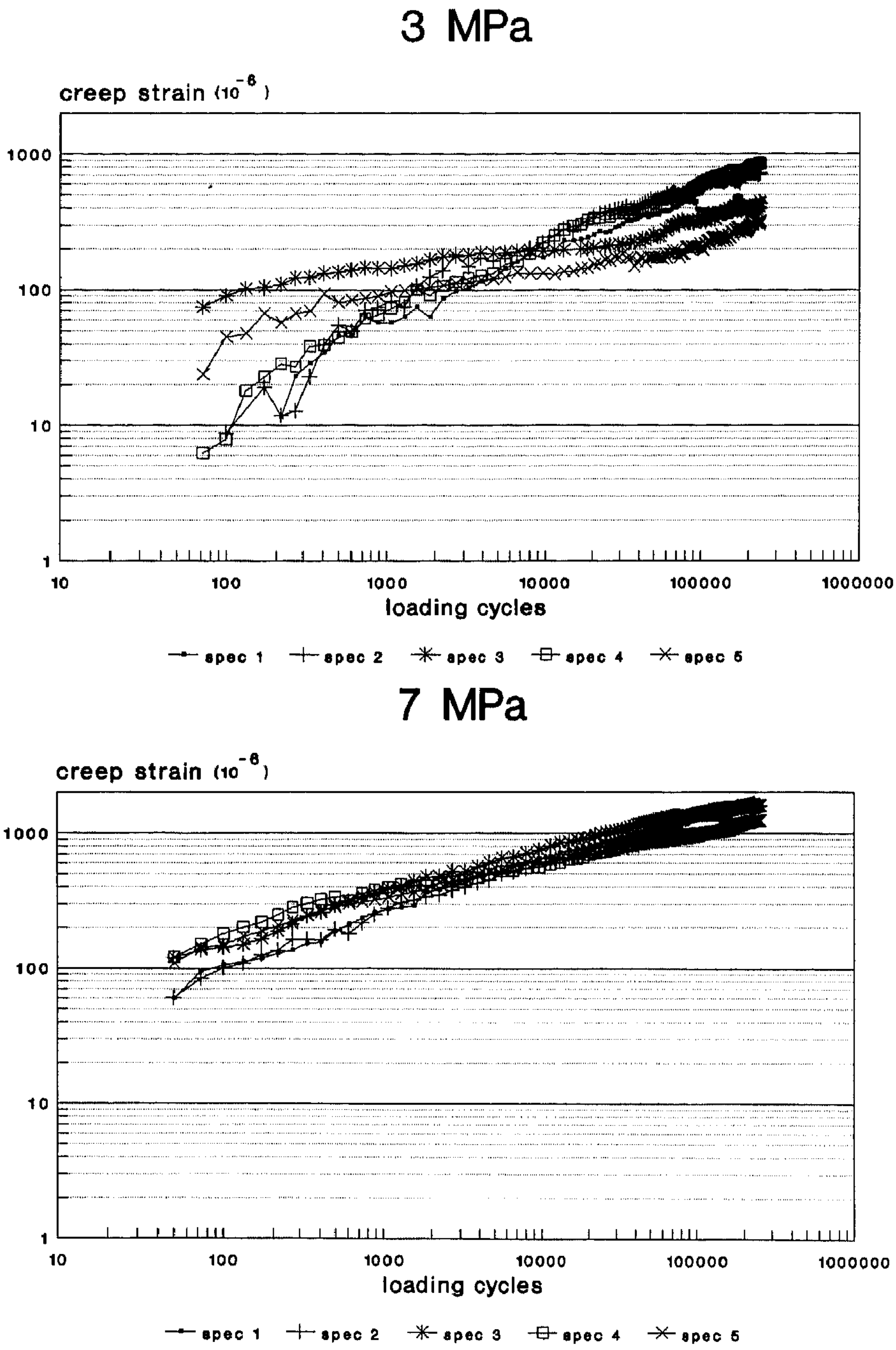

Figure 4. Amplitude creep microstrains as functions of number of loading cycles during the first two creep phases.

Primary and Secondary Creep Phases

The amplitudes of the creep-strains as functions of time were evaluated on a double-logarithmic scale. In the resulting curves, the primary and secondary creep phases could be identified by their more-or-less linear aspect; the beginning of the third phase is signified by a progressive nonlinear course of the curves. The curves representing the primary and secondary phases of all specimens are shown in Figure 4(a–c). The third creep phase was omitted because of the large variety of mechanical behavior occurring in this phase. For the primary and secondary phases of creep, a two-parameter creep model was chosen to linearly interpolate the log–log relationship between the creep microstrain (ϵ_c) and the number of loading cycles (N):

$$\log \epsilon_c = A(\sigma)\log N + B(\sigma) \quad (1)$$

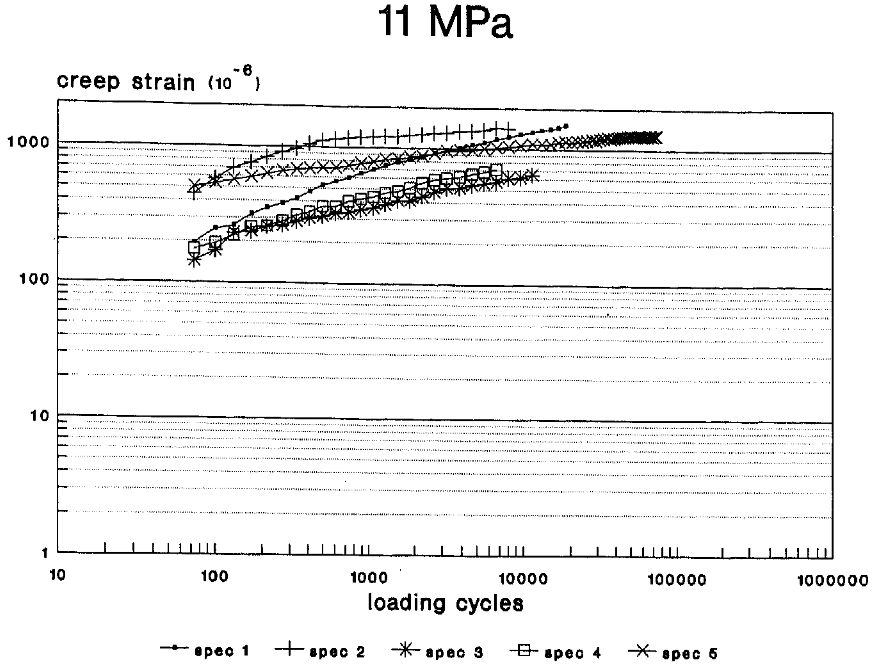

Figure 4. (continued).

where A and B are constants depending on the stress level (σ) to be determined from the tests. Parameter A indicates the slope of the straight line (strain-rate) on a double logarithmic scale; parameter B represents the intersect of the straight line with the strain axis at $N = 1$ cycle. In addition, the square of the correlation coefficient (R^2) was calculated. The values of these parameters (A, B, and R^2) are listed for each stress level in Tables I, II, and III. These tables also include the porosity indexes, the densities, the numbers of cycles, and the total creep microstrains at the ends of the secondary creep phase.

To elucidate the effect of the load levels on the creep-strain values, the average creep-strain amplitudes per group of specimens were calculated (Fig. 5). Strain amplitude levels due to larger loads are considerably higher. The parameter A (the slope) decreases and parameter B (the intersect) increases with higher load levels. However, the relation between these parameters and load level is not linear. In accordance with Chwirut et al.,[3] a logarithmic function was used to evaluate this relationship:

$$A(\sigma) = A1 + A2 \log \sigma \tag{2a}$$

$$B(\sigma) = B1 + B2 \log \sigma \tag{2b}$$

where $A1$, $A2$, $B1$, and $B2$, which are assumed independent of the load level, are the new parameters to be determined. Applying Eq. (2) to the data, the stress-independent parameters were determined as 0.4113, −0.1160, −0.0977, and 1.9063 for $A1$, $A2$, $B1$, and $B2$, respectively.

TABLE I. Parameters of Group 1

Cyclic Tensile Creep Test (3 MPa)							
			Number of Cycles (*1000)	$\log \epsilon_c = A \log N + B$			Total ϵ_c
Spec	Porosity Index	Density (g/cm³)	Primary and Secondary	A	B	R^2	Microstrain
1	0.047	1.09	250	0.3872	0.6407	0.92	515
2	0.075	1.16	250	0.4641	0.4246	0.95	739
3	0.046	1.16	250	0.1997	1.5218	0.95	433
4	0.033	1.16	250	0.4973	0.2869	0.98	871
5	0.075	1.13	250	0.2462	1.3311	0.92	321
Mean	0.055	1.14	NA	0.3589	0.8014		
(SD)	(0.019)	(0.028)		(0.1314)	(0.5152)		

TABLE II. Parameters of Group 2

			Cyclic Tensile Creep Test (7 MPa)					
			Number of Cycles (*1000)		$\log \epsilon_c = A \log N + B$			Total ϵ_c
Spec	Porosity Index	Density (g/cm³)	Primary and Secondary	Tertiary	A	B	R^2	Microstrain
1	0.043	1.17	163	1.8	0.3582	1.3066	0.98	1332
2	0.036	1.17	231	12.6	0.3645	1.2909	0.99	1621
3	0.044	1.16	251	30.6	0.2990	1.6356	0.98	1575
4	0.055	1.14	168	3.4	0.2525	1.7429	0.95	1172
5	0.050	1.17	329	1.8	0.2498	1.7396	0.99	1265
Mean	0.046	1.16	228	10.04	0.3048	1.5431		
(SD)	(0.007)	(0.014)	(68)	(12.34)	(0.0552)	(0.2273)		

Although only three measuring points were available to determine these parameters, which makes the fitting procedure a precarious matter, the model seems to fit nicely to the experimental data as Figure 6 demonstrates.

It can be seen that within each group relatively large variations in the creep-strains amplitude appear, especially in groups 1 and 3 (Fig. 4). In an attempt to explain these differences, the porosity and the density of the specimens were examined (Tables I–III). The porosity indexes do not signify the actual porosity but were derived by digitizing the radiograms. The average porosity indexes and the densities in each group were not statistically different ($p = 0.05$; Student t-test). This indicates that the division of the specimens over the three test groups was acceptable. The standard deviations for group 2 were smaller as compared to the other two groups. This might explain the smaller deviations in the creep curves produced in group 2. However, a closer examination revealed that no relation could be established between porosity index or density and the creep parameters.

We found average initial Young's moduli of 2158, 2301, and 2489 MPa for groups 1, 2, and 3, respectively. Traditional theories and some experimental data[8,13] indicates that polymeric materials act stiffer when exposed to higher strain rates, which would agree with the present findings. However, all literature data concerns constant strain rates. Cyclic test results have not been reported. There was no relationship between porosity index or density and the initial Young's moduli. Young's moduli of the specimens were affected by the repetitive loading pattern. In general, specimens of group 1 showed an increase in modulus. The moduli of the group 2 specimens were hardly affected by the duration of the tests, and group 3 showed a decrease in moduli when loading proceeded. This may demonstrate the higher amount of internal damage built up in the higher loaded specimens, leading to lower elastic moduli. However, the interspecimen variations were also relatively large.

Tertiary Creep Phase

In this phase local fracture of the cement material developed, that is, microfractures were formed and finally complete failure of the specimens occurred. The tertiary creep phase was not always registered by the extensometer because microfractures developed outside its range. However, the consequence was always traceable by the displacement pattern of the actuator (these specimens even-

TABLE III. Parameters of Group 3

			Cyclic Tensile Creep Test (11 MPa)					
			Number of Cycles (*1000)		$\log \epsilon_c = A \log N + B$			Total ϵ_c
Spec	Porosity Index	Density (g/cm³)	Primary and Secondary	Tertiary	A	B	R^2	Microstrain
1	0.032	1.16	20	<1.8	0.3809	1.6213	0.95	1551
2	0.043	1.16	10	<1.8	0.2696	2.2009	0.75	1387
3	0.130	1.12	13	<1.8	0.3363	1.5161	0.84	614
4	0.042	1.13	8	<1.8	0.3543	1.5488	0.93	710
5	0.048	1.18	73	5.4	0.1390	2.4530	0.95	1258
Mean	0.059	1.15	25		0.2960	1.8680		
(SD)	(0.040)	(0.022)	(27)		(0.0969)	(0.4300)		

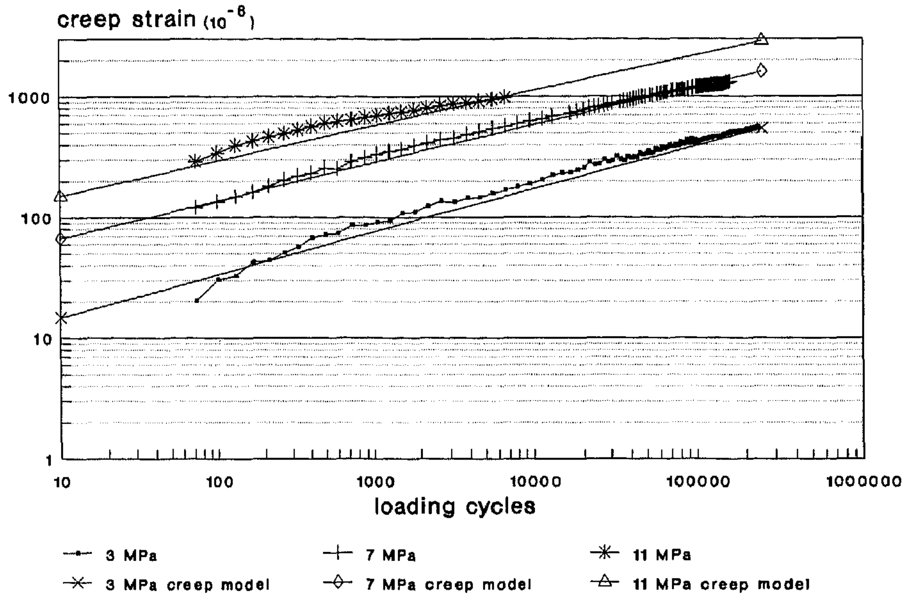

Figure 5. Average amplitude creep microstrains as functions of number of loading cycles and the fitted creep model for the three testing groups.

tually failed outside the measuring area of the specimen). Thus, the exact amount of tertiary creep within the measuring area was difficult to determine and was therefore omitted in Figure 4. However, the number of cycles spanning this elongation phase can be determined. The duration of this final phase was very different from one specimen to the other, even within one testing group (Tables II, III). This is probably caused by the fact that although specimens are exposed to the same load levels, locally the stresses may differ significantly. The elongation in the tertiary creep phase was also very different. One has to keep in mind that at a later stage the strain signal was only recorded every 1800 cycles. This is the reason that we were sometimes unable to measure any tertiary creep at all, while in other cases we measured elongations of up to 50 μm.

The specimens of group 3 fractured after significantly less loading cycles as compared to group 2 ($p < 0.001$). To explain the rather large variations in numbers of cycles to failure, the fracture surfaces were photographed and digi-

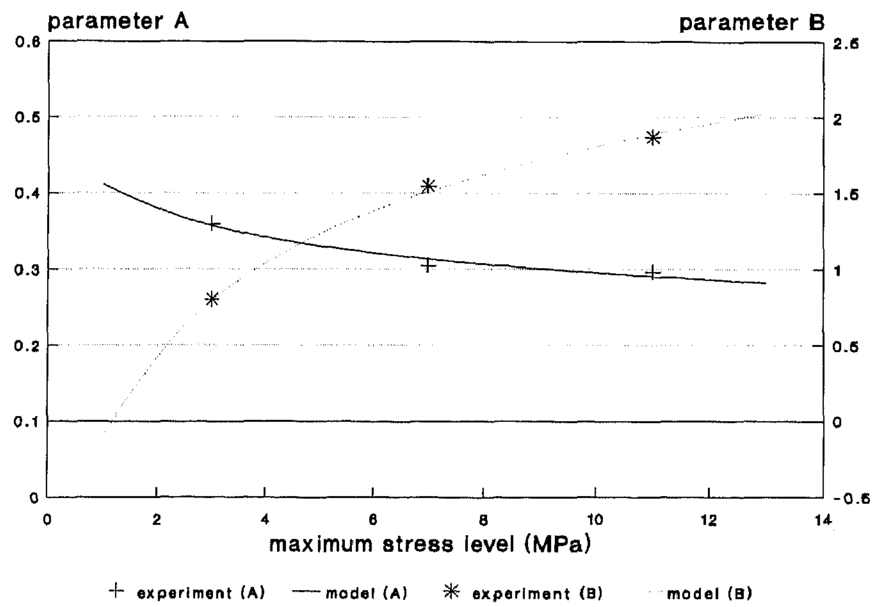

Figure 6. The effect of maximal stress level on parameters *A* and *B* obtained from the experiments and fitted by the creep model.

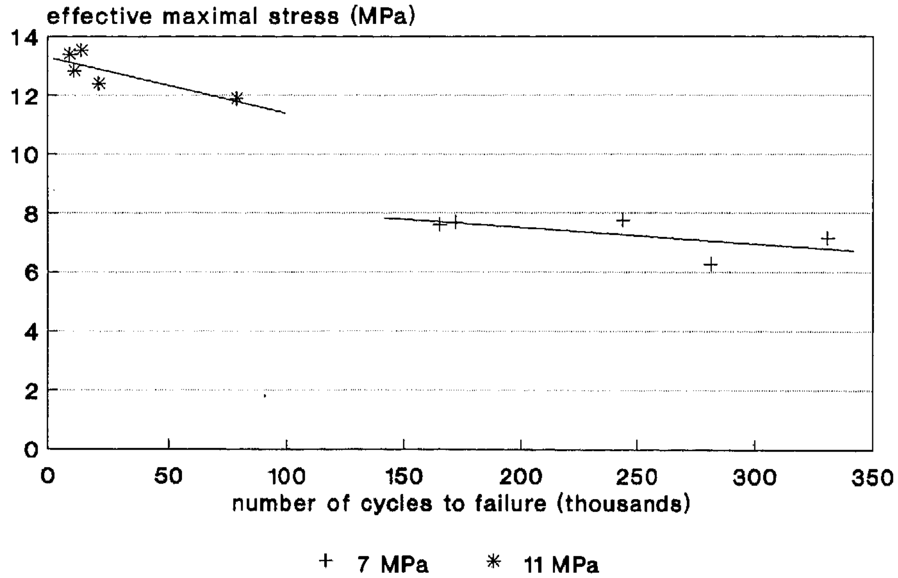

Figure 7. The influence of effective maximum stress level on the number of loading cycles to failure.

tized. In this way the effective area of the fracture surface could by determined. Knowing the effective area, the effective stress could be calculated that had been acting on the fractured section. A tendency of more cycles to failure with decreasing effective stress was found (Figure 7) as expected.

DISCUSSION AND CONCLUSIONS

This study indicates that acrylic cement creeps under physiological loading conditions. After 250 000 loading cycles, a creep-strain amplitude was found of about 50% of the elastic static strain. The model chosen to quantify the relationship between the creep-strain and test duration, often used in static experiments of creep behavior of plastics, seems appropriate. The creep experiments produced a linear relationship between the logarithmic values of the strains and the number of loading cycles, although one might argue that a bilinear one would be more appropriate in some cases. However, as we were interested in the global creep behavior of bone cement, we used only one linear equation. Therefore we accepted a small error between the model and the experimental data.

The strain rate is a function of time and of stress level. In the early stage, the creep-strain rate is considerably higher when higher loads are used. As loading proceeds the strain rates of the highly stressed specimens tend to decrease more rapidly than those of specimens loaded at lower stress levels. This phenomenon can be seen in Figure 5 where the creep lines, after extrapolation, will intersect at some point in time. However, it is not likely that this point will ever be reached because the specimens will probably have failed at that point in time.

Lee et al.[7] measured the creep of bone cement under dynamic loads using a four-point bending test. To be able to compare our results, we simulated this experiment using finite element techniques and implemented the creep law as obtained from our experiments. The results were very similar with less than 10% difference. Lee et al. also demonstrated that when using intralipid as a storage and test medium the creep rate was considerably higher. Davidson et al.[14] investigated the effect of various test media on the environmental stress cracking susceptibility of bone cement. They found an increase of over 20% in cracking susceptibility when tested in lipid solution relative to a saline medium. With respect to these findings it must be recognized that our creep experiments in which we used saline solution as a storage and test medium, may underestimate the creep strain rate and may overestimate the fatigue lives of bone cement.

The experiments not only revealed the creep behavior of bone cement but also the fatigue performance of the material. A number of investigators have reported the number of cycles to failure as a function of load level.[15–20] For a load level of 11 MPa fatigue lives of 10 000 to 20 000 cycles were reported for bone cement under tensile loading. Fatigue tests at lower load levels are more difficult to interpret because these stress levels are close to the fatigue limit of bone cement. Pilliar et al.,[16] while testing in air, found a fatigue limit of about 10 MPa. Cipoletti and Cooke[21] tested their specimens in saline at a temperature of 37°C and reported a fatigue limit of about 6 MPa. In our experiments we did not establish the fatigue endurance limit because the experiments were terminated deliberately after 250 000 loading cycles. Only the specimens loaded at a maximal tensile stress of 3 MPa survived this amount of loading cycles.

Although the creep model applied produces a good fit of the relationships between strain, time, and load level, it must be appreciated that variations between specimens are considerable. These cannot be explained completely by differences in porosity. Other factors such as nonhomogeneous mixing, variations in molecular orientation, internal stresses, and the degree of polymerization can also be responsible for variations in the creep characteristics of bone cement.

This study was performed to establish the dynamic creep behavior of hand mixed Simplex P bone cement, stored and tested in saline solution. A number of parameters of major clinical importance were not investigated. Although the porosity was considered to explain variations between the specimens, the actual effect of porosity was not investigated as a parameter. As an increasing number of clinicians use vacuum mixing or centrifugation it would certainly be worthwhile to investigate the effects of these advanced mixing procedures on the creep properties of bone cement. It has also been demonstrated that bone cement is very susceptible to environmental conditions.[7,14] Therefore, it is important to establish the effects of various storage and test media (e.g., intralipid). Finally, as Chwirut et al.[3] already demonstrated, different brands of bone cement reveal different creep behavior under static loads. It is certainly of interest to determine the creep properties of these different brands under dynamic, physiological loading conditions.

This study was performed to investigate whether bone cement creeps under pseudophysiological circumstances. It appeared that this is the case. This may affect the long-term endurance of total joint reconstructions. Due to creep, the prosthesis could subside in the cement mantle without the presence of cement cracks. As the bone cement creeps quicker under higher load levels, high stresses in the bone cement mantle may be reduced in time. The present data will be very useful for future investigations focused on the actual response of joint reconstructions with respect to subsidence and relaxation of stresses in the cement mantle.

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